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Review

Review on the Hybrid-Electric Propulsion System and Renewables and Energy Storage for Unmanned Aerial Vehicles

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The unmanned aerial vehicle (UAV) is an aircraft without a human pilot, and thus the primary applications of UAVs are surveillance without human loss. A low altitude surveillance aircraft is the foundation for the use of light sensor payloads in a small airframe. As surveillance usually needs to be performed covertly, thus the silent flight's capability allows the use of low altitude aircraft. For the UAV propulsion, Photovoltaics are useful to harvest solar energy during the daytime, whose one part is being used directly to power the propulsion unit and onboard instruments while the remaining part is being stored in energy storage system for night-time. In this context, electrochemical energy sources stored in batteries and fuel cells are the two best candidates because of the highest gravimetric energy density. To conclude, this review aims to improve the high-altitude long-endurance of a UAV equipped with the hybrid-electric propulsion system.

Keywords: Unmanned aerial vehicle; Photovoltaics; Battery; Fuel cell; Hybrid electric propulsion system; High altitude long endurance

1. INTRODUCTION

Recently, unmanned aerial vehicles (UAVs), popularly known as drones have attracted the attention of worldwide scientists due to technological development in aeronautics and astronautics. For instance, sensors, motors and control devices have become more accurate, smaller and lighter as well as the fact that the number of UAV applications have also been booming over the past few years for both military and civil targets. Thus, there is no doubt that studies on UAVs have been embraced by both industry and academia. In comparison with manned aerial vehicles, UAVs express a low-risk, affordable and repeatable flight environment. Besides, they play an important role as an initial platform for technological advances, which may then be served for commercial applications. However, the applications of drones have been limited due to some problems related to the energy storage of electrical or liquid fuel sources. As a result, it is necessary to find out sustainable energy sources or technological advances to solve these problems. Normally, drones operate at the elevated altitudes, and thus, solar energy is a good suggestion for applying as the propulsion system. However, there are some disadvantages of solar energy such as its low power density and weather dependence. The hybrid solutions that combine photovoltaic (PV) panels with industrial-grade rechargeable battery should be considered as the propulsion system for UAVs. This system composed of PVs as a renewable and rechargeable battery or unitized regenerative fuel cell (URFC) works as the electrochemical energy storage system.

Flight vehicles powered by electrical power source were conducted in the latter half of the 19th century. At that time, the electric system revealed more advantages when compared to the steam engine; however, it became weak with the arrival of gasoline engines, the abandoned work on electrical power for aircraft and the long dormancy of the fields. In 1954, Daryl Chapin developed the first PV cell to convert the sun's energy into electricity to power equipment and it was used to power the Telstar Communications Satellite, leading the way to other space applications [1]. Furthermore, R.J. Boucher debuted the first aircraft with a wingspan of 9.75 m and weight of approximately 8.6 kg powered by solar energy in 1974, under the project funded by the Advanced Research Projects Agency [2]. The first aircraft version of this project named Sunrise I reached the altitude of more than 1200 meters in November 1974, and the updated aircraft version called Sunrise II had a service ceiling of about 22000 and 7600 in summer and winter, respectively. With the same dimensions, the updated versions were developed to reduce its weight to 10.2 kg and retrofit about 4500 solar cells, and thus their power reached t600 W thanks to the efficiency of 14%. In 1980, Paul MacCready created a big step forward when the human-crewed aircraft powered by PV was launched. This concept craft was retrofitted with 16,000 solar cells on its wings, corresponding to the power of 2.5 kW without energy storage devices [3].

Electric power has been favoured for unmanned aerial vehicles because of its advantages such as high efficiency, reliability, lower noise as well as precise control [4-5]. These key features are the prominence of the electric power compared to the internal combustion engine (ICE) despite the higher power densities of ICEs. Drones powered by a hybrid system of a battery and an ICE can exploit both their advances as described in [6-7]; however, the polluted environment and the greenhouse effects are still a high-priority criterion in this field. There is a fact that many commercial UAVs are powered by batteries with their flight time of about two hours. However, despite all the advantages of battery characteristics, they are still unable to adapt long and persistent UAV missions when used as a unique power source due to their low power density [8-10]. Multiplying batteries is not a perfect solution to solve the problem due to its space and weight constraints because UAVs have to bring an extra energy source [11-14]. In this context, a fuel cell system is a good solution due to its high power density and fast refuelling. Thus, the fuel cell plays the role as the main power source and other sources will be activated in special operating conditions [15-17]. For this reason, the hybridization system of fuel cell and solar energy is a good option for UAVs because they can bring solar cells in their wings. Consequently, the flight distance can be extended, and hydrogen can be saved [18-22]. The research results in [23-25] also concluded that the power system of the photovoltaic cell and the fuel cell is the most investigated solar-fuel cell coupling. In Reference [26] they combined the power systems of photovoltaic, PEM fuel cell, Li-ion battery. Ramadan proposed a system coupling solar thermal system and fuel cell. As a result, the PV system is used to power an electrolyser to generate hydrogen for the fuel cell. The study examined the power supply in terms of the efficiency of the PV system daily [27]. During the operating conditions, UAVs conduct complicated missions such as take-off, lift-of and climbing, so the adaptable power should be instantaneously supplied. To adapt this work, some researchers selected supercapacitors as the power supply system due to their very high power density [28-29]. The hybridization system is a key solution to enhance the flight distance; however, the choice of the suitable energy system is so complicated due to the consideration of both power sources characteristics and mission types.

This review aims to analyse the fundamental operation of aircraft powered by electricity, solar cell as well as a fuel cell to show the panorama of these power sources applied to UAVs and focuses on the design of hybrid power system with URFC and PV for UAVs. It also illustrates a new design methodology and contributes to addressing the problems related to the flight distance and propulsion power management system. For these proposals, the contribution concerning this methodology lies on four pillars: simplicity; large design space; concrete and experienced-based; flexibility and versatility. The review article contributes to the realization of a fully functional unmanned aerial vehicle. The design methodology was not limited to a theoretical study only verified with simulations, but we aim to verify it through the comparison of previously studied results. This review provides the modest ambition to draw up a state of the art on UAV aviation with URFC and PV from its beginning until now, referencing the major scientific papers on the subject. An exhaustive list of all UAV aviation with URFC and PV flew to date is presented in this review. In conclusion, we tried to analyse the development of solar aviation in the next decades.

2. POWER SUPPLY ARCHITECTURES FOR UAVs

2.1. Techniques of battery power source solution for UAVs

The battery power source has become an integral element of modern life, applied to communication and navigation devices, deployed sensors, portable multimedia players, and especially power energy for propulsion systems. In general, a battery converts chemical energy into electricity by redox (reduction-oxidation) reactions between active elements such as anode, cathode, and electrolyte. In the battery's architecture, the electrolyte located between the anode and cathode electrode plays the role as the shared medium for reactions of the redox process as described in Fig. 1.

The battery currently arises due to the electron transfer between the anode and cathode. In the discharge process, the reduction reactions at the cathode happened due to electrons produced and transferred from the oxidation reactions at the anode side. Since electrons do not move backward, electrical neutrality is maintained due to the ion movement via the electrolyte. Oppositely, a salt bridge will join the two electrolyte solutions if there is any different electrolyte of each reduction-oxidation reaction. Normally, the same electrolyte is used for both side of the anode and the cathode, and ions transport via the electrolyte itself, eliminating the needed salt bridge. However, when a separator is inserted between the anode and the cathode, it prevents the contact between the anode and cathode side; and if the contact is formed, it would short out the battery as the electrons can move directly without moving via the external circuit.

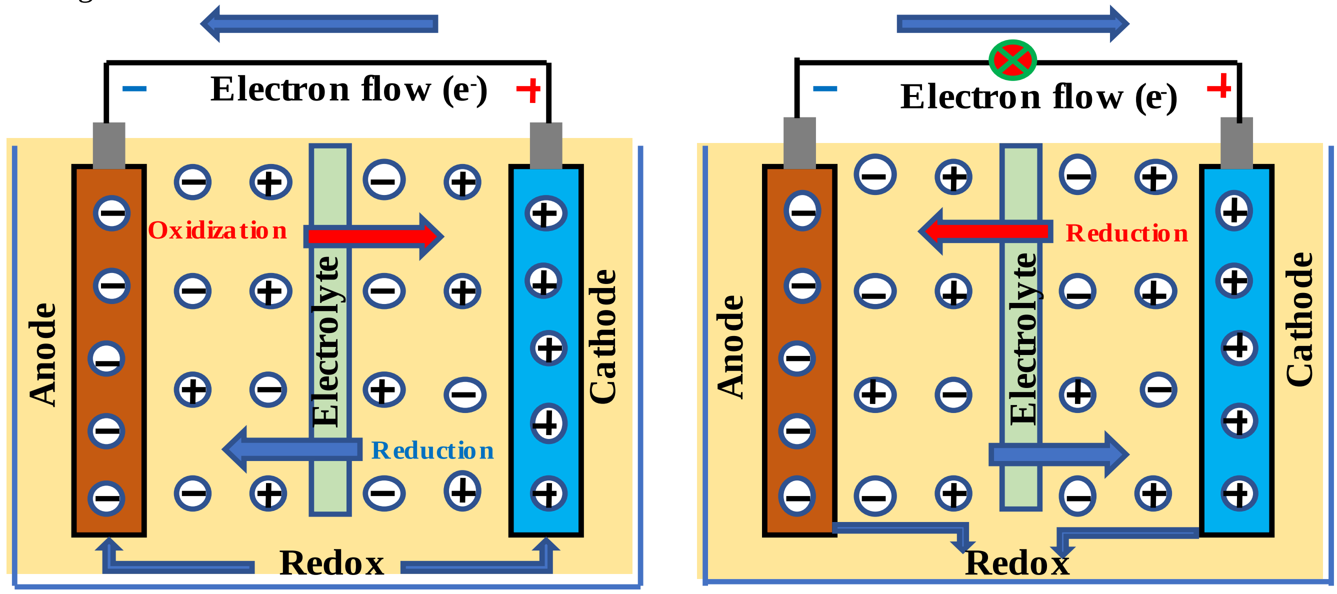

Figure 1. Battery cell operation under (a) charging mode and (b) discharging mode

Alessandro Volta, an Italian physicist invented the first battery in 1800 by stacking copper and zinc discs separated by a cloth soaked in salty water [30]. The lead-acid battery invented in 1859 is one of the most enduring batteries and has been popular until now. In 1980, John Goodenough invented lithium battery in which the lithium could migrate through the battery from one electrode to the other electrode as Li^+ lithium. Lithium is a light element and has huge electrochemical potentials, and thus these advances could generate a highly possible voltage in the most compact and smallest volume [31-33]. As mentioned in many studies, the battery could prove to be of great potential power for UAVs. Maximum flight time is one of the biggest challenges in this field, so larger batteries would be the best solution for this issue. However, larger design relates to the increase in the size of the battery. Therefore, it becomes inefficient in some operation cases [34-35]. As a result, battery technologies can deal with enhancing the battery density by altering the chemical composition such as Lithium polymer, Lithium-ion, Lithium Cobalt oxide, Lithium Iron-phosphate. To measure the flight time, Azeta J performed an experiment of the DJI Inspire 2 drone model composing of two 4280 mAh batteries with a net weight of 515 g. The results of this experiment showed that the two flight batteries could support the flight time of 25-27 minutes under ideal conditions [30]. In another research shown in [36], the UAV model powered by LiPo batteries can fly with a maximum flight time of 90 minutes. Table 1 shows the flight time of some commercial UAVs available in the global market [37-38]. It can be observed that the flight time varies according to the configuration of the UAVs. The flight time is normally about 20 to 30 min on average. Especially, the fight time can reach up to 90 mins with the design of the Skylark II model powered by a 4kW electrical motor made by Elbit Systems. This flight model features a 10 kg payload and can operate in medium and low altitudes with a maximum altitude of approximately 5 km.

Table 1. Parameter characteristics of some commercial UAVs powered by electrical sources

Flight model	Flight time (min)	Max flight speed (km/h)	Weight (kg)
Autel X-Star premium	25	56	1.6
DJI Phantom 3	23	57	1.28
DJI Phantom 4	28	71.5	1.38
DJI Inspire 2	27	21.5	3.44
DJI Inspire Pro	15	17.8	3.5
DJI Matrice RTK	27	82.2	3.80
KAIDENG K70C	10	-	0.57
Parrot bebop 2 power	30	-	0.525
JXD 509G	10	-	1.2
Quanum Nova	15	-	0.875
SYMA X8HG	7	-	1.5
Yuneec Tornado H920	24	39.8	4.9
Typhoon K	25	7.2	1.7
Typhoon H+	28	14.4	1.645
Walkera Scout X4	20	56	2.27
Voyager 3	25	-	3.650
Kaideng k70c	10	-	0.579
UAVER Avian-P	90	63	4.7
Skylark II	90	40	4
Drone Metrex Topodrone	60	80	4.5
FoxTech Kraken-130	15	10	6

In the operation of UAVs, the propulsion system powers the motion of UAVs by converting the stored electrical source of batteries into mechanical power generated by the motor-propeller system according to the typical propulsion system diagram mentioned in Fig. 2. As a result, the energy management system (EMS) plays the role of the control system to split between the onboard power sources to achieve high performance and efficiency. In this mission, the EMS system composed of current and voltage sensors to measure the power flow handles the power output according to the power management strategy thanks to the processing unit [36]. The electrical power source distributes the power to the DC bus via the converter to control the charging and discharging process of the battery. Meanwhile, The EMS sends the control signals to the converter to control the power flow. Normally, a brushless electric DC motor is used to power propellers due to its advantages in the high efficiency and power density, good torque characteristics, reliability, and long lifetime as mentioned in [36, 39-40].

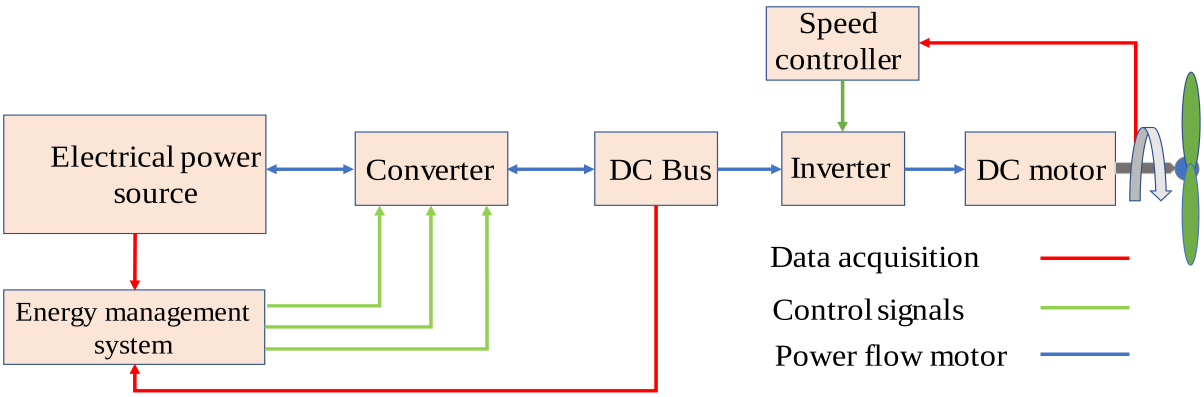

Figure 2. A typical propulsion system diagram of UAVs

The normal operation time of UAVs is normally 20 to 30 minutes as shown in Table 1, and thus it limits the UAVs flight range and as well as their applications. For continuing flight, the UAVs batteries need to be charged after some specific time. It can be performed using wired power transmission using some physical connection. The wireless power transmission has been also used recently event its less wireless efficiency thanks to its lower maintenance and safety [36, 41]. Figure 3 proposes the wireless battery charging system for UAVs including main parts such as wireless power transmitter (WPT), power receiver, receiving coil, battery charger and control unit [42]. The WPT is a process of transferring electromagnetic energy from the energy source to the receiver without any connecting cables [43-46]. The fundamental has been determined when Nicola Tesla described his invention of transferring energy through the air without using any intermediates [43]. The transmitter converts electrical energy into the "time-varying electromagnetic field", and thus it is transferred to the receiver via the transfer converting the electromagnetic field into the electricity [43, 47].

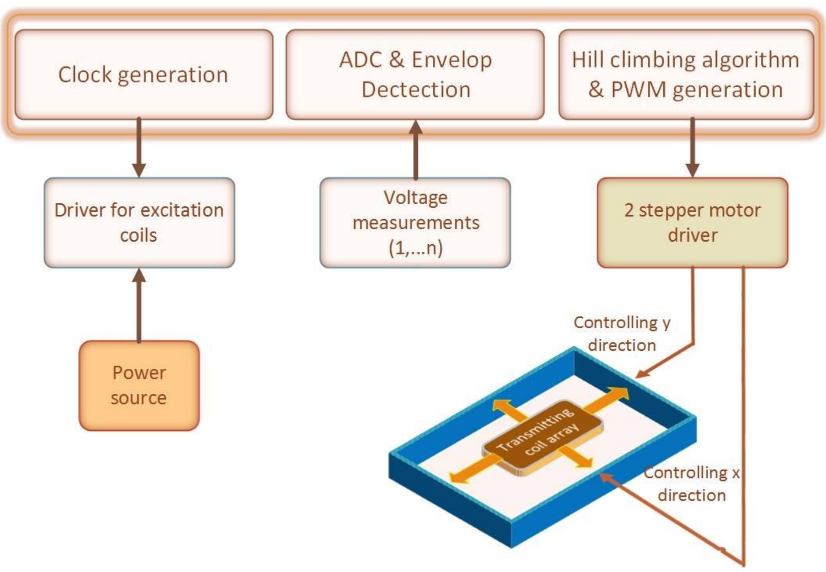

Figure 3. The proposed wireless battery charging system of the quadcopter

2.2. Hydrogen fuel cell (HFC) for UAV solutions

Batteries are relatively low in power density, supporting only enough power for short flight time. Meanwhile, internal combustion engines provide higher energy densities than other energy sources, but they suffer from a much higher initial cost and require extensive regular maintenance and overhaul. As described in detail in [48-52], fuel cell plans are more efficient than the conventional thermal power ones because they are not limited by the Carnot cycle. However, the operating efficiencies of the fuel cell are lower than the idea efficiency because of the losses as mentioned in many previous studies [48-52]. The flow-field plates are normally constructed from a porous material, such as carbon graphite, metal or ceramic. Meanwhile, the gas diffusion layers (GDLs), manufactured from carbon paper, or carbon cloth play the role as an electrical conductor transferring electrons to and from the catalyst layer. The catalyst layer is in direct contact with the membrane and the gas diffusion layer. The catalyst material primarily depends on the temperature operation of the fuel cell. Low-temperature cells require effective catalysts such as platinum; however, common metals such as nickel can be used when the fuel cell operates at high temperature. In the development of fuel cell technology, various types of fuel cells have been considered to respond to a variety of missions. The six classes of the fuel cells are the following: Proton exchange membrane fuel cell (PEMFC), Alkaline electrolyte fuel cell (AFC), Solid oxide fuel cell (SOFC), Phosphoric acid fuel cell (PAFC), Molten carbonate fuel cell (MCFC), Direct methanol fuel cell (DMFC). However, PEMFC has been applied in worldwide applications, especially used to power for UAVs due to its advances in high efficiency, power density as well as low operating temperature. Proton exchange membrane fuel cells produce electricity by an electrochemical reaction in which oxygen (O_2) from the air and a hydrogen-rich fuel (H_2) combine to form water.

Key advantages and benefits of applying PEMFCs source for UAVs include flight time and endurance enhancement, greater efficiency, low-maintenance operation cost, zero emissions, rapid refuelling, typically taking less than five minutes, and especially flexible connection in parallel for high power requirement. However, compressed hydrogen systems maybe not practical for small UAVs because they are not downwardly scalable [53]. Recent advances in compressed hydrogen-powered PEMFCs fuel cells achieved power densities of up to 1.4 kW/kg in the range of 100 kW range and only 250 W/kg for 1 kW commercial model. In this case, it is more advantageous to use liquid fuel in which fuel storage and delivery are considered more critical than the battery power density itself. In this design, the fuel cell system powers an electric motor which drives a propeller. The main disadvantage of the application of fuel cells is their low power density and thus restricting the performance of UAV. Consequently, a fuel cell is normally combined with a battery as the hybrid system to power UAVs. Especially in the case of DMFC and AFC, there are no commercial products found due to their very low power density; however, it can be observed some research results as mentioned in [54]. This research applied a 200-W DMFC stack to power a UAV and the UAV cruised for about 10 minutes as well as to maintain an altitude and airspeed 75-175 m and 20-55 km/h, respectively. The specific power density of a PEMFC system is about 700–1000 W/kg and has been increased dramatically; this will enable electrical UAVs of a large commercial aircraft [55]. For the UAV propulsion composed of batteries and fuel cells, hydrogen fuel is stored in very high-pressure bottles or chemical compounds. There are also other complicated systems in which hydrogen is generated onboard by an electrolyser using the electric energy from photo-voltaic cells. Fig. 4 shows the schematic configuration of the UAV power system.

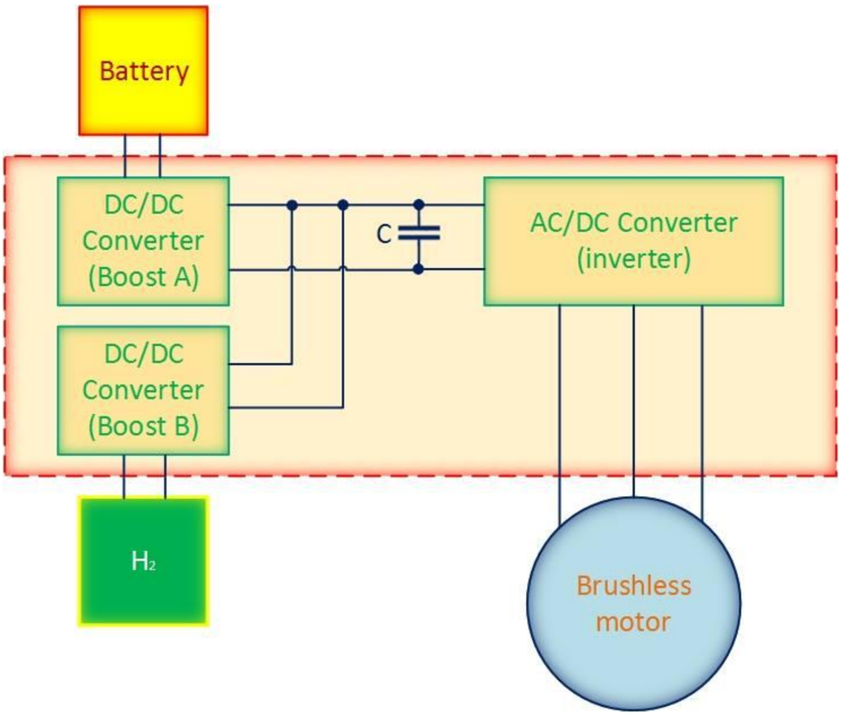

Figure 4. UAV hybrid power system of Fuel cell and Battery

Normally, the electric engine is a brushless motor cooled by air to save weight. The motor-case is connected to the electronic boards. This is the best method for the layout integration and cooling since the cooling air flows along the motor wing and contacts to the converter surface. The power system includes the battery and the fuel cell system composed of a fuel cell stack, heating system, air and water management system and electrical and electronic support system as mentioned in [55]. Karen E et. al developed 1.1 kW PEMFC as the propulsion for a UAV without any battery [56]. And thus, the fuel cell power must be sufficient to take off and climb out, and then bring enough fuel for long endurance. This research used an electrical power generated by the fuel cell to drive brushless DC motor with the maximum power of 2.2 kW. This UAV can take off at an airspeed of 5.6 m/s and reach the maximum altitude of 10 m. In another research with the same topic, Marco K and Johan M designed a 0.1 kW PEMFC to produce sufficient power for a UAV [57]. This research designed an adaptive controller to switch off either a fuel cell or battery mode via the RC transmitter as shown in Fig. 5.

In the fuel cell mode, the hydrogen-oxygen supply valve is opened and the valve for the purging opens for 10 ms after every 10 s. Since the objective is to describe level flight using only the power from the fuel cell, the battery is only used to take off the UAV. It would also power the control servos. The UAV propulsion components for composes of an electric motor and a speed controller the propeller. And thus, the electric motor will receive a voltage of 12 V from the fuel cell system. The motor is a brushless and able to draw 55 A at the maximum throttle and a speed controller corresponding to the maximum current of 60 A.

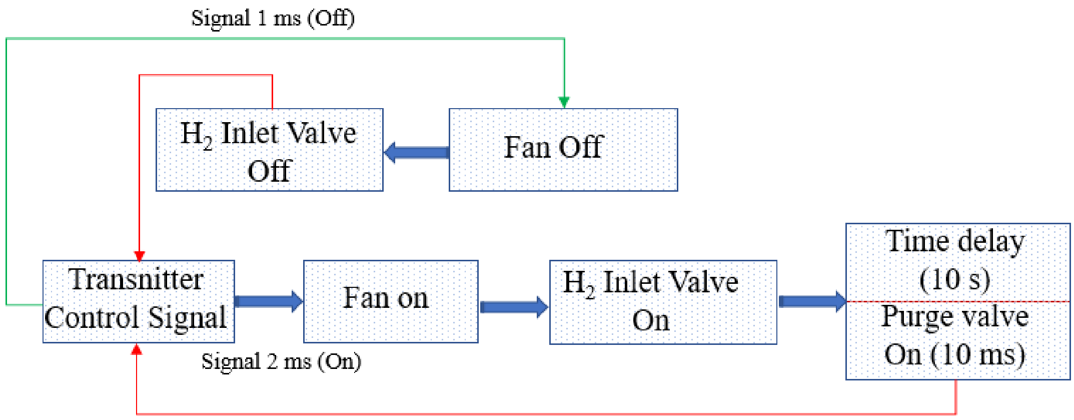

Figure 5. Flow diagram design of the fuel cell controller

2.3. Solar Power Solutions for UAVs

Solar energy is an alternative and inexhaustible energy source. It can be used for heating water, room, cooling or other heat generation processes. It has been known as photovoltaic cells or solar panels and can be observed in some applications such as spacecraft, rooftops and calculators. Radiation of the sun is the source of energy exploited in solar cell devices. Ambient thermal radiation contributes to electronic processes of photoactive devices, and this phenomenon is used in arguments based on the detailed balance that supports fundamental information of semiconductors interaction with radiation [58]. The advantages include high reliability and being environment-friendly while disadvantages are low power density and conversion efficiency, high manufacture cost and instability due to its dependency on meteorological conditions. Also, the power of photovoltaic cells during cloudy periods or at night is small; and thus, the energy storage system must be equipped for obtaining continuous power. Regarding the application of the solar power for UAVs, it needs to identify some important parameters for the system due to its dependence on the latitude as described in [59-61]. The geometrical relationship between solar radiation and the UAV is one of the main reasons affecting the solar energy performance listed in [62-63]. The research results in [50] also showed that the power density will reach the maximum power when the solar panel surface is perpendicular to the incidence angle of the solar radiation and dramatically reduce when the angle differs from 90 degrees [64-65]. It also proved that the roll angle of UAVs wings can be used to detect the sun to enhance the energy produced by the solar panels fixed on the wings. As a result, the UAVs attitude must be compensated with the yaw angle control to conduct a photogrammetric mission. This will be achieved thanks to a control method based on the super-twisting technique that ensures convergence in finite time even in the presence of bounded perturbations. Mingjian W also showed that the solar cells equipped in the UAVs wing need to convert sufficient solar energy into electrical energy during the daylight time flight to achieve perpetual flight [66]. It can be observed that the optimal Z-shaped wing is more advantageous than the planar wing in achieving longer flight time, improving perpetual flight latitude, especially for the middle and high latitude regions during low light intensity days [67-68]. These studies also concluded that the solar irradiance amount depends on the location and operating time, so thus the relation between the size of the solar cell with the location and the day of the year intended for operation should be conducted in this field to enhance the system efficiency.

For continuous flights, solar energy needs to combine with batteries as the hybrid system. Consequently, solar panels are arranged and connected in a certain configuration and retrofitted on the wing surfaces or other UAV parts such as the tail and fuselage. In case of the high-intensity light time, the solar panels convert light into electrical energy using the converter to ensure that the maximum amount of power is generated from the solar panels. This power is used for supplying the power for the propulsion group and the onboard electronics and charging the storage battery with a surplus of energy as shown in the diagram in Fig. 6. In the same research topic described in [69], the solar energy conversion, power converter and electric drives were optimized to obtain the goal fight efficiency corresponding to about 64 m of the wingspan. It shows the design in details of the Boost DC/DC converter and solar system design for a UAV. As shown in Fig. 7, a DC/DC power converter was designed to minimize the converted mass in the frame of radio-controlled UAV retrofitted a solar energy system. The driving circuit, DC link voltage and engine propulsion designed to operate at 16 V; meanwhile, the open-circuit voltage is about 20 V to maximize the point track. The solar energy system was designed to assure that the DC/DC power converter is not needed under the optimal conditions. However, under the conditions of reduced insolation or aircraft control, the DC/DC converter enhances partial compensation of battery charge consumption.

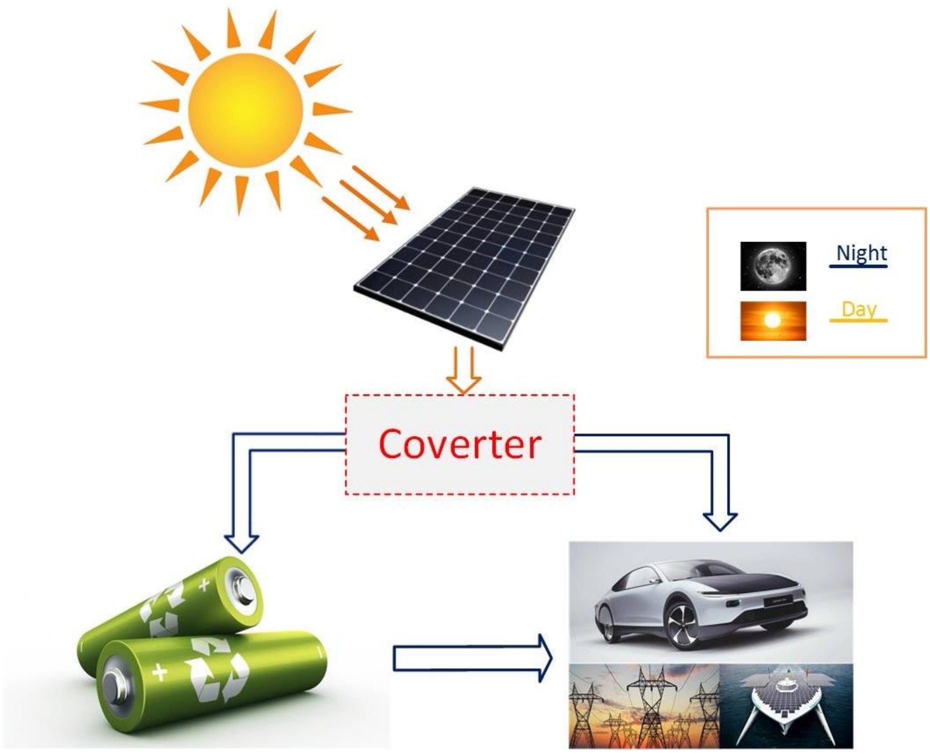

Figure 6. Diagram representation of the power transfer

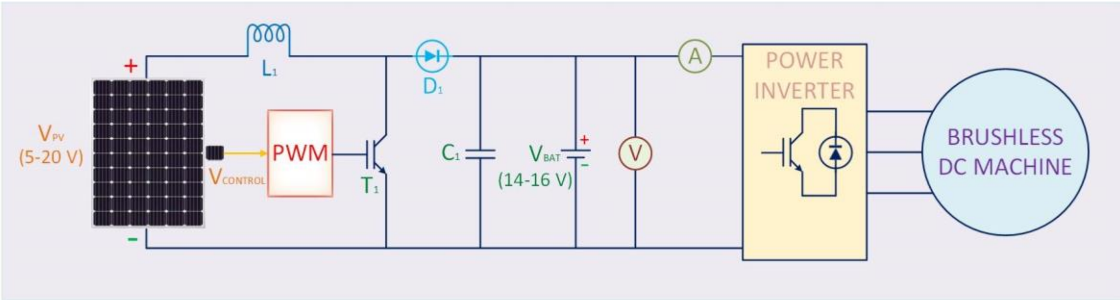

Figure 7. Power system design of the solar system for UAV

3. UAVs POWERED BY THE HYBRID PROPULSION SYSTEM OF SOLAR CELLS, FUEL CELLS, AND BATTERIES

As mentioned about, due to low power density, batteries provide only sufficient power for short time flight missions of UAVs with much longer recharge time than the provided flight duration. Meanwhile, internal combustion engines have higher energy densities compared to batteries; however, they suffer from a much higher initial cost, require extensive regular maintenance and especially emit a large amount of exhaust. Indeed, due to the advantages of high power density and efficiency, spark ignition (SI) engine are still used to power UAVs, especially two-stroke engines as mentioned in [70-75]. Some research studies converted original engines for UAV power to adapt the mission as described in 70, 72]; other studies performed stepped piston charged engines [71] or opposed piston-cylinder [73]. However, two-stroke engines produce high gaseous and particulate emission [76-78]; thus four-stroke engines have been conducted to apply for UAV power as clearly mentioned in [79-81]. It can be observed that the 2-stroke and 4-stroke engines have the same power output level regardless of their speed regimes [82]. In comparison with internal combustion engines, fuel cell and solar energy are a silence, reliable source of energy with low-maintenance cost, and clean emissions to solve these above problems [83-84]. Consequently, the combination of the fuel cells, solar cells and battery as the hybrid system is a potential method to enhance flight time of UAVs. Lee [85] simulated combined propulsion power of solar cells, fuel cells, and batteries using Matlab/Simulink and verified with the manufacturer's data. Ó. González-Espasandín also concluded that hybridization of fuel cells and electric batteries should be applied in most cases due to the low power density of either fuel cells or batteries [53]. In fundamental, the hybrid power source is well-known as multiple energy sources. The most popular implementation is the combination of both gas and electricity as widely implemented in the transportation in which both engines and batteries are retrofitted in vehicles. In this case, an internal combustion engine and a battery are combined. The power required depends on the missions to activate either one or both power sources. However, the fossil energy powering UAVs has limited flight time, depending on their carried fuel storage.

It is not possible to bring too much fuel on-board due to weight limitation. The most potential candidate energy sources to power the UAVs are solar energy and fuel cell. With the solar panels and energy storage devices such as a battery and fuel cells, the UAVs can operate for very long-range distance with enough energy for the auxiliary electrical loads. In this combination, solar energy powers UAVs during daylight and generate electricity for storage in the battery or for the electrolysis process. The rechargeable fuel cells will operate in case of the low light intensity when the irradiance is weak; and thus, a very small amount of energy can be harvested from the solar panels. The rechargeable battery also supports the difference between the burst load power and the output power of the solar panels and/or fuel cells, and it can also be recharged by the solar panels.

Generally, the solar panels powering UAVs are equipped with solar cells covering its wing, and they retrieve energy from the sun to supply power for the propulsion system and the control electronics with the help of unitised regenerative fuel cells (URFCs). URFCs are alternative propulsion systems for UAVs such as Drones. URFCs are electrochemical systems that store and convert the chemical energy contained in fuels directly into electric energy. URFCs are capable of storing energy (up to 400 Wh/kg) by splitting water into H_2 and O_2 when renewable electricity is available. In theory, the power density of the electrochemical reaction of hydrogen and oxygen is about 3.6 kWh/kg. It can be reduced under 1 kWh/kg when hydrogen and oxygen are stored in the tanks; however, it is dramatically higher than that of batteries [86]. Furthermore, Dhar described that URFCs systems can achieve comparable power to individual electrolyser and fuel cell units [87]. During times when wind or solar resources are not available, the H_2 and O_2 are recombined to produce water once again, providing electricity for the grid in the process or any other applications. The URFCs work as a dual-processor such as charging and discharging. During charging, it acts as an electrolyser, which splits water into H_2 and O_2 to form the renewable resource electricity (solar or wind). During discharge, it works like a fuel cell mode, which recombines stored H_2 and O_2 to produce electricity. The URFC systems are being applied for many applications, high altitude long endurance (HALE) solar rechargeable aircraft (SRA), zero-emission vehicles, hybrid energy storage/propulsion systems for spacecraft, energy storage for remote (off-grid) power sources, peak shaving for on-grid applications, and portable power systems. However, this technology is currently yet to be largely deployed, because it is too expensive to compete with existing technologies. This high cost associated with the deployment of URFCs hinders the commercial viability of the technology. One major reason for the high cost is associated with the precious metal group such as Pt and IrO2 used in the URFC`s electro-catalyst. In the existing URFCs proton exchange membrane (PEM) is commonly used as the electrolyte. This proton exchange membrane provides an acidic environment which limits to the platinum group metals as an electrocatalyst. The acidic corrosive environment requires platinum group metal catalysts that substantially increase the cost of the device.

3.1. UAVs conceptual design

Normally, the power density of the battery, fuel cells or fuel-cell-powered UAVs is smaller than that of a conventional fossil energy source. Therefore, the aerodynamic configuration design of UAVs powered by the former power source is more difficult in comparison with that of a traditional energy source [69]. Most aerodynamics design characteristics are related to the aircraft conceptual design process; and thus, it is very complicated to find out the best methodology for each type of UAVs. In the design process, scientists normally perform a baseline configuration in the first design step. Next, they need to conduct some iterations of the baseline configuration depending on the design database. Considering the power density and weight of structural materials of the power sources, it needs to reduce production costs, achieve design goals and optimize the power system's efficiency. Concerning the relationship between lift and drag forces, there is a specific speed range that minimizes the power requirement for a specific altitude. The power demand for a particular altitude can be described as the function of the zero-lift drag coefficient and induced drag factor, assuming that the power required can be reduced by the optimization process. Hence, power capacity and weight can be deduced. The lift force requirement for cruising can be adjusted downward. In conclusion, the optimal design can effectively reduce the UAV cost. Varsha [88] performed a conceptual design of UAV to carry a payload of 300kg based on the empirical relations and the datasheets. The methodology design conducted by Escobar-Ruiz is based on the flight mission and the environmental conditions to define the main wing and the elevator [89]. To enhance the maximum ratio of the lift and drag force, Oktay [90] designed the profiles of UAV's nosecone and tail by performing aerodynamic modifications and active flow control. He also designed the flight control system for both passive and active morphing tactical UAVs to enhance the UAV performance [91]. To conducted surveillance missions, a fundamental design was shown in [92] based on the energy management strategies and the estimation of weight, aerodynamic parameters. With the different approach, Rajendran [93] collected the sunlight data in many cities to evaluate the potential energy of these places. This research also concluded that smaller and lighter solar power for UAV can be applied for the cities near the equator. By considering the characteristics such as geography, energy storage and the payload, Karthik designed the UAV power by retrofitting the PV cells onto the UAV's wings [94] based on the calculation and analysis of the energy and exergy efficiencies. In [95], the demand power to adapt flight mission was simulated using the 2-DoF model and the results showed that the UAV can fly at the altitude above 16 km with the proposed control strategy. The research results in [96] illustrated the effect of altitude and weight on designed parameters including PV dimension, wing's aspect ratio, and required thrust. In [97], Gao evaluated the effect the solar irradiation, the charging rate, battery power density, and UAV altitude in the energy storage. In [98], the author concluded that the evaluation of UAV's structural such as airfoil, wing position, size, and type of wing is very important to adapt the flight mission. Normally, aircraft have huge lifting force thanks to their large wing surfaces. As a result, solar panel modules can be mounted on such UAVs, so that they can stay in the air for more hours/days. It can be observed that the flight time can be prolonged despite the increased mass of the installed solar system. In the hybrid system, the power is combined of three power sources: (1) battery source, (2) fuel cell and (3) photovoltaic cells. The forces acting on the UAVs during the operation are the lift force F_L and the drag force F_D described as:

$$F_L = 1/2 C_L A \rho V^2 \quad (1)$$

$$F_D = 1/2 C_D A \rho V^2 \quad (2)$$

where CL and CD are respectively the lift and drag coefficient, ρ is the air density, A is the area of the wing and V is the relative velocity of UAVs. Therein, CL and CD are the functions of the wing profile, attack angle, Re and Mach number. Also, the drag coefficient can be calculated via the airfoil drag and the parasitic drag of non-lifting parts. During the operation, the lift force needs to be higher than the total UAV weight. And thus, it can be observed that the mechanical power (P) needed for the cruising speed is as follows [59]:

$$P = 1/2 C_D A\, \rho [2mg/(\rho C_L A)]^{3/2} \qquad (3)$$

where m is the total mass of the calculated UAV determined via the total mass of the power system sources including battery, fuel cell, solar panels and converter devices, aeroplane structure, propulsion group composed of the motor, gearbox and propeller.

As can be seen in the equation (3), UAV drag coefficient is an important parameter affected directly by the aerodynamic characteristic. In this design, the wing profile dramatically contributes to the UAV's aerodynamic characteristics and efficiency [99]. And thus, it is very important to understand the wing and airfoil design to ensure that the UAV has a suitable aerodynamic profile to meet the mission requirements. In the experimental design, the wing profiles are normally designed to create a superior pressure distribution on the top and bottom surfaces of the wing to maximize the lift coefficient as well as minimize the drag coefficient. The main wing parameters are the aspect ratio, sweep angle, and taper ratio as mentioned in [99]. Indeed, the aspect ratio relates to the induced drag, zero-lift drag, and slope of lift coefficient. When the aspect ratio increases, the wing's induced drag can be reduced. Besides, a decrease in the aspect ratio contributes to the wing tip stall in case of high attack angle and reduces the wing's weight and the bending moment at the wing root.

3.2. System design and components

In the hybrid system of fuel cell and solar cell, traditional fossil fuel is replaced by renewable energy. Photovoltaic panels convert the solar irradiance into electricity powering UAVs during the daytime, but there is no solar irradiance during the night. Therefore, UAVs have to be retrofitted with other energy sources for flying. These power sources should also have the ability to absorb the extra energy generated by the solar panel. Normally, rechargeable batteries have been widely used in for this work because they can store the remaining solar energy and power the UAVs when there is no irradiance. Unfortunately, to support enough power for the long night-time UAVs, the battery dimension needs to be very huge to match the energy demand due to the low power density of batteries; and it is, therefore, not suitable for the UAVs. The fuel cell can solve this problem because of its higher energy density compared to conventional batteries. Some previous studies showed that the hybrid solar panel/fuel cell power system is a good suggestion to generate enough power for UAVs for the whole day. Indeed, the fuel cell will power UAVs during the night; otherwise, energy can be produced from the solar panel during the daytime. This energy will be used to power the flight, and the remaining energy can be used to trigger chemical reactions to generate the hydrogen used for fuel cell operation. However, the fuel cell has a slow response due to its natural electrochemical reactions. As a result, the hybrid solar panel/fuel cell system cannot provide enough energy to power UAVs during night flights when the fuel cells only generate energy. Also, batteries are normally cheaper than fuel cells or PV cells [100-102]. Some previous studies mentioned in [102-103] also pointed out the higher efficiency of the charge and discharge compared to with that of fuel cells and solar cells. The center gravity of UAVs may be changed when the fuel cell is activated due to the hydrogen consumption [104]. Besides, the power requirement is almost constant for stable flights, but it requires higher power for climbing or the auxiliary electrical load. Combining a battery with the hybrid solar panel/fuel cell system is a good solution to this problem. Size and weight can be designed small because it only operates during critical conditions and it is not the primary energy source. However, it should have a high enough power density to meet the peak requirement. Compared to the primary energy source, rechargeable batteries are much better since they can be recharged on board by solar energy. For the idea power design, the peak power is the first design to match, and then the flight endurance is expanded as long as possible; therefore, the battery should be fully charged and then extra energy is used for the hydrogen production. Figure 8 describes the designed hybrid power system of battery, fuel cell and solar energy for UAVs [105]. In this design, the photovoltaic panel is the primary energy source for the UAV converting solar irradiance into electricity. It consists of solar panels to absorb and convert sunlight into electricity, a boost inverter to convert the output from direct to alternating current and other electrical accessories. To harvest the maximum energy from the solar panels, the solar tracking system can be used to enhance the system performance based on the INC MPPT method to track the maximum power point as mentioned in [105-107]. And thus, the step size of the INC MPPT method is normally kept constant. A larger step size of the power drawn results in faster dynamics, but it causes low efficiency in case of excessive steady-state oscillations. This situation is reversed when the MPPT operates with a smaller step size [107].

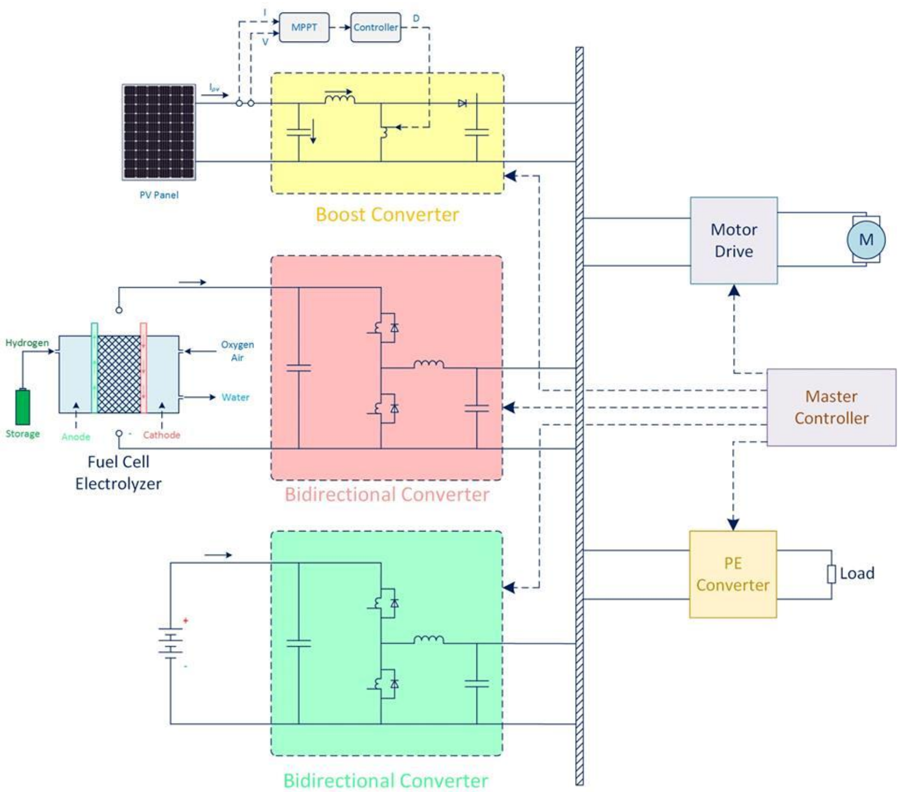

Figure 8. Hybrid power system of battery, fuel cell and solar energy for UAVs

As mentioned above, the PEM fuel cell power source will be activated to convert the chemical energy into electricity during night-time or under low radiation conditions. The fuel cell system normally includes the fuel cell stacks, energy storage components, reactant tank, and auxiliary components. It can be factually distinguished from the non-regenerative and regenerative fuel cells. However, in the hybrid system, the regenerative fuel cell retrofitted in the electrolyzer stack is preferred. Recently, URFCs are highly appreciated and advanced fuel cell technology [108-111]. Generally, in the URFCs operation, H_2 and O_2 are stored separately in separated tanks as the fuel and oxidant. Their power density is about 0.4–1.0 kWh/kg including the mass of gas tanks [112-113]. Furthermore, URFCs also have advantages compared to batteries due to their durability in the charge and discharge process. However, the efficiency of Batteries is normally higher than that of URFCs because of the sluggish oxygen reactions [114-115]. The high cost, fuel storage problem and low technology readiness also restrict the URFCs application [116-118]. Despite the above advantages, URFC technology has still not applied in the worldwide application. However, it still attractive scientists to research for improving URFC performance, energy efficiency and cost-effectiveness.

In the operation of URFC, the electricity is produced through the round-trip energy conversion of the fuel cell mode and the electrolyzer mode. The overall reaction mechanism of URFC operating in the fuel cell and electrolyzer mode are respectively described as follows.

$$4H^+ + O_2 + 4e_- \rightarrow 2H_2O \qquad (4)$$

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \qquad (5)$$

When the intensity of the solar radiation is low, the fuel cell mode is activated; and therefore, the hydrogen and oxygen are respectively passed to the anode and cathode to generate the electricity. Generally, the hydrogen molecules are dissociated into protons and electrons in the hydrogen electrode. The proton moves through the MEA to arrive at the cathode side; meanwhile, the electron moves through the external circuit. The production of this Mode is water and electricity. Oppositely, in the electrolyzer mode, the water is supplied to the -anode for the process to split water into proton, oxygen and electron. The protons move through the membrane and the electrons travel through an external circuit. In cathode, the proton and electrons recombined and hydrogen is produced. This process uses the electricity harvested from the PV system and the produced oxygen and hydrogen gases which can be stored and used as a fuel for the fuel cell mode. The schematic procedure of round trip energy conversion of URFC is described in Fig. 9.

In the design of the hybrid system as described in Fig. 9, a bi-directional DC/DC converter connects the URFC to the DC link. The nominal voltage of the fuel cell stack is 48V; meanwhile, the DC bus voltage is approximately 28 V. At the fuel cell mode, the power flows from the fuel cell to the DC link and the bi-directional converter works as a buck converter. Otherwise, when the extra power from the PV panel is supplied to the electrolyzer, the power flow is reverted from the DC link to the fuel cell and the bi-directional converter plays the role as a boost converter; and thus, the fuel cell works as an electrolyzer. In the case of critical conditions, the battery is responsible for this work. For example, when the fuel cell is the only primary power source at night, the battery will be activated to supplement the shortage of power. When the peak power occurs, the solar system power satisfies the peak load by itself, and then the battery will be deactivated. Otherwise, it supports the power difference between the solar source and the load. Therefore, the battery power needs to be designed in a way that it can be adapted to the missions above. And thus, the power capacity of the battery is designed corresponding to the duration of the peak power during one night.

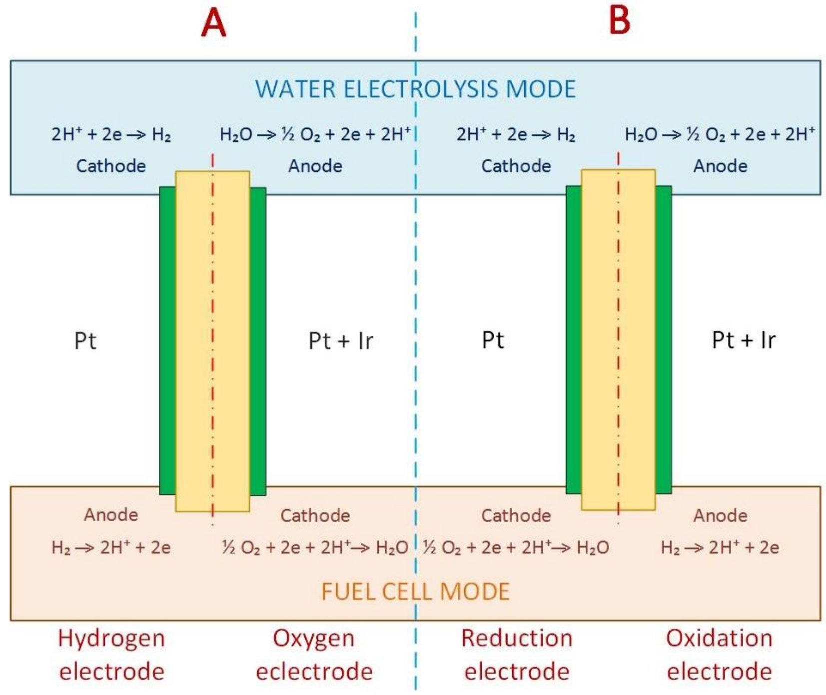

Figure 9. Schematic procedure of the working principles of the URFC system

The battery cannot be recharged at night time because the fuel cell power only provides the average load. In the case of strong irradiance, the battery is recharged by the solar source if the solar source has remained power after providing the load. Also, the solar power normally can charge both the fuel cell and the battery in case of irradiance; however, the power system should be designed with a priority to charge for battery over the fuel cell because the peak load is more critical than the flight time expansion. Generally, the battery is also designed to connect with the DC bus via a bidirectional converter for the charge and discharge target. Currently, the DC brush motors are being replaced by the brushless DC motor in UAV applications because the main problems of DC brush motors include producing electrical noise and also increasing the maintenance process. The brushless motors use the power electronic devices to fulfil the function of the brush. Consequently, it contributes to minimizing the problem in maintenance and also enhances efficiency. However, the control of brushless motors is more complicated than that of DC brush motors. Besides, the brushless motors are not very cost-effective in case of high power rating operation. Nevertheless, they are still a good solution for UAV applications. Induction motor is very popular and inexpensive. It can be also applied for both in low and in very high power conditions. However, it has low efficiency and the speed drive of the induction motor is complicated. Besides, the cooling process for the rotor is difficult during high-altitude flights. For low power applications, the brushless motor is more preferred for UAV applications due to the complication in combining the above power sources, the control system is very important. Normally, it is composed of the main controller and other local controllers to control the power flow of each converter. The main controller connects local controllers and distributes power flow demand corresponding to the load requirement. One of the local controllers maintains a voltage of 28 V for the DC bus. The battery's bidirectional converter is used to fulfil that. Other local controllers keep their converter in current control mode with the reference current provided by the main controller. The solar converter is only used to harvest the maximum power from the solar panels and it does not receive signals from the main controller.

3.3. Energy efficiency and Power Management Strategies

As mentioned above, hybridization is the most suitable architecture for UAVs propulsion system due to their advantages. Thereby, a power control strategy must be conducted for power real-time splitting among power sources to adapt the optimal conditions such as system efficiency, quick response, fuel consumption reduction, power demand, and critical flight conditions. This procedure has been considered as an effective strategy in which it converters control the power outputs via the power management unit. Power can also be provided using passive methods broadly applied for small UAVs as mentioned in [119-120]. Consequently, the power sources are connected to a DC link and provide the propulsion based on their characteristics. Various energy management methods of hybrid power system have been described in the previous studies. When combining more than 2 power sources, the most common configurations are series, parallel, and power-split. In the case of the series configuration, the electric motor supplies power to the drive train. This design operates well for low-speed and high-torque conditions; however, the final system efficiency would be low as described in [84, 121]. The parallel configuration takes advantage of redundancy, and thus, it is suitable for civilian and military applications. In this case, it is so complicated to the control the torque from the individual or combined power sources to enhance the total efficiency [123]. The power-split configuration combines the various energy sources; however, this design requires complicated control strategies and high-cost operation [124]. Many other studies have been performed to design the combination of the solar cell, fuel cell, battery as described in [125-128]. Shiau [125] designed the solar power management system including maximum power point tracking, battery, and power conversion. The research results [126-127] showed that the active control is a good solution to manage the fuel cell power under the maximum efficiency and power strategy, and adaptive control strategy corresponding to the hybrid system of fuel cell and battery using a DC-DC converter. Erdinc and Uzunoglu conducted a review of PEMFC hybrid system trends focusing on application areas, architecture design and the energy management strategies [129-130]. Motapon presented a comparison of different energy management schemes for a fuel cell hybrid emergency systems based on the simulation model verified by experiments on the 14-kW power system. It concluded that the state machine control scheme has better efficiency compared to other schemes and the classical PI control scheme has the lowest fuel consumption [131]. The research in Reference [132] developed the energy management method to adapt the power flow control to power the UAV aloft as long as possible. Consequently, solar panels have the priority to discharge. They always operate at the maximum power point to fly or charge the battery. Meanwhile, the battery cooperates with the solar panels and fuel cell in case of the peak power demand. The fuel cell was designed to work in the region with high efficiency. The PEMFC generally has the lowest output priority and mainly operates at night due to the hydrogen storage limitation. The energy management strategy is activated at any moment affected by the controller frequency to distribute output power sources. The process is first implemented when UAV flight initial conditions and status parameters of the propulsion system are set including data and time of takeoff, longitude and latitude of takeoff place, takeoff weight, and heading angle. The initial status parameters of propulsion system consisting of the lowest available power of solar panels, the battery initial state of charge, charged thresholds to prevent overcharge and discharge, the initial state of pressure in hydrogen tank, the lowest available pressure of hydrogen, and the minimum, maximum and rated power of the fuel cell. Secondly, the time of the control system with step size is recorded and updated. In the next step, the power demand information from the flight profile and avionics model will be received to calculate the total power output. Also, every power source states such as solar irradiance, charge state and hydrogen pressure will be checked. The solar panels can be used or not based on the irradiance conditions. In the case of high irradiance conditions, the solar panels are activated to supply power for the propulsion system. If the battery is available, the remainder power demand is compared with the maximum output power the battery. In case the battery satisfies the remainder power demand, the control system time will be recorded and updated. Otherwise, the power flow between the battery and fuel cell will be distributed. If the battery and solar panels power are lower than the demand power, the fuel cell will be activated.

The aircraft efficiency is essential to its functioning required to achieve the operational goals of range, endurance and other specific missions. Because of the limitations of the space and mass availability of UAVs, there is often a need to compromise between the onboard available energy and achieving the operational goals. Generally, small UAVs are popularly powered by ICEs with the maximum thermal efficiency by about 40% [133]. With the electric motor powerplant, the system efficiency can be up to 100% [133]. However, it required the storage system driving the electric motor to power the UAV. Normally, the storage system uses a battery with a large weight and dimension. Furthermore, it has a limited operating time and requires to charge after some operating hours. The first aircraft powered by solar energy was activated in 1974 with approximately 4100 solar cells producing 450 W of power and 11% efficiency. Zephyr investigated a solar power source with 19% efficiency and a battery of 600 Wh/kg energy density. In 2009, a study performed the monocrystalline solar panels with 18% efficiency and an 84 W battery with an energy density of 240 Wh/kg [134]. The study described in [135] mentioned the advantages of fuel cells in their low emissions, high efficiency, modularity, reversibility, and fuel flexibility, range of applications, low noise, and low infrared signature. Also, some of their disadvantages about high cost, electrode catalyst to poisons, their experimental state, and the hydrogen shortage were mentioned. In systems powered by internal combustion engines, fuel produces only power of about 18–25% of its potential energy; meanwhile, fuel cell-powered UAVs efficiency is about 44%. Recent technologies in PEM fuel cells contribute up to 1.4 kW/kg in the 100 kW range to power densities and only 250 W/kg in the 1 kW range. When the weight of the electric motor is added, it leads to a worse state than other systems because of the addition of about 20% of the weight. Moreover, the weight of hydrogen storage is also a big problem; it further worsens figures concerning conventional fossil fuels. However, the energy conversion process is very efficient compared to internal combustion engines with great long-life operation time as well as maintenance cost. Its high energy density also makes them very suitable for a long-endurance surveillance mission. For instance, the Puma UAV version retrofitted with a PEMFC can fly 9 hours, which means a 2-hour flight time enhancement compared to the same battery-electric UAV version. However, the fuel cell system also requires auxiliary systems such as heat management, humidification system, tanks, and controller. Their weight may reach from 15% to 80% [135-136]. And thus, for a future aircraft energy-efficient issue, using the power of hydrogen-fueled systems is a good suggestion such mentioned in [137]. As a future work; improvement of the UAVs efficiency can be up to 80% compared to the mechanical conversion efficiency of 55%. This work can be applied in the worldwide application of UAVs' propulsion development to improve the fuel consumption of the aircraft indirectly [138].

4. CONCLUSION

UAVs applications have been received huge interest from researchers all over the world. However, the power supply source of UAVs for long flight missions is still a challenge for scientists worldwide. This manuscript has, therefore, dealt with a comparative and critical study on UAVs supplying sources and architectures. This aims to provide a basis and insights about the choice of the appropriate power supply devices considering sources features and flight requirements. It has also discussed supplying solution to specific missions when battery-based drones have to operate continuously, namely swapping, laser-beam inflight recharging, and tethered technology. It can be observed that hybrid systems of battery, fuel cell and solar energy reveals many in advantage for extending the flight time as well as exhaust emissions reduction. And thus, it is the most suitable architecture for UAV propulsion system due to the combination of advantages and performances of different power sources. For this purpose, the battery charged by the solar panels and fuel cell combines with the solar panels and fuel cell and is responsible for sharp fluctuations of the peak power demand. Considering the cycle life of the battery, the largest discharge depth is limited to 70%. With limited storage of hydrogen, the PEMFC generally has the lowest output priority and mainly operates at night. The energy management strategy is implemented at any moment to distribute output power sources. The novel results of this research are the foundation for encouraging the research in applying hybrid systems of fuel cell and solar energy in UAV propulsion. Overall, this review identifies the gaps in the body of research and development and provides several insightful directions which can be suggestions for future investigation and essential development.

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