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Original Article

Energy Management Strategy Based on Fuzzy Logic and State Machine for Spraying UAV Hybrid Power System

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Abstract *- Hybrid power systems increase the autonomy of electric vehicles, including UAVs, for agricultural spraying tasks. However, their implementation requires incorporating an Energy Management Strategy (EMS) to distribute energy from various sources efficiently. This research addresses the design of an EMS for a hybrid UAV composed of a Fuel Cell and a battery. The power control aspects of each energy source are examined in detail, considering the power profile associated with the typical flight of a spraying UAV. A State Machine and Fuzzy Logic approach accomplishes power control management. The EMS is implemented at the simulation level using the MATLAB-Simulink® tool. The results consider a specific mission scenario where the takeoff requires more power, stabilizing the consumption in the cruise mode flight operated in the spraying activities. Finally, the simulation results indicate that the state machine facilitates transitions between power sources and, in convergence with fuzzy logic techniques, can adequately control the energy of the UAV and thereby increase the autonomy of operation.*

Keywords *- Battery, Energy Management Strategy, Fuzzy Logic, Hybrid power system, Spraying UAV.*

1. Introduction

Initially, the development of drones or Unmanned Aerial Vehicles (UAVs) was for military purposes due to the cost and complexity of their operation; however, their applications experienced remarkable growth in recent years to cover a wide range of civilian uses, optimizing various economic activities, including agriculture [1, 2]. The agricultural sector needs to improve production processes and manage soil conditions to meet the food demand estimated by FAO for the coming years [4]. In this context, UAVs have become invaluable allies for remote sensing and crop spraying tasks, significantly reducing operational costs, supplies, labour, and agrochemical exposure. Furthermore, they substantially reduce the time required compared to traditional manual spraying methods [5].

Lithium-Ion (Li-Ion), and Lithium Polymer (LiPo) batteries predominantly serve as the primary energy source for most commercial UAVs [6]. Despite widespread adoption, these batteries exhibit a relatively low energy density, significantly limiting UAV flight autonomy [7]. This limitation is especially critical in applications where the mission must be continuous, such as coverage of large agricultural areas. Flight time limitation increases operational costs due to the need for multiple takeoffs and frequent battery replacements [8].

Engaging this issue requires the integration of energy sources with higher energy density [9]. Scientific literature has explored various configurations of these sources, encompassing combinations of Fuel Cell (FC), battery, and solar panel [10], as well as hybrid systems incorporating fuel cell, battery, and supercapacitor [11, 12].

In these systems, batteries, supercapacitors, and solar panels usually function as backup sources rather than a hybrid system. However, other studies propose using fuel cells and batteries as one of the most promising alternatives regarding flight autonomy, energy efficiency, and component lifespan preservation [13]. Nevertheless, hybridization necessitates incorporating an Energy Management Strategy (EMS) to interchange the supply of primary and secondary energy sources to extend the devices' flight times [14, 15].

Nevertheless, integrating two energy sources to power a spraying drone or a specific UAV presents significant challenges due to operational complexity and technological devices to integrate [16]. The problem lies in efficiently managing the transition and complementarity between the two energy sources, i.e., the energy accumulated in the batteries and the energy coming from an additional generation system (such as a photovoltaic panel) [10]. Coordinating these energy sources is crucial to ensure a constant and reliable energy supply during flight and spraying manoeuvres [14]. In addition, workload variability and environmental conditions can dynamically impact power demand, requiring an adaptive power management strategy [16].

Efficiency in EMS design is essential to avoid operational disruptions, maximize drone autonomy, and ensure efficient response to fluctuations in power demand during agricultural operations. Requires precise engineering in integrating power sources and effective implementation of control and monitoring strategies that allow a smooth and optimized operation of the spraying drone [1, 14].

These Energy Management Strategies (EMS) enclose rule-based approaches [10], State Machines [13], Fuzzy Logic [17], as well as approaches based on Adaptive Neuro-Fuzzy Inference Systems (ANFIS) [18, 19]. The use of fuzzy state machines [20], as well as the implementation of EMS based on the combination of Particle Swarm Optimization (PSO) algorithms and Fuzzy Logic (PSO-Fuzzy Logic) [21], have also been investigated.

A well-designed EMS must efficiently coordinate the utilization of multiple energy sources. The strategy can prioritize the utilization of stored battery energy during critical times of high demand, while solar cells or a combustion engine can operate in favourable sunlight or fuel availability. In addition, the EMS must constantly monitor battery charge and atmospheric conditions to optimize flight efficiency and ensure maximum range [15].

Despite the existing literature on UAV energy management, studies on the EMS for spraying UAVs to improve energy autonomy and better fulfil agricultural tasks still need to be completed. For this reason, the proposal involves designing an EMS by implementing a fuzzy state machine control. This system aims to facilitate proper energy management in a hybrid system that combines a fuel cell and a battery in UAVs. The focus is on ensuring efficient energy management at different stages of UAV operation, considering changing power requirements and characteristics of energy sources to maximize UAV performance, with a particular focus on agricultural UAVs used for spraying.

The following is the organization of this article. Section 2 describes the methodological aspects, Section 3 explains the configuration of the hybrid system, Section 4 models the designed energy management strategy, and Section 5 demonstrates the simulations and results. Finally, Section 6 provides the conclusions.

2. Methodological Aspects

The process of analyzing and designing an optimal EMS for hybrid vehicles encompasses the following four steps methodology [22]:

Step 1 : Designing the hybrid vehicle control system involves utilizing control theory to model continuous and discrete dynamics, considering the vehicle configuration and operation,

Step 2 : Applying numerical methods involves using techniques like Sequential Quadratic Programming (SQP) to determine the power distribution and transition ratio,

Step 3 : Development of a Fuzzy Logic and rule-based system that uses the numerical statistics derived from the previous step to define the actions to execute the transitions between the power sources,

Step 4 : Optimization of the operation parameters. Artificial Intelligence algorithms can be applied to optimize the operational parameters, using a large set of collected data to optimize membership function parameters, rule weights, and fuzzy rule sets.

The methodology demonstrates its effectiveness and applicability through simulation results [22]. In addition, the review article [23] addresses several methodological considerations regarding the EMS for UAVs with hybrid power systems. Some of these considerations are:

- Classify the architecture of the energy system, which can be centralized, distributed, or hybrid to propel the UAV,
- Understanding the missions and flight manoeuvres the UAV must perform to accomplish its tasks must also consider the time and space scale for designing the EMS,
- Review of control algorithms that may be required to operate online or offline to distribute electrical power to the UAV dynamically,
- Comparative analysis of EMS designs considering complexity, precision, and efficiency parameters &
- Analysis of the integration of machine learning methods to optimize the design of EMS for UAVs.

In this sense, this research considers the first three steps of the methodology proposed. In addition, it feels like control algorithms based on fuzzy logic for a hybrid architecture of a spraying UAV whose main task is to fumigate agricultural fields.

3. Hybrid Energy System

3.1. Hybrid System Architecture

The goal of the hybrid power system, coupled with an efficient EMS, is to enhance the flight endurance of UAVs, in this case, UAVs dedicated to spraying tasks. The proposed configuration for this hybrid power system comprises a Fuel Cell as the primary energy source, a battery serving as a second source, and DC-DC converters to interface the sources with the bus DC. The battery supplements power during takeoff and ascent stages and stores energy during cruise flight stages. Figure 1 presents the detailed arrangement of its components.

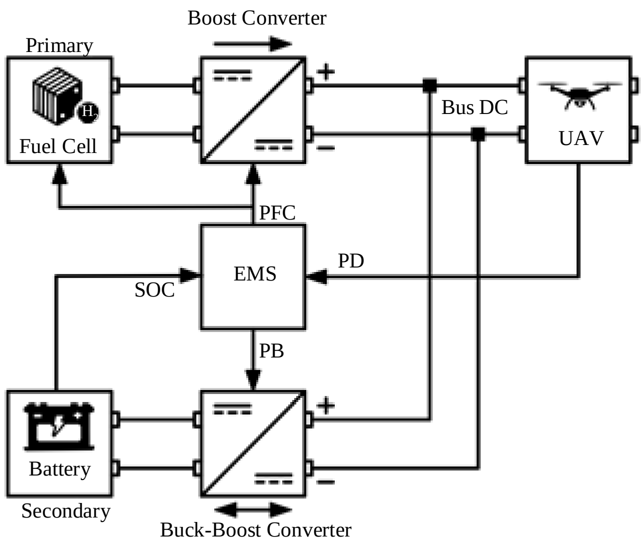

Fig. 1 Hybrid power system architecture

The unidirectional DC/DC (boost converter) increases the voltage supplied by the Fuel Cell and regulates the voltage on the bus DC. Additionally, the bidirectional DC/DC (buck-boost converter) regulates the battery voltage and enables changing the flow of electric charge depending on the system's power requirements.

Implementing these converters ensures optimal and secure operational conditions for the UAV. Finally, the EMS determines and controls the energy charge/discharge between the battery and the Fuel Cell. To illustrate the methodology employed in this study, the researchers designed an EMS for the MG-1P UAV hybrid energy system. Batteries initially power the MG-1P and are utilized for agricultural spraying applications.

It features a payload capacity of up to 10 kg, a flight time of up to 9 minutes, a hovering power consumption of 3800W, and a maximum power consumption of 6400W. The UAV's battery model is the MG-12000P, a LIPO battery with a capacity of 12,000 mAh, a nominal voltage 44.4V, and a weight of 4 kilograms [24].

3.2. Fuel Cell (FC)

The Fuel Cell is distinguished by its high efficiency, between 50 and 60% [18], high energy density, and zero emissions, thus minimizing the environmental impact [19, 25]. These characteristics make the Fuel Cell (FC) an excellent choice to satisfy the specific demands of UAV applications. One of the fuel cell types, the Proton-Exchange Membrane Fuel Cell (PEMFC), is one of the most widely employed Fuel Cells due to its lower operational temperature range (30-100°C) [10].

This feature reduces material corrosion, improves component durability, and facilitates implementation [13], [23, 26]. The output Voltage generated by the Fuel Cell (V_{FC}), as shown in Equation 1, is obtained from the difference between the Nernst Voltage (V_N), Activation Voltage drops (v_A), Ohmic Voltage drops (v_Ω), and Concentration (v_c) detailed in Equations 2, 3, 4, and 5, respectively, multiplied by the number of cells that make up the Fuel Cell [10, 13, 21].

$$V_{FC} = N(V_N - v_A - v_\Omega - v_c) \tag{1}$$

$$V_N = 1.229 - 8.5x10^{-4}(T_{FC} - 298.5) + 4.3085x10^{-5}T_{FC}\left[\ln(P_{H2} + \tfrac{1}{2}\ln(P_{O2})\right] \tag{2}$$

$$v_A = -0.9514 + 0.00312T + 7x10^{-5}\ln(C_{O2}) - 1.87x10^{-4}T \cdot \ln(i_{FC}) \tag{3}$$

$$v_\Omega = i_{FC}R_\Omega \tag{4}$$

$$v_c = 0.016\ln(1 - J/1.5) \tag{5}$$

Where,
T_{Fc} : Fuel Cell temperature [K].
P_{H2} : Hydrogen Pressure [atm].
P_{O2} : Oxygen Pressure [atm].
i_{FC} : Fuel cell current [A].
R_Ω : Internal electrical resistance [$\Omega \cdot cm^2$].
J : Fuel cell current density during operation [A/cm^2].

For the calculation of Equation 3, which is the activation voltage drop, it is necessary to use the C_{O_2} value described in Equation 6.

$$C_{O_2} = \frac{P_{O2}}{5.08x10^6 \exp(-498/T)} \tag{6}$$

The polarization curve of the FC, presented in Figure 2, illustrates the power behaviour and voltage as a function of current and enables the definition of the optimal operating region of the FC.

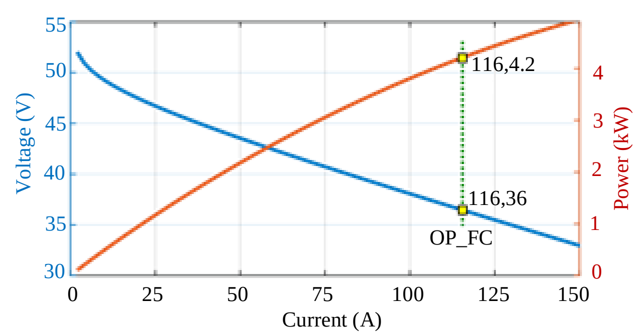

Fig. 2 Fuel Cell characteristic curve

The FC is selected to fulfil the power need required by the UAV up to 4200W; the battery will supply the remaining power.

3.3. Battery

Integrating a battery as a secondary power source enables the UAV to adjust and respond effectively to different scenarios, providing operational flexibility and improving safety and efficiency against various flight conditions and power requirements. Due to its relatively high power density, it improves the system's response speed and extends the fuel cell's helpful life [27].

The mathematical model describing the charge and discharge of the battery is given by Equations 7 and 8 [10, 13, 20]:

Charging:

$$V_{bat} = E_0 - R_0 \cdot i_B - K\frac{Q_B}{i_Bt - 0.1Q_B} \cdot i^* - K\frac{Q_B}{Q_B - i_Bt} + A\exp(-B \cdot i_Bt) \quad (7)$$

Discharging:

$$V_{bat} = E_0 - R_0 \cdot i_B - K\frac{Q_B}{Q - i_Bt}(i_Bt + i^*) + A\exp(-B \cdot i_Bt) \quad (8)$$

Where:

V_{bat} : Battery voltage [V].
E_0 : Battery constant voltage [V].
K : Polarization constant [V/(Ah)].
Q_B : Battery capacity [Ah].
i_Bt : Actual battery charge [Ah].
A : Exponential zone amplitude [V].
B : Exponential zone time constant inverse $[(Ah)^{-1}]$.
R_0 : Internal resistance [Ω].
i_B : Battery current [A].
$i*$: Filtered current [A].

The State of Charge (SOC) is an indicator that reflects the quantity of charge available in the battery, performing a crucial role in planning and optimizing UAV operations. Furthermore, the SOC facilitates the establishment of limits for safe charging and discharging processes, thus contributing to operational safety. Its behaviour is modelled by Equation 9, according to [10].

$$SOC = 1 - \frac{\int_0^t i_B dt}{Q_B} \quad (9)$$

For the hybrid UAV system detailed in this article, select the battery to satisfy the power demands between the maximum power supplied by the FC and the maximum power consumption of the UAV.

Ensuring a fully charged battery at the start of the flight is crucial. The battery recharge will occur exclusively when the power demand is lower than required for a cruise flight. The recharge's magnitude will depend on the battery's SOC and the FC's remaining capacity to generate energy.

3.4. Unidirectional Boost Converter

When working with a fuel cell, evaluating the voltage variation concerning the consumed current is necessary. The operating point will vary along the linear polarization region. Thus, a unidirectional DC-DC converter is required to adapt to changes in input voltage levels and maintain a constant voltage on the Bus DC in response to the current requirements of the load.

For the present study, the researchers considered a unidirectional Boost Converter, and its circuit is presented in Figure 3.

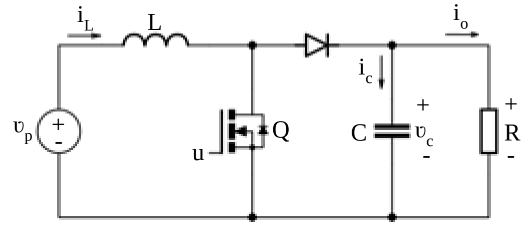

Fig. 3 Boost converter [9]

Equations 10 and 11 express the average differential equations modelling the converter's behaviour.

$$\frac{di_L}{dt} = \frac{v_p - v_C(1-d)}{L} \quad (10)$$

$$\frac{dv_C}{dt} = \frac{i_L(1-d) - \frac{v_C}{R}}{C} \quad (11)$$

3.5. Bidirectional Buck-Boost Converter

A bidirectional converter is essential in hybrid systems to efficiently manage energy in environments with multiple power sources and voltage levels.

In the context of the proposed system, this converter will be fundamental in integrating the battery into the bus DC, enabling bidirectional energy transfer that dynamically adjusts according to the power needs of the load, the SOC, and the control signals provided by the EMS. This study incorporated a bidirectional Buck-Boost Converter circuit shown in Figure 4.

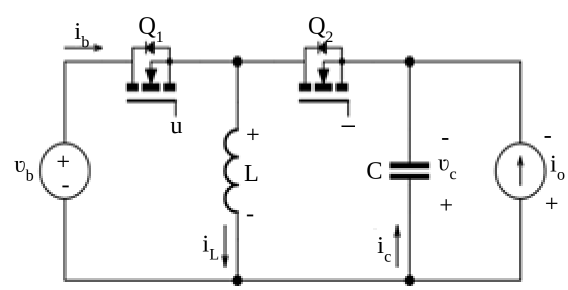

Fig. 4 Buck-boost converter [9]

The average differential equations that model the Buck-boost converter's behaviour are represented by Equations 12 and 13.

$$\frac{di_L}{dt} = \frac{v_b \cdot d - v_c \cdot (1-d)}{L} \quad (12)$$

$$\frac{dv_c}{dt} = \frac{i_L \cdot (1-d) - i_o}{C} \quad (13)$$

The design of voltage and current controllers for unidirectional and bidirectional converters, as well as Equations 10, 11, 12, and 13, are addressed in [9].

4. Energy Management Strategy (EMS)

The EMS is crucial in optimizing energy distribution derived from various sources in a hybrid system. This article proposes an EMS that ensures the fuel cell and battery operate within their defined operational parameters, efficiently distributing energy to satisfy the specific power demands of the flight profile.

The configuration of the EMS incorporates a state machine considering a control limiting the Power supplied by the Fuel Cell (PFC) and control of the charge and discharge power of the battery based on fuzzy logic. Figure 5 depicts the implementation process flow of the EMS. This approach achieves a more efficient and precise management of energy flows, thereby optimizing the overall system performance.

The proposed design of EMS aims to satisfy the demands of the power profile, as depicted in Figure 6. This profile consists of various segments: Power-up, accelerated climb, climb, hover, acceleration to cruise, cruise, disturbances, and power-down. The characteristics of the energy demand curve presented in [9] have been used for the power profile, adapting its values to those obtained from the specifications sheet of the UAV MG-1P.

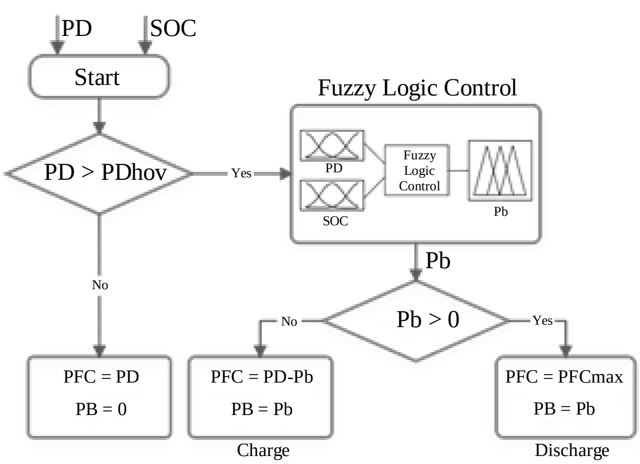

Fig. 5 Scheme of the Energy Management Strategy

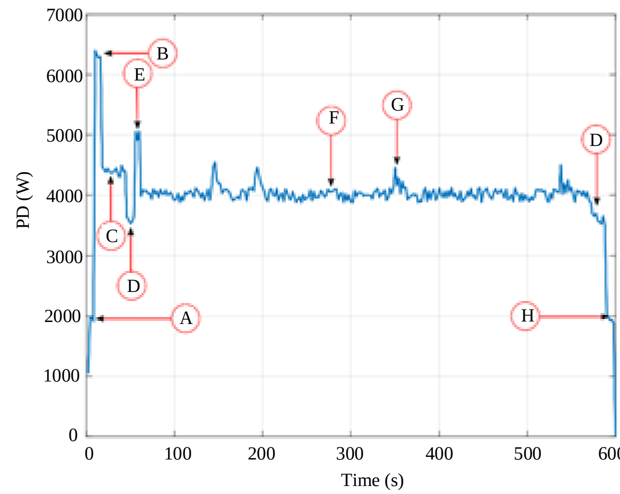

Fig. 6 Typical power profile of a UAV: (A) Power-up, (B) Accelerated climb, (C) Climb, (D) Hover, (E) Acceleration to cruise, (F) Cruise, (G) Disturbances, and (H) Power-down.

4.1. Fuel Cell Power Control

It is necessary to regulate the amount of hydrogen supplied to the fuel cell to effectively manage the power to ensure proper flight and manoeuvring of the UAV, which impacts fuel consumption.

Equation 14 shows the Hydrogen flow [3, 20], which enables adjusting the input flow to the fuel cell. This adjustment can be made based on the current requirements of the system.

$$H_2Fr = \frac{60000\, R \cdot T \cdot N \cdot i_{fc}}{2F \cdot 101325 P_{H2} \cdot \frac{Uf_{H2}}{100} \cdot H_2\%} \quad (14)$$

Where:

R : Universal gas constant 8,3145 [J/(mol·K)].
T : Temperature [K].
N : Number of cells.
i_{fc} : Current generated by the fuel cell [A].
F : Faraday's constant 96485 [C/mol].
$P_{f(H2)}$: Absolute pressure of fuel supply [bar].
Uf_{H2} : Nominal hydrogen utilization.
$H_2\%$: Percentage of hydrogen in the fuel.

A maximum threshold for the hydrogen flow has been established, limiting its total power supply. Furthermore, add a threshold for the total value of the boost converter's duty cycle.

The duty cycle is calculated through steady-state analysis of the boost converter, as shown in Equations 10 and 11. It utilizes their average differential equations for both the inductor current (i_L) and the capacitor voltage (v_c). This voltage is the same as the bus DC voltage [9].

From the steady-state analysis of Equations 10, and 11, Equations 15, and 16 are deduced.

$$V_c = \frac{V_p}{1-D} \tag{15}$$

$$I_L = \frac{V_c}{(1-D)\cdot R} \tag{16}$$

Rearranging Equation 15 and solving for D, obtain the Duty Cycle, as shown in Equation 17.

$$D = \frac{V_c - V_p}{V_c} \tag{17}$$

4.2. Fuzzy Logic Control

The Fuzzy Logic Controller (FLC) handles reasoning approximately; this characteristic grants the FLC the ability to tolerate inaccurate measurements and variations in input variables, providing robustness against system uncertainties [15, 21].

The input parameters of FLC are the battery State of Charge (SOC) and the total Power Demanded (PD) by the system. At the same time, the control output corresponds to the charge or discharge Power of the battery (Pb). Table 1 presents the values of the considered control parameters, maximum Power Fuel Cell (PFCmax), average Power Fuel Cell (PFCavg), maximum Power Demanded (PDmax), hover Power Demanded (PDhov), and cruise Power Demanded (PDcruise).

Table 1. EMS parameters

Parameter	Power (W)
PFCmax	4200
PFCavg	4000
PDmax	6400
PDhov	3600
PDcruise	4000

The Mamdani fuzzy inference method is chosen due to its intuitiveness, interpretability of its rule base, and broad acceptance. The system formulates energy management decisions based on 21 logical rules in each of the seven cases characterizing the UAV power demand, as detailed in Table 2.

Seven membership functions have been allocated for the power demanded by the UAV, encompassing linguistic variables such as Low power (L), Medium power (M), Considerable power (C), High power (H), High-Medium power (MH), Very High power (VH), and Extremely High power (UH). Regarding the battery SOC, three membership functions have been considered, with linguistic variables being Low (L), Medium (M), and High (H), and as for the battery power variation, eight membership functions: High Charging power (CH), Low Charging power (CL), low power around Zero (Z), Low Discharging power (DL), Considerable Discharging power (DC), High Discharging power (DH), Very High Discharging power (DVH), and Highly High Discharging power (DUH).

Table 2. Fuzzy control rules

		SOC		
		L	**M**	**H**
		Pb	**Pb**	**Pb**
PD	**L**	CH	CH	Z
	M	CL	CL	Z
	C	Z	DL	DL
	H	Z	DC	DC
	MH	Z	DH	DH
	VH	Z	DVH	DVH
	UH	Z	DUH	DUH

This control aims to efficiently manage the battery power flow by monitoring its State of Charge (SOC) to maintain this state at a reference value close to 94%.

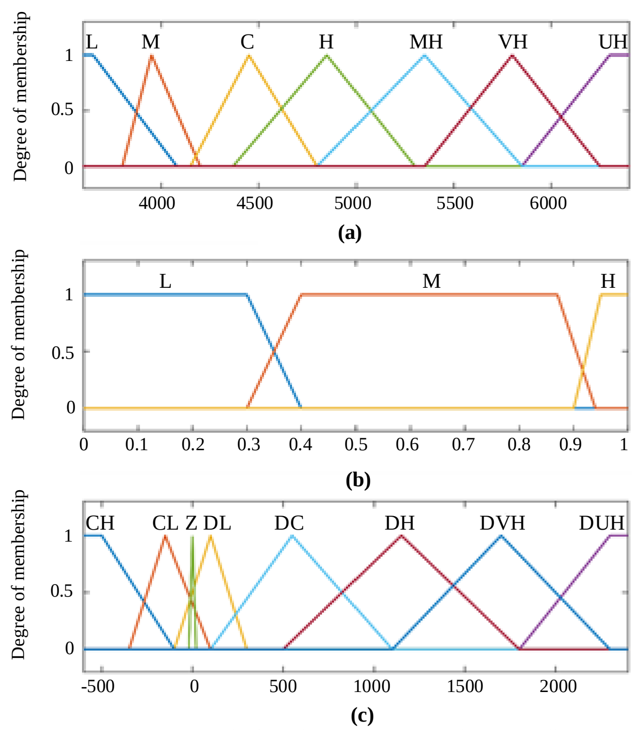

Fig. 7 Membership functions (a) Input variable "PD", (b) Input variable "SOC", and (c) Output variable "Pb".

Figure 7(a) shows triangular and trapezoidal functions used to develop the membership functions for the demanded power. Selecting a Low power (L) corresponding to the power requested by the UAV during hovering was done., a Medium power (M) related to the power asked during cruise flight, a

Considerable power (C) associated with the power required during ascent, and High (H), High-Medium (MH), and Very High (VH) powers corresponding to the powers requested during the acceleration phase of cruise flight. An Extremely High power (UH), linked to the maximum power requested during the accelerated climb phase, has also been included.

Trapezoidal functions have been used regarding the SOC, as observed in Figure 7(b). When the SOC is below 40% and the PD is low, a High Charging profile (CH) charges the battery. Conversely, if the battery charge exceeds 90% and the PD is high, the battery will discharge.

Triangular and trapezoidal functions were applied to model the battery power, as represented in Figure 7(c). When the power demanded by the UAV exceeds 4.2 kW, meaning the maximum capacity supplied by the FC, it is considered a discharge power level. Contrarily, consider charge power levels starting from a value of 3.6 kW. Figure 8 depicts the fuzzy logic rule surface for a bidirectional power converter.

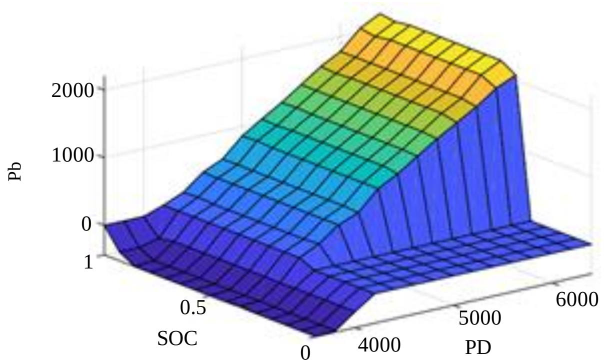

Fig. 8 Battery power converter rule base surface

4.3. State Machine

Due to its ability to provide a clear and modular representation of various states, along with the necessary conditions for transitioning between them, a state machine algorithm has been integrated into the EMS design to determine the power that the FC should supply, as well as the power provided by the battery and the transition between the charge and discharge modes of the battery.

This state machine allows for quick adaptation to system requirements changes, ensuring effective energy distribution management among the sources. This control strategy operates based on four states:

State 1 : This occurs when the power demand is lower than required for hovering. In this context, the UAV is in the initial or final phases of flight, indicating that the battery does not need to release or receive energy. Supplying all the necessary power falls entirely on the Fuel Cell.

State 2 : In contrast, a fuzzy logic controller becomes operational when the power demand exceeds the hovering capacity. This controller determines the intensity and direction of the battery Power (Pb). Positive powers indicate discharge, involving power delivery from the battery to the system, while negative powers signal recharge, representing the battery charging process.

State 3 : The fuzzy logic controller issues a replenish signal in this state. Besides fulfilling the Power Demand (PD), the fuel cell must provide additional power to recharge the battery. This process ensures that the battery is in a constant state of readiness, ready to address future power demands.

State 4 : When the fuzzy logic controller issues a discharge signal, the fuel cell is activated at its maximum power. The battery, in turn, engages to cover the remaining difference, ensuring that the UAV reaches the required power levels for the corresponding flight phase.

5. Simulation and Results

The simulation phase considered characteristics such as battery Voltage (Vbat), maximum Power of the FC stack (PFCmax), initial Voltage of the FC stack (Vfc_0), Fuel Cell Operating Point (OP_FC), bus DC voltage (Vbus), and simulation Time (Tsim). Table 3 describes these characteristics.

Table 3. Simulation characteristics

Parameter	Value
Vbat	36V
PFCmax	4.8kW
Vfc_0	56V
OP_FC	36V,116A, ~4.2kW
Vbus	50.4V
Tsim	600 s

Using the MATLAB-Simulink® platform, developed the energy management and control strategy. The validation process of the proposed EMS on this platform assesses optimization in the distribution and consumption of energy resources.

The simulation results are presented below, with a simulation time of 600 seconds and an initial State of Charge (SOC) set at 100%. This configuration aims to analyze the effects on the battery SOC and observe the evolution of the Fuel Cell power. Figure 9 illustrates the energy management strategy.

Figure 10(a) shows the power demand by the UAV throughout the various flight phases on a standardized trajectory.

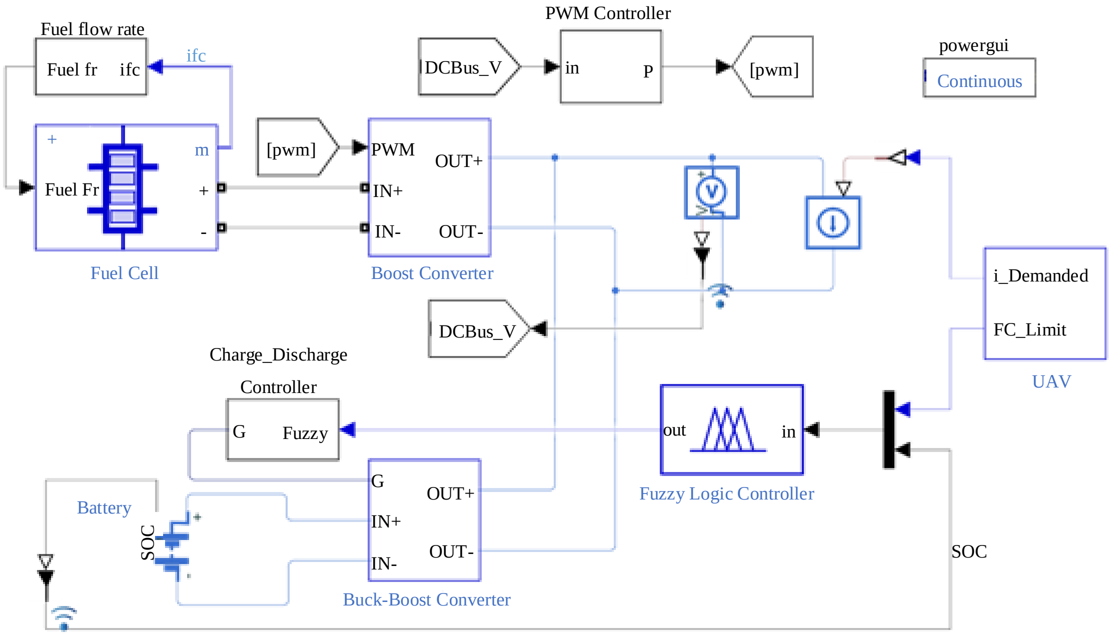

Fig. 9 Energy Management Strategy designed for the MG-1P UAV

In the initial moments of flight, there is an observed peak power consumption, reaching approximately 6.4 kW for a brief period. This increase in power is necessary to propel the ascent phase of the UAV. Subsequently, the UAV ascends at a constant velocity, leading to a significant decrease in power consumption. Once it has reached the appropriate altitude, the UAV enters the hover flight mode, characterized by the lowest power consumption. At this point, the cruise flight phase begins, during which altitude and speed are maintained constantly.

However, an acceleration is required to initiate this phase, resulting in a high-power peak reaching 5 kW. Power consumption during this phase stabilizes around 4 kW, although it is affected by disturbances, noticeable as moderate intensity spikes.

Similarly, Figure 10(b) presents the magnitude of power supplied by the fuel cell, emphasizing that a limit called PFCmax, established at 4.2 kW, constrains the power output generated by the FC. Although this magnitude is exceeded for brief moments, reaching up to an additional 50 W, it remains within the established operational range for the FC. This control confirms its ability to fulfil the power demand of the UAV during the cruise flight phase, as well as to cover the required difference in battery charging operations in situations where the energy demand is below PFCmax.

However, when demands exceed PFCmax, the battery is activated, assuming a complementary role to the FC to meet the Demand Power (PD). Figure 10(c) shows a more precise representation of this, where positive powers indicate that the battery, in collaboration with the power from the FC, supplies power to the bus DC. Conversely, negative powers indicate that the battery is recharging. The battery is charged when the battery Power (Pb) equals zero. Notably, according to the FLC, the battery is charged from a State of Charge (SOC) of 94%.

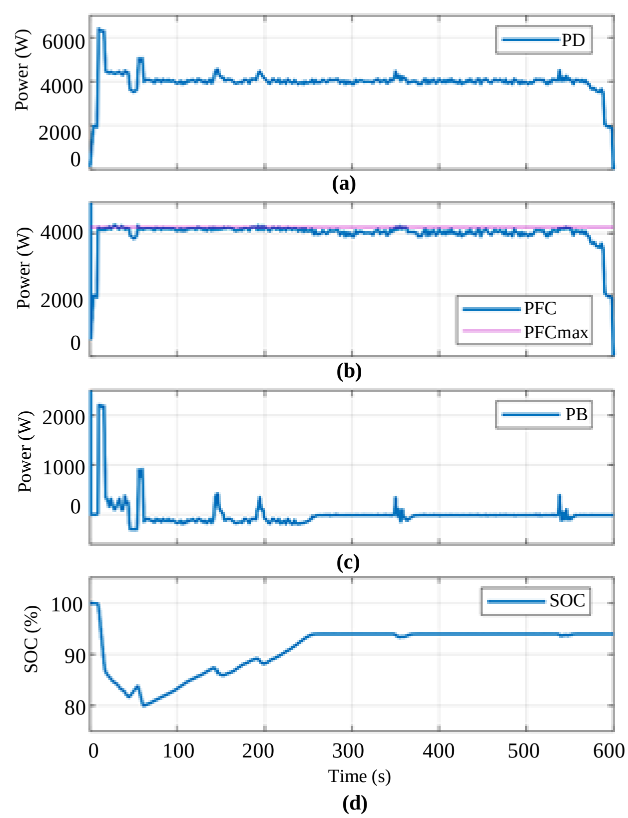

Fig. 10 Power and SOC Curves (a) Demand power, (b) FC power, (c) Battery Power, and (d) SOC.

Additionally, in Figure 10(d), it can be observed that during power peaks, the SOC experiences a decrease, while during the disturbance-free cruise flight phase, recharging occurs.

Obtain the Power output (Po) from the FC power sum and the battery Power's absolute value (Pb). Figure 11 presents a comparative analysis between the demand and output power. The researchers observe that the output power is typically equal to the demand power, with differences occurring at specific moments. This disparity is mainly attributed to the delivery of excess power by the FC during battery recharging, resulting in an output power that exceeds the demand.

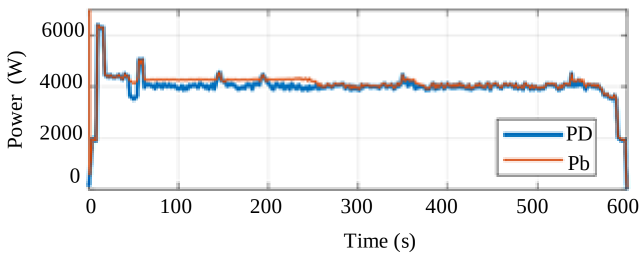

Fig. 11 Demand Power "PD" vs. Output Power "Po"

Figure 12 shows the voltage on the bus DC, demonstrating that the voltage remains regulated at 50.4 volts across varying energy demands from the load, albeit with a ripple.

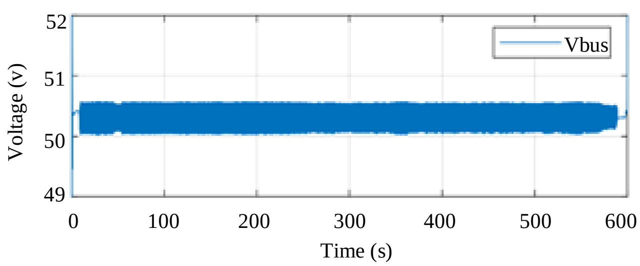

Fig. 12 Bus DC voltage

6. Conclusion

This article presents an energy management and control strategy for a hybrid UAV for spraying tasks, incorporating a PEMFC and a battery. The proposed EMS uses a state machine that incorporates two key elements: first, a control that restricts the power supplied by the Fuel Cell, and second, a power control for the battery's charging and discharging based on Fuzzy Logic. This system demonstrates its effectiveness by optimizing the utilization of each energy source and precisely managing energy distribution.

Simulations in MATLAB have validated the efficiency of the energy flow between the fuel cell and the battery, highlighting the crucial importance of an adequate distribution of energy between the sources of the hybrid system to maximize operational efficiency. The optimal allocation of this energy would not only result in the prolongation of flight time, but it would also have positive repercussions on the overall sustainability of the system, conferring viability to this solution to address the challenges inherent to the energy management of hybrid UAVs for spraying tasks.

In future research, new energy sources, such as supercapacitors, could be explored in this hybrid energy system. Additionally, consideration should be given to the weight and size of each power source to design a more compact hybrid system without sacrificing performance, allowing for the optimization of the power management strategy.

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