POWER SOURCES SWITCHING IN A HYBRID ENERGY NETWORK ON BOARD A SOLAR UAV

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Abstract: *Utilizing a photovoltaic system to power an Unmanned Aerial Vehicle (UAV) enables longer and extended flights. A hybrid energy system, consisting of three distinct energy sources, was investigated. A technical solution was developed to optimize the energy system and mitigate transient effects observed during power source switching. Through a long-term aerial monitoring mission simulation, the study demonstrated the efficiency and reliability of the energetic management system for a solar-powered UAV in providing a constant and stable power supply to the grid throughout the flight. The findings of this study have implications for the development of high-performance UAVs by ensuring optimal and efficient selection of suitable energy sources for flight conditions and uninterrupted power supply to electrical consumers, minimizing operational risks.*

Keywords: *energetic management system, commutation, photovoltaic cells, fuel cell, battery, UAV*

1. INTRODUCTION

Conventionally, the energy required to power all the electrical consumers on board a UAV is provided through an accumulator battery. The limitations of a flight mission are determined by the amount of energy stored or produced on board the aircraft prior to takeoff. Increasing the number of battery cells extends the duration of the electric power supply, but due to the additional weight, the flight range is not significantly increased.

A structural solution to mitigate these operational limitations involves the implementation of a photovoltaic system on the lifting surfaces of the UAV. This way, solar radiation on the photovoltaic cells is converted into electrical energy and transmitted to the consumers and battery, allowing for continuous flight throughout the day.

In terms of complexity, powering a UAV with solar energy also involves the use of other auxiliary energy sources and components. Following an analysis of the main elements used in the construction of a solar-powered UAV, two of them are of particular importance: the photovoltaic cells and the maximum power point tracking (MPPT) device

[14], [12], [7]. The connection between these two elements lies in the optimization of the entire photovoltaic system's performance.

When exposed to solar radiation, an electric current is registered at the terminals of a photovoltaic cell. The relationship between the level of solar radiation and the energy generated by the photovoltaic cells is graphically described through an intensity-voltage curve. Depending on the type of photovoltaic cell, the I-V curve's shape differs from case to case [6].

2. HYBRID ENERGY SYSTEM

Based on the statements from introduction, the capacity of a battery to generate the required power for certain flight missions is limited. Furthermore, the charging time is longer than the time to power the consumers, and landing the UAV and connecting it to a power source is required for recharge.

For this reason, the development of a hybrid energy system, consisting of photovoltaic cells, a fuel cell, and a battery, represents a technical solution to improve the flight time of a solar-powered UAV. In this sense, researchers from the Aerospace Research Institute of South Korea and the National Institute of Aerospace Technology of Spain validated the premise of the outstanding results of a hybrid energy system by performing checks and simulations in the Matlab/Simulink application [3], [13].

In this configuration, the photovoltaic cells integrated on the carrying surfaces of a UAV provide the necessary energy to the consumers during the day, charge the battery, and perform the electrochemical process of the fuel cell. In the case of low solar radiation, when the photovoltaic cells are not functioning at nominal capacity or not generating energy, the fuel cell entirely supplies the electric consumers.

The block diagram presented in Fig. 1 represents the electrical circuit of a hybrid energy system, in which the primary energy source is the photovoltaic system, and the secondary sources are the fuel cell and the battery. The integration of unidirectional or bidirectional converters ensures the flow of energy depending on the direction and time of the power source. In this sense, the direct current generated by the photovoltaic cells is converted into alternating current to power the propulsion system and other electric consumers. The fuel cell and the battery are electric sources for which the energy transfer flow is carried out in both directions, and the type of current differs depending on the case. Bidirectional converters are used to achieve energy transfer and conversion from direct current to alternating current and vice versa. The connection of an MPPT device ensures the photovoltaic system operates at maximum capacity by continuously detecting the maximum value of solar radiation.

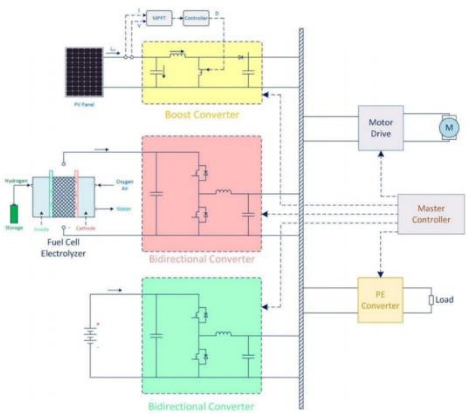


FIG. 1 Block diagram of the hybrid power network for a UAV powered by photovoltaic cells

During the night, the energy generated by the fuel cell is only distributed to the electrical consumers, without charging the battery. A high level of solar radiation allows the photovoltaic system to generate enough energy to power the electrical consumers and charge the battery. Under certain conditions, when additional power is required for the propulsion system and the photovoltaic system is in operation, some of the generated energy is transferred to the fuel cell. Control of the energy flow and priorities for energy transfer is ensured through the energy consumption management system. Depending on the type, weather conditions, and flight mission duration, the command and control unit sets the priorities for electrical power supply.

From the advantages presented above, hybridization represents the most suitable architecture for powering the electrical consumers of a solar UAV. The implementation of a power control strategy at the command unit level ensures outstanding energy system performance through optimal switching of energy sources based on flight conditions and UAV power consumption [1], [8]. When more than two electrical sources are used in the power system, they can be connected in series, parallel, or mixed, depending on their priority in powering the consumers [9], [2].

Series connection of electrical sources is used for UAVs that fly at low altitude and require high power consumption. Most UAVs designed for civilian or military purposes use a parallel connection of energy sources. This configuration benefits from redundancy, but in certain situations, power control becomes difficult when the power supply is simulated through two or more energy sources [11].

Mixed connection of energy sources requires a minimum of three electric sources. From a technical point of view, it presents all the advantages of the two types of connections presented earlier, but manufacturing costs due to complexity are high [10].

3. ENERGY MANAGEMENT UNIT FOR A SOLAR UAV

The energy management unit, based on a mathematical algorithm implemented as a C++ program, ensures continuous power supply to electrical consumers and efficiently switches between energy sources. The main functions of the management algorithm include quickly identifying the maximum power generated by the photovoltaic system, selecting the optimal energy sources, and controlled charging of the battery pack [5], [16].

Photovoltaic cells generate electrical energy only during the day and under certain lighting conditions. Therefore, secondary energy sources are necessary. A technical solution for creating a mixed secondary energy source is to use a battery pack and a fuel cell. From this perspective, supplying consumers through a battery pack requires a charging and discharging control system that ensures its normal operation and significantly prolongs its service life. By using a DC converter, consisting of a capacitive filter and a multi-winding transformer, controlled and optimized charging of a battery is achieved [3].

The practical realization of an energy management unit for a solar-powered UAV contributes to research on the switching mode of power sources and the study of transient effects during power supply to electrical consumers. After analyzing the international standard ISO 10483-1:2004, which specifies the optimal criteria for energy source switching, the main characteristics for designing the electrical scheme of the energy management unit were determined [17].

After establishing the main elements required in the design process, the electrical scheme and 3D simulations of the energy management unit were created using the Proteus PCB Design software. The electrical scheme of the energy management unit for a UAV powered by photovoltaic cells is shown in Fig. 2.

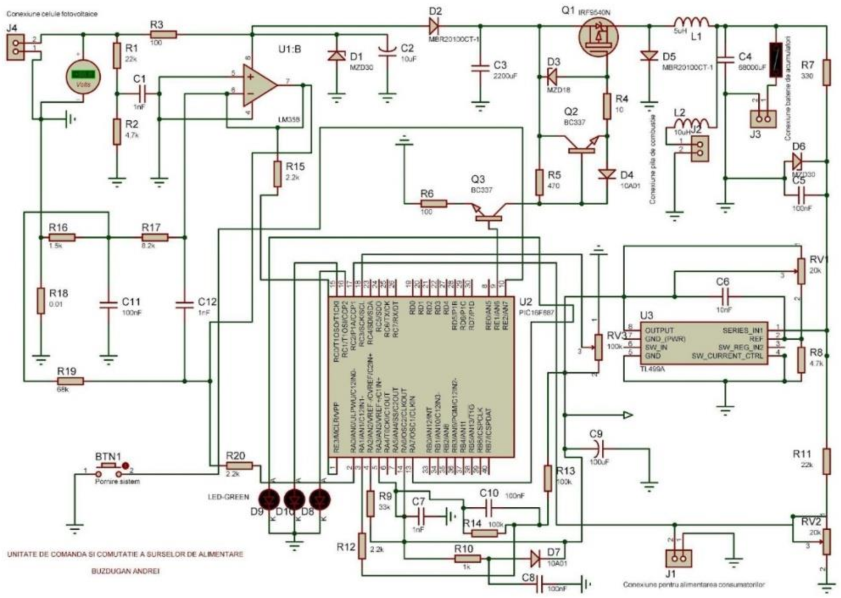


FIG. 2 The electrical diagram of the energy management system unit

Through the two operational amplifiers of the LM358 integrated circuit, the voltage and electric current generated by the photovoltaic cells are measured [18]. The information received from the integrated circuit is processed by the PIC16F887 microcontroller, resulting in an amplitude-modulated signal that is later used in the step-down conversion stage of the electric current [19].

The P-channel MOSFET transistor Q1 is switched in accordance with the signal emitted from pin 9 of the PIC microcontroller. Throughout the operation, transistors Q2 and Q3 ensure the integrity of the amplitude-modulated signal.

The electrical diagram presented in Fig. 2 has the advantage of obtaining a maximum voltage of 12V and a current of up to 3A. The battery charging procedure is gradually carried out in three levels, depending on the solar radiation and electric current generated by the photovoltaic system. During the operation of the fuel cell to supply consumers, the battery is not charged. This method ensures a long battery life and constant discharge during operation.

The TL499A integrated circuit provides a stable and constant voltage of 5V necessary for the operation of the PIC microcontroller.

Depending on the solar radiation level, battery charging capacity, and fuel cell status, the energy management unit selects the optimal power source for supplying consumers without interrupting, limiting, or reducing the supplied electric energy. Throughout this time, the energy source switching is controlled by a mathematical algorithm integrated in the form of a C++ program in the PIC16F887 microcontroller.

After functional testing in the Proteus PCB Design application, the electrical diagram presented in Fig. 2 was exported to the ARES application to simulate a 3D presentation of the energy management system [20]. The dimensions of the electronic board presented in Fig. 3 are 97 mm in length and 48 mm in width.

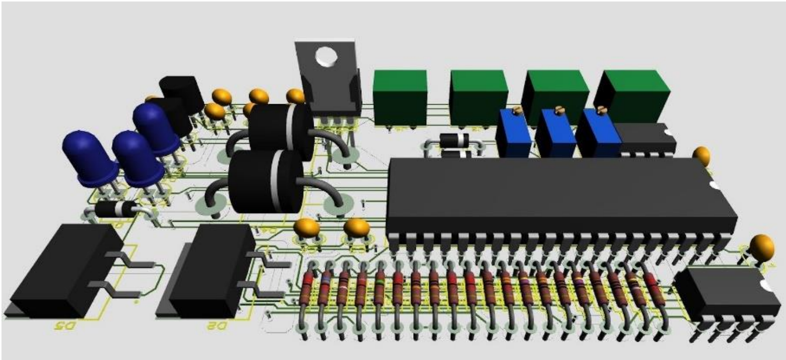


FIG. 3 3D simulation of the electronic board for the energy management system

4. THE EXPERIMENT

In order to validate the experimental model of the energy management system, a series of tests were carried out using an UAV powered by electric energy generated by photovoltaic cells. To obtain similar operating conditions for different flight stages, a test stand with the ability to record parameters was used. Similar tests were carried out in the Solar Flight company laboratories in Italy, which resulted in data regarding the optimization and operation of the energy system for the following UAVs: Solar-Seat Transporter, SunStar, and Sunseeker I and II [15], [21].

The results of the tests presented in this paper were obtained in the on-board Equipment Maintenance Laboratory at Bacau Air Base 95.

The practical realization of a UAV with a wingspan of 151 cm and a test stand for operating regimes made it possible to validate the energy management system by providing a constant and uninterrupted power supply to electric consumers and studying the transient effects observed during the switching of energy sources. The electrical sources used in this case represent a photovoltaic system composed of 10 solar cells, an accumulator battery and a fuel cell [4].

During the experiment, certain aspects were monitored regarding the power ratio generated by the three electrical sources and the power consumed by the propulsion system, as well as the transient effects of the electric current observed during the switching of the power supply mode.

The image presented as Fig. 4 illustrates the solar-powered UAV utilized for conducting functional tests, showcasing its physical design, configuration, and key components.

FIG. 4 UAV powered by solar energy used in the experiment

The research conducted in this experiment aimed to observe the transient effects of electric current during the switching of power sources, and the resulting study presents the findings.

The transient effects of electric current occur when the power source changes suddenly or when the electric current is interrupted. These variations in electric current can cause damage or operational limitations to the electric and electronic systems within the power grid, leading to unexpected behavior or deterioration of these systems.

To minimize the transient effects of electric current, various techniques and devices can be used, such as EMI filters and slow-switching breakers. These help attenuate rapid variations in current or voltage, thereby reducing the risk of damage to connected systems and devices.

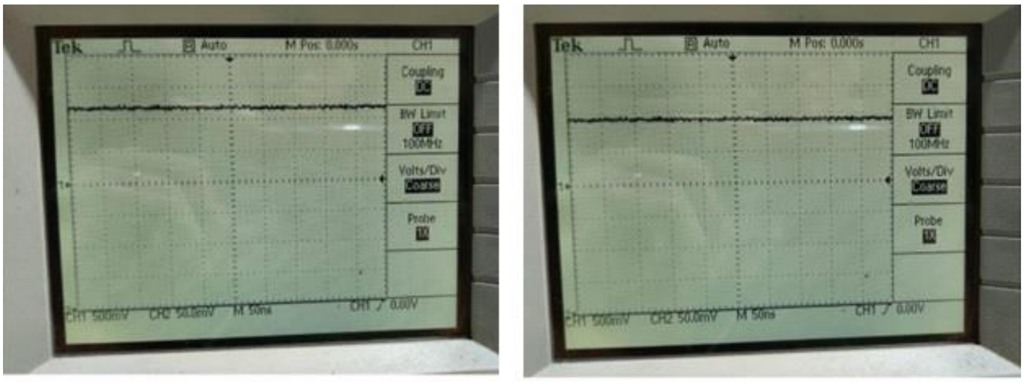
The switching of electrical sources is carried out under the following conditions:

- the voltage generated by the photovoltaic system drops below 12V;
- the power generated by the photovoltaic system does not fully meet the energy needs of the UAV.

Based on these criteria and the number of electrical sources connected to the MPPT device, the experiment was repeated twice. The data recorded using a Tektronix TDS 220 laboratory oscilloscope, connected to the power supply network of the electrical consumers, are the results of a comparison between the two situations [22].

Depending on the number of power sources connected to the energy system, two cases were obtained, and presented in Fig. 5 A and B:

- Fig. 5 A / case 1 - photovoltaic cells, battery pack, and fuel cell;
- Fig. 5 B / case 2 - photovoltaic cells and battery pack.



A B

FIG. 5 The experimental results of energy source switching in both cases

Case 1 - Fig. 5 A:

Under normal illumination conditions, the photovoltaic system operates at its maximum capacity, and the voltage generated by it has a value of 12.5V. The battery connected to the MPPT device indicates a voltage of 12.4V, comparable to that of the photovoltaic system.

After initiating the energy system, the electric motor was accelerated to a speed of 4569 rpm. For this operating regime, the entire energy consumption is provided through the photovoltaic cells. The power resulting from solar energy has a value of 65W, and the power required for the propulsion system at this speed is 36.25W.

To study the transient effects that occur during the switching of electrical sources, the conditions were simulated where the UAV flies a distance during the night when the solar radiation intensity is undetectable. In this regard, the power supply from the photovoltaic cells was interrupted through a switch mounted on the main power supply line.

On the oscilloscope screen shown in Fig. 5 A, a constant supply voltage and current can be observed, even during the switching of power sources. The frequency of display of signal changes is 50 ns, and the voltage oscillation detection mode is selected to be automatic.

During the period when the consumers were being supplied by the three electrical sources, five successive switches were performed. During these tests, the supply voltage value to the consumers remained constant, and no oscillations were recorded on the oscilloscope screen during the switching of power sources. The reason why there were no non-conformities recorded throughout this verification period is due to the fact that the total power generated by the three sources is greater than that required for normal operation.

Case 2 - Fig. 5 B:

To validate the premise resulting from Case 1, the experiment was repeated by disconnecting the fuel cell from the energy supply system. With the energy generated by the photovoltaic system, the electric motor was accelerated to the same speed of 4569 rpm, consuming 36.25W. After activating the switch that disconnects the power supply from the photovoltaic cells, the MPPT time device automatically transfers energy through the battery. Following this action, a sudden reduction in the current supplied to electrical consumers was observed on the oscilloscope screen, as depicted in Fig. 5 B.

Comparing the results obtained in Case 1 and Case 2, the following conclusions have been drawn:

- the MPPT device performs the switching of power sources under the initially imposed conditions;
- in the case of a complete interruption of the energy flow generated by the photovoltaic system, when only the photovoltaic cells and the battery are connected to the MPPT device, the supply current value drops;
- under certain conditions, when electronic devices and the propulsion system require a standard current and electrical voltage value, there is a risk of them shutting down.

CONCLUSIONS

To be able to perform long-distance and high-altitude flight missions, a UAV needs to be powered by multiple energy sources. In a hybrid energy network, where photovoltaic cells are the main source, the use of an energy management system can ensure a constant supply of electricity to consumers throughout the entire operation.

After comparing the characteristics of energy management systems used in solar UAVs, the active command system (APM) was found to be the most suitable for powering consumers by switching energy sources.

The use of photovoltaic cells together with a battery and a fuel cell ensures in-flight power supply for the UAV at different times of the day and for extended periods. Depending on the flight conditions and power requirements, the power supply can be provided in a mixed mode from all three sources or individually.

To ensure efficient selection of energy sources and supply all electric consumers in the most efficient way possible, a proposed technical solution involves developing and experimentally implementing a control unit with integrated MPPT function. This will select the optimal power supply source based on solar radiation levels, battery charging capacity, and fuel cell condition. The switching of energy sources will be controlled by a mathematical algorithm.

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