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Equivalent Consumption Minimization Strategy based on fuzzy logic control for the energy management of hybrid Unmanned Aerial Vehicle

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ABSTRACT

With the development trend of carbon neutrality and emission reduction in the aviation industry, hybrid-electric propulsion system (HEPS) is one of the feasible solutions that can significantly reduce fuel consumption, carbon emission and maintenance cost. HEPS with multiple power sources requires the reasonable energy management strategy (EMS) to monitor and regulate the working status of each component in real time. Equivalent consumption minimum strategy (ECMS) can distribute the output power of the engine and battery effectively, but it cannot maintain the state of charge (SOC) within permitted range. Therefore, combining the advantages of robustness and adaptability in fuzzy logic control (FLC), we proposed the fuzzy logic control-equivalent consumption minimum strategy (FLC-ECMS) for series hybrid Unmanned Aerial Vehicle (UAV). Under the cruise flight mission profile, the simulation results showed that hybrid UAV with the ECMS and FLC-ECMS can reduce fuel consumption and CO_2 emissions by 22% versus the engine-only UAV. Moreover, compared to ECMS, FLC-ECMS can decrease fuel and emissions while maintaining the battery SOC in the tolerance interval, and keeping the smaller front-to-back difference of SOC, which verifies the effectiveness of this strategy.

Keywords: equivalent consumption minimum strategy, energy management strategy, fuzzy logic control, hybrid-electric propulsion system, unmanned aerial vehicle

NONMENCLATURE

Abbreviations	
ECMS	Equivalent consumption minimum strategy
EMS	Energy Management Strategy
FLC	Fuzzy Logic Control
HEPS	Hybrid-Electric Propulsion System
SOC	State of Charge
UAV	Unmanned Aerial Vehicle

1. INTRODUCTION

In pursuit of sustainable development of the aviation industry, the International Civil Aviation Organization (ICAO) listed "Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)" as the only global industry mechanism to offset carbon emissions [1]. CORSIA employed the eligible emission unit to offset the incremental carbon emissions, with a short-term goal of emission peak and a long-term goal of carbon neutrality [2]. Despite the significant impact of the COVID-19, major emitters such as China, the United States and the European Union have responded positively with specific initiatives to reduce emissions, of which hybrid-electric propulsion system (HEPS) is one of the absolutely promising programs to reduce emissions significantly.

The energy source of HEPS is primarily the engine and energy storage device, where the presence of the latter brings a new degree of freedom of energy flow. Therefore, energy management strategies (EMSs) are required to find the most efficient way to split the power demand between engine and battery. Under the premise of satisfying parameter constraints such as torque, speed, efficiency and power, EMSs serve as a control layer to achieve the optimal fuel cost and maintenance cost.

Rule-based fuzzy logic control (FLC) with the advantage of good robustness and adaptability and optimization-based equivalent consumption minimum strategy (ECMS) with the advantage of low complexity and online management, are both promising solutions. Online FLC energy management controller was designed to implement the power distribution of fuel cell and

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battery for hybrid UAV, and simulation results show that FLC strategy reduced the hydrogen consumption compared with the state machine and passive control strategy [3]. Relying on the FLC strategy, Li et al. developed an adaptive energy management framework for a light electric aircraft, realized the power demand distribution between fuel cell and battery, which can improve the fuel economy and dynamic performance of the aircraft [4]. However, the FLC strategy relies heavily on the accuracy of the established rules and cannot implement online control.

Moreover, Malo et al. compared the three energy management strategies of state-machine (SM), FLC and ECMS for PV/FC/battery hybrid UAV, and it is concluded that ECMS can minimize hydrogen consumption and life degradation while ensuring stable bus voltage and output power [5]. However, conventional ECMS cannot achieve online maintenance of the battery's SOC, and SOC is not in the stability interval from the landing safety of the aircraft [6].

In this paper, aiming at the series hybrid UAV, combined with the robustness and adaptability of FLC, we have established the fuzzy logic control-equivalent consumption minimum strategy (FLC-ECMS) to dynamically allocate the power of the engine and battery in order to achieve the optimal fuel, maintenance costs and minimal carbon emissions, which provides a reference of EMS control strategy for UAV's HEPS.

2. HYBRID-ELECTRIC PROPULSION SYSTEM

HEPS architectures are available in three main types of configurations: series, parallel and series-parallel. The series HEPS architecture has a simple control system and its engine output shaft is not directly connected to the propeller, which decouples the engine from motor and ensures that the engine always operates near the optimal operating point with high efficiency and good emission performance. Therefore, a series hybrid UAV of the same magnitude as the DA36 E-Star2 is selected as the object of study in this paper [7]. The propulsion system architecture is shown in Fig. 1, consisting of power generation system, energy storage system and electric propulsion system.

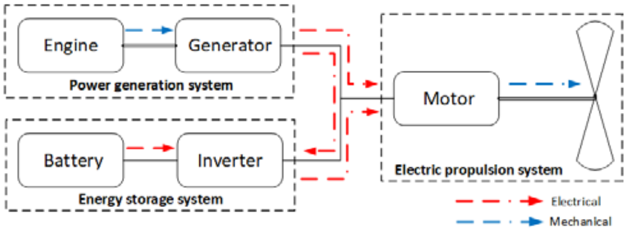


Fig. 1. The architecture of series HEPS

In the power generation system, the engine is considered as the main power source, and the generator is linked to generate electricity, both of which complete the conversion from internal fuel energy to mechanical energy and to electrical energy. Meanwhile, the battery in the energy storage system is discharged to deliver electrical energy to the electric propulsion system together with the generator. The motor converts the electrical energy into mechanical energy to drive the propeller, thus providing thrust for hybrid UAV.

HEPS can take advantage of multiple power sources to rationally adjust power output under different flight conditions. When the engine output is less than the required power, the battery will provide auxiliary power to ensure that the engine operates near the optimal operating point. When the required power is small, the excess power can charge the battery to achieve the effect of charge and discharge balance. Therefore, exerting the optimal performance of the hybrid-electric propulsion system and realizing the dynamic allocation of engine and battery power particularly must require reasonable and effective energy management strategies.

3. ENERGY MANAGEMENT STRATEGY

3.1 *Energy management statement of hybrid-electric propulsion system*

The energy management of HEPS is an optimal control problem, and its essence lies in the transient energy management of the power flow from the energy management controller to achieve the control objective. The optimal control objective essentially requires global optimization and the control behavior entails local optimization in time. The energy management optimization problem is to find the control rate that minimizes the HEPS fuel consumption, while ensure that the change of SOC value in battery is smaller. Define *J* as a performance evaluation function, and its mathematical descriptions is given below:

$$J=\min_{g_i(x),l_j(x)}\{f_1(x),f_2(x)\}$$
$$s.t.\begin{cases}g_i(x)=0, i=1,2,...m\\ l_j(x)\geq 0, j=1,2,...,n\end{cases} \qquad (1)$$

where $g_i(x)$ and $l_j(x)$ represent the linear and bound constraints of this optimal problem. And $f_1(x)$ and $f_2(x)$ can be expressed as below.

$$f_1(x)=\int_{t_0}^{t_{total}}\dot{m}_{fuel}(u(t),t)dt$$
$$f_2(x)=x(t_0)-x(t_{total}) \qquad (2)$$

where $\dot{m}_{fuel}(u(t),t)$ is the fuel consumption rate of engine, t_0 and t_{total} represent the initial time and total mission time of UAV flight profile. Select the state of charge *SOC* and battery power as the state variable *x(t)* and control variable *u(t)*.

$$\begin{gathered} x(t) = SOC \\ u(t) = P_{bat} \end{gathered} \tag{3}$$

The battery is modeled with a first-order RC equivalent circuit, and its exact expressions for the state variable are solved as follows.

$$\dot{x}(t) = \frac{1}{\eta^{sign(I_{bat})}} \frac{V_{oc}(x) - \sqrt{V_{oc}^2(x) - 4u(t)[R_{in}(x) + R_1(x)(1 - e^{-t/\tau})]}}{4Q_{bat} \cdot [R_{in}(x) + R_1(x)(1 - e^{-t/\tau})]} \tag{4}$$

where V_{oc}, Q_{bat}, R_{in} and η are the open circuit voltage, nominal capacity, internal resistance and efficiency of the battery, τ represents the time constant of the transition reaction course, and its value is $\tau=R_1(x)C_1(x)$.

The minimization of *J* is subject to the local and global constraints of state variables and control variables. Firstly, the total power requirement P_{req} of HEPS accounts for the electric propulsion system power P_{eps} and other electronic loads power P_{load}, and the mathematical description is given below.

$$\begin{gathered} P_{req}(t) = P_{eps}(t) + P_{load}(t) \\ P_{eps}(t) = \frac{P_{prop}(t)}{\eta_{mot} \cdot \eta_{inv}} \end{gathered} \tag{5}$$

where η_{mot}, η_{inv} are the efficiency of motor and inverter. The power requirement $P_{req}(t)$ is fulfilled together by the power generation system and energy storage system, so it is easy to find that there exists a power balance between the power producers and consumers, as shown in equation (6).

$$P_{eg}(t) + P_{ess}(t) = P_{req}(t) \tag{6}$$

In addition, it is necessary that the battery has enough power to ensure the safe landing of UAV in case of engine failure. With regard to local constraints, the state variable *SOC* should be maintained between a given maximum and minimum value to enable the battery work efficiently and sustain its cycle life. And the control variables and component parameters are guaranteed to operate physically within their limits by imposing local constraints such as speed and torque, as shown in the following equations.

$$\begin{gathered} SOC_{\min} \le SOC(t) \le SOC_{\max} \\ P_{bat,\min} \le P_{bat}(t) \le P_{bat,\max} \\ T_{eng/mot,\min} \le T_{eng/mot}(t) \le T_{eng/mot,\max} \\ N_{eng/mot,\min} \le N_{eng/mot}(t) \le N_{eng/mot,\max} \end{gathered} \tag{7}$$

3.2 *Equivalent consumption minimization strategy*

In the HEPS of UAV, the battery is only used as an energy buffer, and ultimately all energy consumption comes from the fuel, so the battery can also be regarded as an auxiliary and reversible fuel tank. Moreover, the core idea of ECMS is to associate the equivalent fuel consumption with the use of electric energy during the charging and discharging process of battery. The equivalent virtual (future or past) fuel consumption $\dot{m}_{fuel,vir}(t)$ is added to the current engine actual fuel consumption $\dot{m}_{fuel,cur}(t)$ to obtain the equivalent instantaneous fuel consumption rate $\dot{m}_{fuel,eqv}(t)$, and the following equation is given as below,

$$\dot{m}_{fuel,eqv}(t) = \dot{m}_{fuel,cur}(t) + \dot{m}_{fuel,vir}(t) \tag{8}$$

The current fuel consumption of the engine can be expressed as,

$$\dot{m}_{fuel,cur}(t) = \frac{P_{eng}(t)}{\eta_{eng}(t) Q_{fuel}} \tag{9}$$

where Q_{fuel} is the fuel heating value, $P_{eng}(t)$ is the power of engine, $\eta_{eng}(t)$ represents the efficiency of engine. And the equivalent virtual fuel consumption is expressed as,

$$\dot{m}_{fuel,vir}(t) = \frac{s(t)}{Q_{fuel}} \cdot P_{ess}(t) \tag{10}$$

where $P_{ess}(t)$ is the power of energy storage system, and *s(t)* is the equivalent factor of charging and discharging the battery, which is used to allocate the cost of electricity usage and convert the electricity into equivalent fuel consumption.

The ECMS is resolved sequentially according to the time sequence, and in each time step t_s, the optimal control problem can be expressed as,

$$\begin{gathered} \min_{x(k)} [\int_{(k-1)t_s}^{kt_s} \dot{m}_{fuel,cur}(t)dt + \int_{(k-1)t_s}^{kt_s} \dot{m}_{fuel,vir}(t)dt] \\ k = 1, 2, ..., t_{total} / t_s \end{gathered} \tag{11}$$

The efficiency of engine and electrical energy variation of energy storage system can be calculated by,

$$\begin{gathered} \eta_{eng}(k) = \frac{\int_{(k-1)t_s}^{kt_s} P_{eng}(t)dt}{Q_{fuel} \cdot m_{fuel,cur}(k)} \\ \Delta E_{ess}(k) = \int_{(k-1)t_s}^{kt_s} [P_{bat}(t) + P_{loss}(t)]dt \end{gathered} \tag{12}$$

Hence, solving for the above equations can yield the calculation of *s(t)* as below.

$$s(k) = \frac{\int_{(k-1)t_s}^{kt_s} [P_{bat}(t) + P_{loss}(t)]dt \cdot \int_{(k-1)t_s}^{kt_s} \dot{m}_{fuel,cur}(t) Q_{fuel} dt}{\int_{(k-1)t_s}^{kt_s} P_{eng}(t)dt \cdot \int_{(k-1)t_s}^{kt_s} P_{bat}(t)dt} \tag{13}$$

Therefore, the global problem of total cost minimization using ECMS is simplified to the problem of local instantaneous minimization of $\dot{m}_{fuel}(t)$. And the implementation of ECMS requires the following steps as shown in Fig. 2.

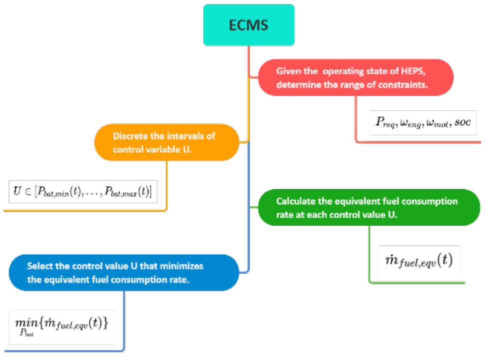


Fig. 2. Implementation roadmap of ECMS

3.3 Fuzzy logic control

Fuzzy control methods are robust and adaptable to nonlinear systems and complex problems, and can be used to solve the problem of battery SOC in ECMS. FLC converts experience into fuzzy rules, fuzzifies the real-time signal to obtain fuzzy variables, and outputs to the actuator after completing fuzzy inference according to the set fuzzy rules. The design of fuzzy logic controller includes the procedures of determining the variable domain, defining the variable affiliation function and designing fuzzy rules.

3.3.1 Determine the variable domain

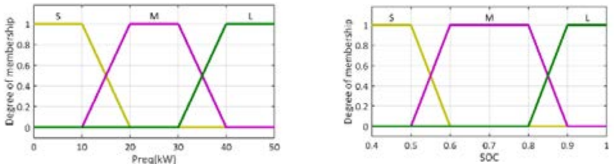
The UAV's required power P_{req} and battery *SOC*, the engine's output speed $N_{eng,out}$ and torque $T_{eng,out}$ are selected as the input variables, and the output variables (motor and engine input speed $N_{mot,in}$ and $N_{eng,in}$) are reasonably determined by the variation of the input quantities so that the engine can work as efficient as possible. The fuzzy domains and subsets of the input and output variables are shown in Table 1, where VS, S, M, L, and VL represent very small, small, medium, large, and very large values of the variables.

Table 1. Fuzzy input and output variables in FLC

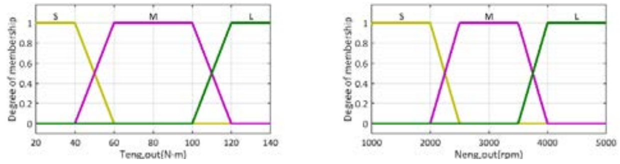
	Name	Domain	Fuzzy set
Input variable	P_{req}	[0, 50] kW	S, M, L
	SOC	[0.4, 1]	S, M, L
	$T_{eng,out}$	[20, 140] N•m	S, M, L
	$N_{eng,out}$	[1000, 5000] rpm	S, M, L
Output variable	$N_{mot,in}$	[1000, 5000] rpm	VS, S, M, L, VL
	$N_{eng,in}$	[1000, 5000] rpm	VS, S, M, L, VL

3.3.2 Define the variable affiliation function

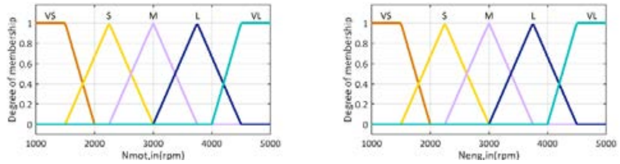
In addition, the affiliation function of each variable needs to be designed to enable the controller to convert the exact values of the input and output variables into fuzzy variables. Since the triangular and trapezoidal affiliation functions are simple in structure, fast in operation and effective in control, a combination of these two affiliation functions is used for the input and output variables of the controller. Combining relevant experience and theoretical analysis, the designed input and output affiliation functions are shown in Fig. 3.



(a) input variable P_{req} (b) input variable *SOC*



(c) input variable $T_{eng,out}$ (d) input variable $N_{eng,out}$



(e) output variable $N_{mot,in}$ (f) output variable $N_{eng,in}$

Fig. 3 The affiliation function of input and output variables

3.3.3 Design the fuzzy rules

The fuzzy rules can be formulated with reference to the experience of rule-based control strategy, and the power output of the engine and battery can be adjusted in time according to different flight conditions. When the required power is small and the battery SOC is within the allowable range, the battery can power the motor alone when it meets the power demand. When the battery SOC is small, the engine must not only provide power output, but also charge the battery to ensure that the battery works within a stable range. Under the premise of satisfying the power performance of hybrid UAV, the engine operating point with better fuel consumption and emission is selected as the output torque and speed by combining with MAP diagram of engine. Finally, the centroid method is used for the defuzzification process of the output variables.

4. ENERGY MANAGEMENT STRATEGY

4.1 Flight conditions of UAV

The research object of this paper is a low-to-medium-altitude hybrid UAV that performs conventional cruise missions including three stages: take-off and climb, cruise, and descend. Considering the aerodynamic and power-weight coupling characteristics of the UAV, the defined cruise flight profile altitude is selected as 2100 m, and the flight profile is drawn with the horizontal coordinate as the flight distance and the vertical coordinate as the flight altitude.

The flight trajectory tracker in the flight control system tracks the position of the UAV in real time according to the defined flight profile, and only the flight height is selected as the profile curve reference quantity to simplify the calculation. The simulated and defined flight profile are shown in Fig. 4, where the results indicate that the maximum error of flight altitude is 6% in the descend phase, and the minimum error is about 2% in the cruise phase, which verifies the execution effect of the flight trajectory tracker.

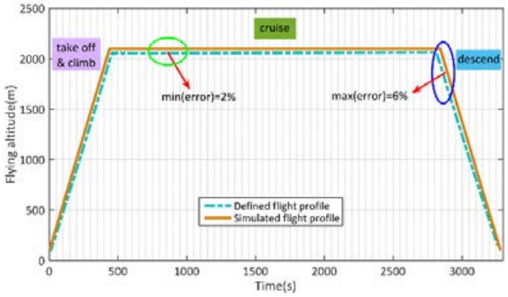


Fig. 4. The cruise flight mission profile of series hybrid UAV

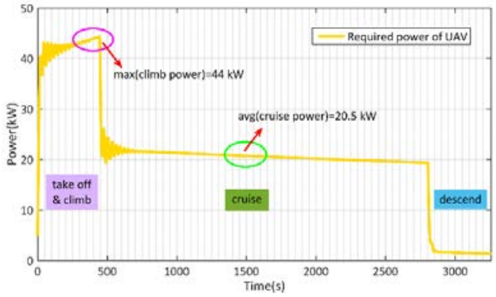


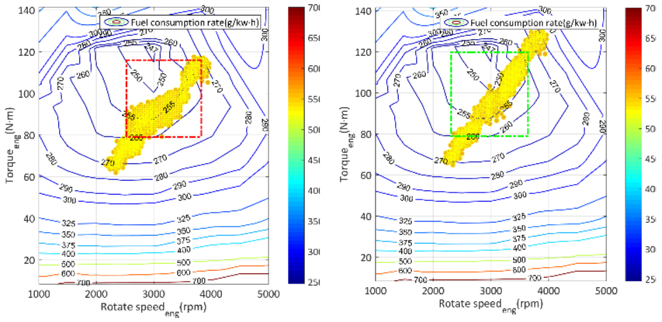
Fig. 5. The required power curve of series hybrid UAV

Also, the required power of the UAV under the cruise mission is shown in Fig. 5, with a maximum required power of 44 kW during the climb phase and an average cruise power of 20.5 kW, both within the engine and motor power range.

4.2 Simulation Results

The system simulation analysis and energy management strategy verification are carried out on the basis of the Matlab/Simulink hybrid UAV simulation platform [7]. The effectiveness of HEPS energy management strategy can be evaluated in terms of fuel consumption, CO_2 emissions and SOC difference. Moreover, the total duration of hybrid UAV cruise flight is 3260 s and the simulation step is set to 0.02 s. Variables schematic diagrams characterizing the operating conditions under the ECMS and FLC-ECMS methods are obtained.

Combined with the MAP diagram of the engine, the operating point distribution of the engine in the HEPS under the two control strategies is shown in Fig. 6. It is to be noted that the operating points where both engine torque and speed are zero are not identified. The distribution of the engine fuel consumption rate in the (250, 260) g/kW • h interval is shown at the rectangular mark.



(a) ECMS (b) FLC-ECMS

Fig. 6. Distribution map of engine operating point

Fig. 7 visually depicted the engine operating point histogram distribution, with the fuel consumption rate interval in the horizontal coordinate and the percentage of operating points in the vertical coordinate, where the fuel consumption rate is mainly in the (250, 260) and (260, 270) intervals. Compared with the ECMS, the FLC-ECMS has a larger percentage of fuel consumption rate in the (250, 260) interval and a smaller percentage in the (260, 270) interval.

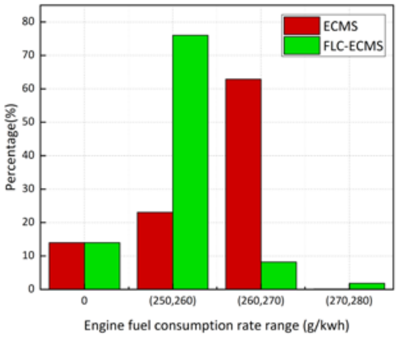
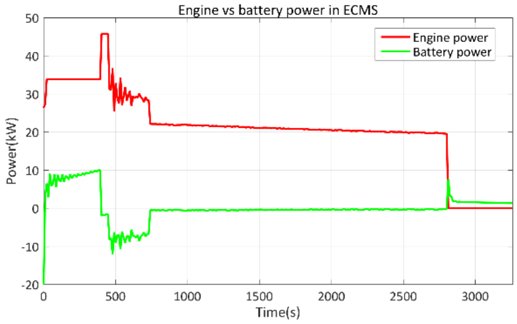
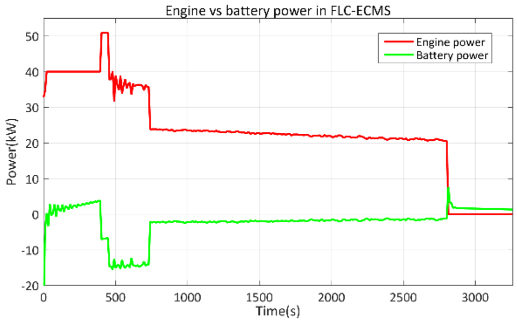


Fig. 7. Histogram distribution of engine operating point

The output power variation curves of the engine and battery in each flight phase of the HEPS are shown in Fig. 8. In the takeoff and climb phase, the engine and battery provide required power together, and their power values are positive. In the cruise phase, the required power is smaller, and the engine provides power alone, and the excess power charges the battery. In the descend phase, the power of engine decreases abruptly, and the battery provides power output to ensure the normal landing of the UAV. Compared to ECMS, the engine output of FLC-ECMS under takeoff climb and cruise phase is higher but always in the high efficiency fuel range. In addition, as shown in Fig. 9, battery's SOC in FLC-ECMS is always kept within the (0.4, 1) allowed range, which ensures the safety of aircraft landing after the engine accident, and the deviation at the beginning and end of SOC is greatly reduced, which cuts the maintenance cost of the battery.



(a) ECMS



(b) FLC-ECMS

Fig. 8. Power curve of the engine and battery

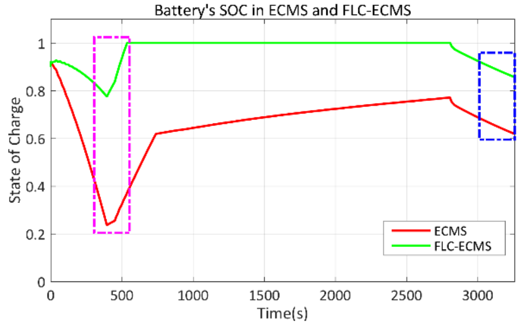


Fig. 9. SOC change curve of battery

Table 2. Comparison of simulation parameter results

Type	EMS	Fuel/ kg	CO_2/ kg	%	ΔSOC
UAV	—	12.82	40.40	—	—
Hybrid UAV	ECMS	10.00	31.50	-22%	0.28
	FLC-ECMS	9.91	31.21	-22.7%	0.04

The fuel consumption, CO_2 emissions and SOC difference of the powertrain under the two energy management strategies were calculated, and as shown in Table 2, hybrid UAV with ECMS and FLC-ECMS can reduce fuel consumption and CO_2 emissions by at least 22% compared to engine-only UAV. Meanwhile, the FLC-ECMS compared with ECMS achieved the fuel and CO_2 emissions optimization rate of 0.9%, while achieving dynamic maintenance of SOC.

5. CONCLUSIONS

In the trend of carbon neutrality and emission reduction in aviation, the optimization research of hybrid UAV energy management strategy is carried out. Based on the characteristics of good robustness and adaptability of fuzzy logic control strategy, the traditional ECMS is combined with FLC to form FLC-ECMS in order to improve the problem that the SOC in ECMS cannot be maintained dynamically. Simulation results show that under the cruise flight mission, hybrid UAV with ECMS and FLC-ECMS energy management strategies reduced fuel consumption and CO_2 emissions by at least 22%.The FLC-ECMS achieved about 0.9% fuel and CO_2 emissions optimization compared with ECMS, significantly reduced the difference of front-to-back SOC, and the SOC value can ensure normal UAV landing in case of engine failure, so these advances present new insights for the optimal control of the aircraft power system.

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