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Journal of Earth Energy Engineering

Publisher: Universitas Islam Riau (UIR) Press

Saving Hydrogen Fuel Consumption and Operating at High Efficiency of Fuel Cell in Hybrid System to Power UAV

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Article History:

Received: September 24, 2020
Receive in Revised Form: October 31, 2020
Accepted: November 12, 2020

Keywords:

Fuel cell, hybrid system, UAV, fuzzy logic control, energy management.

Abstract

The present fuel cell technology is under considerations as a potential power source for Unmanned Aerial Vehicles. Fuel cells are an electrochemical power plant that takes hydrogen and oxygen as inputs and produces electricity, water and heat as outputs. Most of the global hydrogen production is from non-renewable fossil fuels. Therefore, this paper investigates how to save hydrogen fuel consumption and operate at high efficiency in the fuel cell/battery hybrid system to power a small Aircraft. We achieved that by working on the power management of the fuel cell/battery hybrid propulsion system for small UAV by using the fuzzy logic controller and charging up the batteries. The hybrid propulsion system consists of a 1.2kW PEM fuel cell, three 12V batteries, DC/DC converters, and an electric engine. The fuzzy logic controls the batteries' output powers through the bidirectional DC/DC converter. It will help maintain the fuel cell operates at an optimal point with high efficiency as the main power supply for different flight phases to achieve the desired power.

INTRODUCTION

Conventional aircraft use gas turbines or piston engines for propulsion. Nowadays, there is increasing pressure to reduce all modes of transport's environmental impact, including air travel. The aim is to reduce fuel burn and increase efficiency, thus reducing Carbon Dioxide (CO_2) and Nitrogen Oxides (NOx) emissions by jet-powered aircraft per passenger-km. In addition to this, there are also operational restrictions, especially in Europe, regarding aircraft noise. Noise has historically been the principal environmental issue for aviation. It remains high on the agenda of public concern (EUROCONTROL, 2015).

The scientists are pursuing developing technological advancement of aviation as the proposed solutions to be more efficient and reduce environmental issues regarding emissions. The new proposed advances for fuel cells as the power supply to the back-up hydraulic circuits and ailerons are under consideration on large commercial aircraft (Airbus, 2008). Fuel cells are a high potential candidate to power the entire aircraft for smaller aircraft such as UAVs (Hissa et al., 2018). The first small two-seater FC powered aeroplane had been successfully tested for Boeing flight in 2008 (Dorange & Koehler, 2008). A proton exchange membrane fuel cell (PEMFC)/Lithium battery hybrid system had replaced the motor glider of a Super Dimona HK36TTC from Diamond Aircraft Industries as a power supply to drive a variable pitch propeller for a brushless DC electric motor. During take-off and climb for aircraft, the FC could be acted as the primary power source with battery assistance. As secondary power source, in emergency power systems and the Auxiliary Power Unit (APU) could apply the other types of fuel cell which acted as aircraft systems to reduce the noise and emissions during flight.

Fuel cells are an electrochemical power plant that takes hydrogen and oxygen as inputs and produces electricity, water and heat as outputs. They are efficient, reliable, emission-free, and quieter than hydrocarbon fuel-powered engines. They offer tremendous potential environmental benefits and operational savings. A fuel cell operates like a battery by converting the chemical energy from the reactants

DOI: 10.25299/jeee.2021.5630
eISSN: 2540-9352 pISSN: 2301-8097

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into electricity. However, it differs from a battery in that as long as the fuel (such as hydrogen) is supplied, it will produce electricity (plus water and heat) continuously (Larminie et al., 2013; Romeo et al., 2005). Today, hydrogen production is around 500 billion cubic meters (b m^3) per year worldwide. Non-renewable fossil fuels, significantly steam reforming methane, contribute 96% of hydrogen productions. There are attractive properties in hydrogen that are higher two times than solid fuels (50 MJ/kg). It will act as energy carriers and high energy densities (140 MJ/kg) (Kumar & Himabindu, 2019). Therefore, the requirement is to reduce hydrogen consumption as much as possible.

The Proton exchange membrane Fuel Cells (PEMFC) have an advantage that could operate at relatively low temperatures around 80 ^{0}C, which can be used to start-up quickly without warming time. In this investigation, a Proton Exchange Membrane Fuel Cell (PEMFC) was chosen as the fuel cell type to act as the primary power source, with an assisting battery to achieve the desired power at different phases of flight. Also, they have a high power density up to 1-Acm^{-2} or more that can be delivered from PEMFC. The thinness of the membrane electrode assemblies are advantages of low weight and volume (Larminie et al., 2003; O'hayre et al., 2016).

Hybrid system and power management

1. Fuel cell/battery hybrid propulsion system set-up description

The maximum Nexa FC efficiency is about 50% at part load and drops to 38% at full power, used in this study. FC/battery hybrid system consists of a 1.2kW Nexa PEMFC, three 12V lead-acid batteries, and a unidirectional step-down DC/DC converter connected to the Nexa FC. It also includes a bidirectional DC/DC converter connected to the batteries and programmable electronic load. The bus voltage between the two converters is 27V. This architecture in Fig. 1 enables us to achieve high-energy-density from the fuel cell and the batteries' high-power density (Blackwelder & Dougal, 2004; L. Gao et al., 2004; Jiang et al., 2004) to meet desired power for different phases of flight. In this experimental work, engine demand's load profile was implemented via the programmable electronic load. The PCI-6259 data acquisition (DAQ) was used to communicate between MATLAB and the hardware for sending and receiving data. The external connection, the NI SCB-68 connector block, was used for interfacing I/O signals and to plug-in the data acquisition device via a 68-pin connector. The SCB-68 rack can only accept voltage levels up to 10V, so a voltage divider was used to step down voltages above 10V. The readings were then scaled back in the software. Numerous AMP25 Linear-to-60A Hall sensors used to sense the current flowing through the various devices.

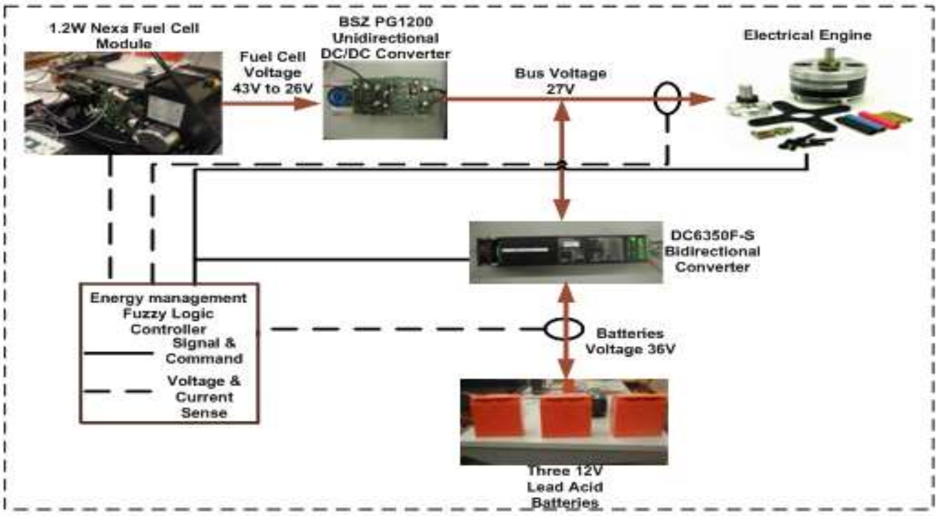

Figure 1. The propulsion system of Fuel cell/battery hybrid.

The simulation model of the hybrid system consisting of a 1.2kW Nexa PEMFC (del Real et al., 2007), three 12V lead-acid batteries, a unidirectional step-down DC/DC converter, and a bidirectional DC/DC converter (Kazimierczuk, 2015; Moussaoui et al., 1996; Sander, 2009). The electrical engine was developed in MATLAB/Simulink. For the aircraft model, a non-linear six-degree-of-freedom model with a conventional high wing and the positive dihedral configuration of the PiperCub J3 aircraft has been developed by Thomas & Cooke (2009) and de Lomas (2009). It is to emulate accurate flight dynamic characteristics of the aircraft. The model has been subject to modifications with the replacement of the piston engine by an electrical motor. The Dualsky XM5050CA DC engine was selected for the electric motor to drive the PiperCub J3. The motor was tested for different throttle commands inputs. It was found that the motor requires 1290 Watts at 47.4A to generate the maximum RPM of 5460.

2. Fuzzy logic controller

The propulsion system's power should be controlled so that the PEM fuel cell operates at an optimal point with high efficiency. It serves as the main power supply for the electric engine driving the propeller. If the fuel cell cannot wholly meet the power demands in any flight phases, the battery will provide the short burst power demands as required. At the same time, keeping the battery at all times sufficiently charged. A fuzzy logic controller is employed in this study to manage the power between two sources. Many studies developed fuzzy logic controller in automotive applications to determine the power split between different power sources and shown promising results (D. Gao et al., 2008; Kisacikoglu et al., 2009; C. Y. Li & Liu, 2009; X. Li et al., 2009). Fuzzy logic incorporates a simple, rule-based IF X AND Y THEN Z. Approach to a solving control problem rather than model a system mathematically. The rules are usually expressed in the form of IF variable IS property THEN action. The fuzzy logic model is empirically-based, relying on an operator's experience rather than their technical understanding of the system (Mukaidono, 2011; Nedjah & de Macedo Mourelle, 2006; Zimmermann, 1996).

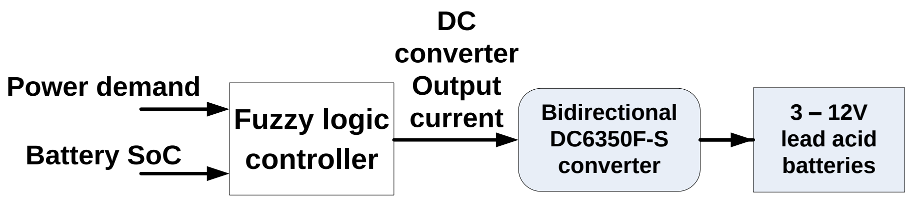

Figure 2. Schematic diagram of the fuzzy logic controller

The schematic diagram in Fig. 2 shows the fuzzy logic controller used in hardware-in-the-loop and Simulink to manage the power between two sources (FC and batteries). There are two input variables and one output variable in the controller systems. The input variables are the electrical engine power demand and the battery state of charge (SoC) represented by the battery voltage. The battery requires to be charged when the total voltage was less than 30V. Here 33V and 36V or more correspond to 50% and 100% SoC, respectively. The output variable is the bidirectional DC/DC converter output power (how much current to be supplied to or from the batteries). For example, IF the power demand is high, and the battery SoC is high THEN, the battery will supply power to help the FC operate efficiently. When the power demand is low, and the battery's SoC is low, the FC supply power to the engine and charging up the battery through the bidirectional DC/DC converter (battery maximum charging current is -5.4A). The controller always maintains FC operation at high optimal efficiency.

METHODOLOGY/CASE STUDY

In the case study, the aircraft taxing at the beginning of the flight scenario takes off at t = 150 seconds to climb to a height of 20m and performs a circuit with a radius of 1550m in the cruise phase 1237 seconds. It descends at t = 1658 seconds, and then a slow climb was simulated before lands at t = 2480 seconds. The throttle commands plot for the scenario is shown in Fig. 3. For energy management, a fuzzy logic controller was implemented in the simulation and hardware-in-the-loop to manage the power between the two sources to meet the electric motor demand for all flight phases. One input to the fuzzy logic controller is the battery state of charge (SoC) represented by the battery voltage. The fuzzy logic control system included the condition that the batteries needed to be charged if the total batteries voltage was less than 30V. Here 33V and 36V (or more) correspond to 50% and 100% SoC, respectively.

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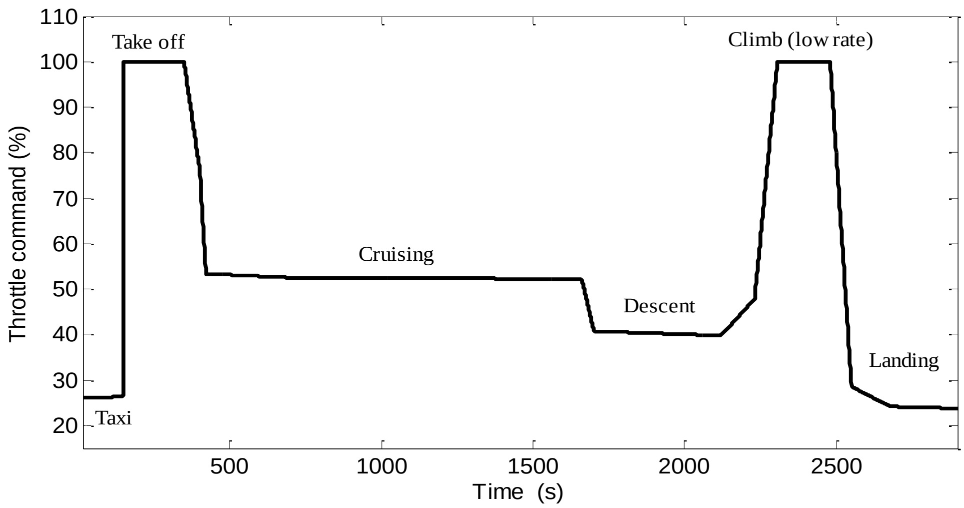

Figure 3. Throttle commands during different flight phases.

Table 1 illustrates the maximum power demands for each stage of flight. The minimum power demand occurred when the aircraft taxi and land (24-26% throttle). In comparison, maximum power demand occurred during take-off and climbed with 100% throttle. For the other two stages (cruising and descent), the required power is 470W and 215W, respectively.

Table 1. Study case of power demands in the flight phases.

Throttle command (%)	Flight Phases	Power demands (W)	Simulation time (s)
26%	Taxi	78	0-150
100%	Take off	1285	150-421
53%	Cruising	470	421-1658
40%	Descent	215	1658-2124
100%	Climb	1285	2124-2480
24%	Landing	74	2480-2898

RESULTS AND DISCUSSION

1. First journey with the battery full charge

The throttle commands plot for this scenario is shown in Fig. 3. The engine's corresponding current profile load and power demand are shown in Figs 4 and 5, respectively. For the first 150 seconds, the aircraft is taxiing, and the engine requires only 79W, which draws 2.8A, which is supplied entirely from the FC; see Fig's 4, 5 and 6.

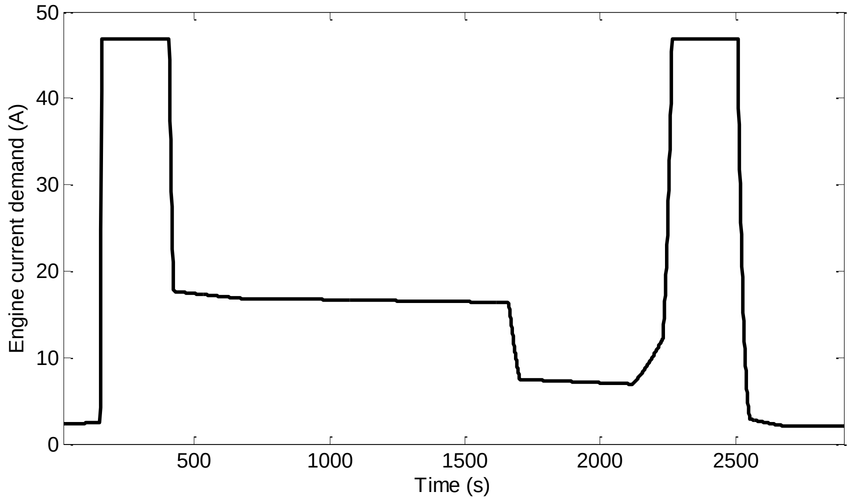

Figure 4. Engine current demand during different flight phases.

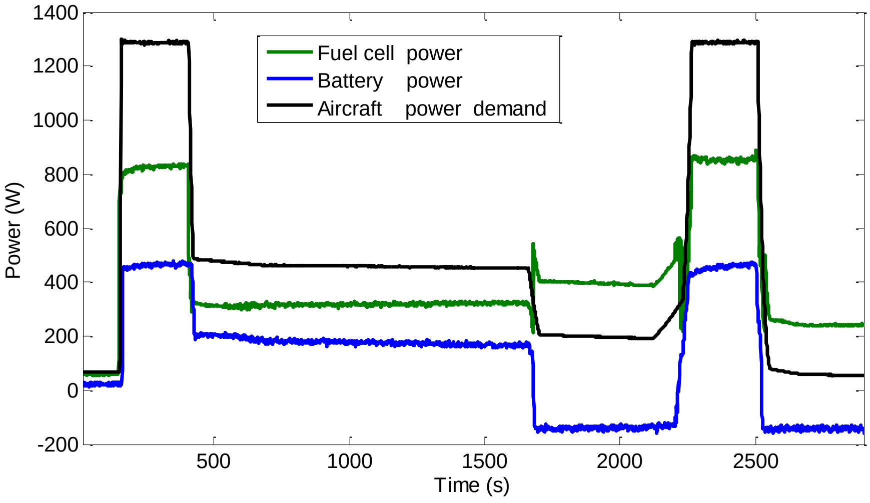

Figure 5. Engine power demand, FC power and battery power during different flight phases.

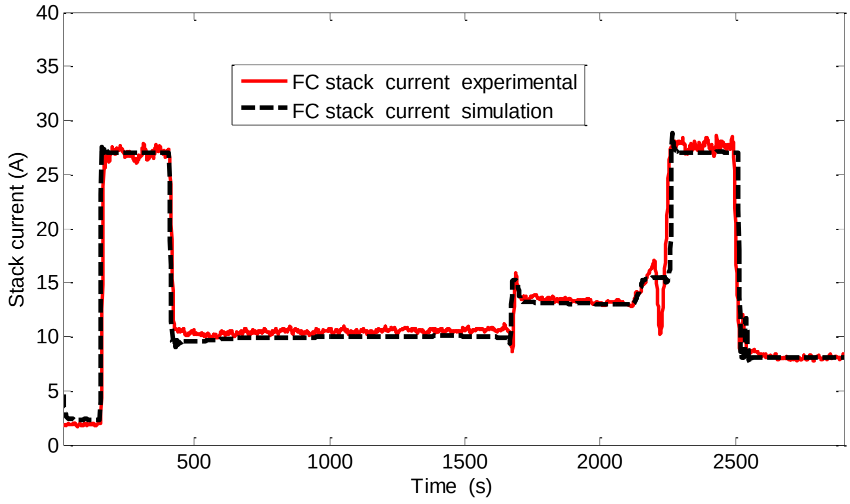

Figure 6. Fuel cell stack current during different flight phases.

During the take-off phase, the throttle jumps from 26% to the maximum value of 100% in about 3 seconds—the corresponding total power demand for reading 1285W and current 46.5A. This demand's

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duration is 271 seconds, from 150 to 421 seconds; see Fig's 3, 4 and 5. For this stage, the FC stack current increased from 2.3A to 27.7A (see Fig. 6), while stack voltage drops from 41V to 29V to supply 827W. The fuzzy logic controller sent a signal to the bidirectional converter to make up the batteries' power shortfall. Battery current increased sharply from about 0A to 15A in line with the throttle changes; see Fig. 7. The corresponding battery voltage decreased, as shown in Fig. 8. During this take-off stage, the power-sharing made the PEMFC operate at its optimum efficiency point while delivering power to the electric engine and acting as the primary power source.

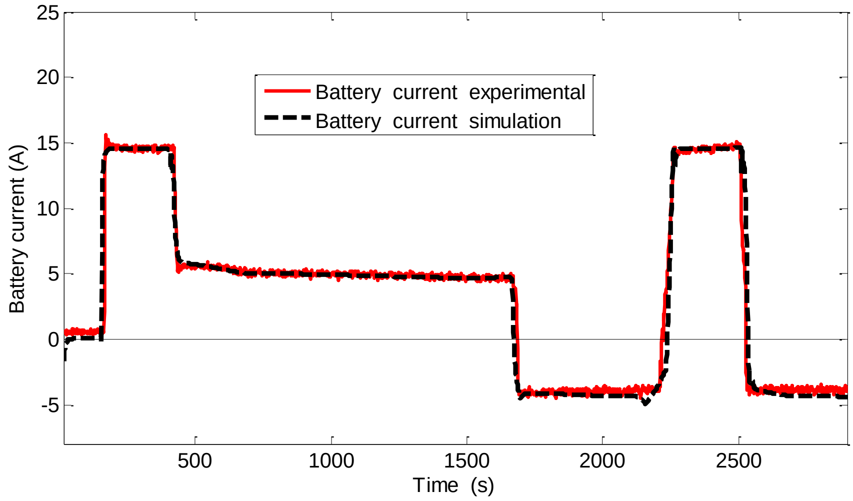

Figure 7. Battery current during different flight phases.

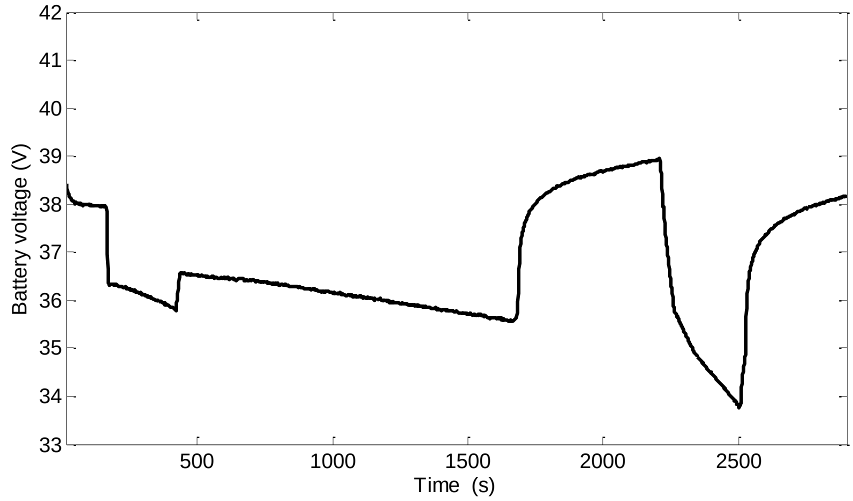

Figure 8. Battery voltage during different flight phases.

At 421 seconds, the aircraft starts cruising, and this continues until 1658 seconds (1237 seconds). While cruising, the aircraft requires 460W, the FC supplies 318W, and the batteries supply 142W (please note that it depends on their SoC). At 1658 seconds, the aircraft begins a shallow descent which lasts 466 seconds. Fig. 5 shows the overshoot at t = 1658 seconds and undershoot at t = 2124 seconds in FC power, current and voltage response. These due to the bidirectional converter switch to charge and discharge the battery, respectively. At the time of the descent stage, the power demand drops to 200W. The FC can now provide power to both the engine and charge the battery in nominal operating conditions with maximum efficiency (50%), as shown in Fig. 9. The negative values of battery current in Fig. 7 correspond to the battery being charged. Battery voltage is given in Fig. 8.

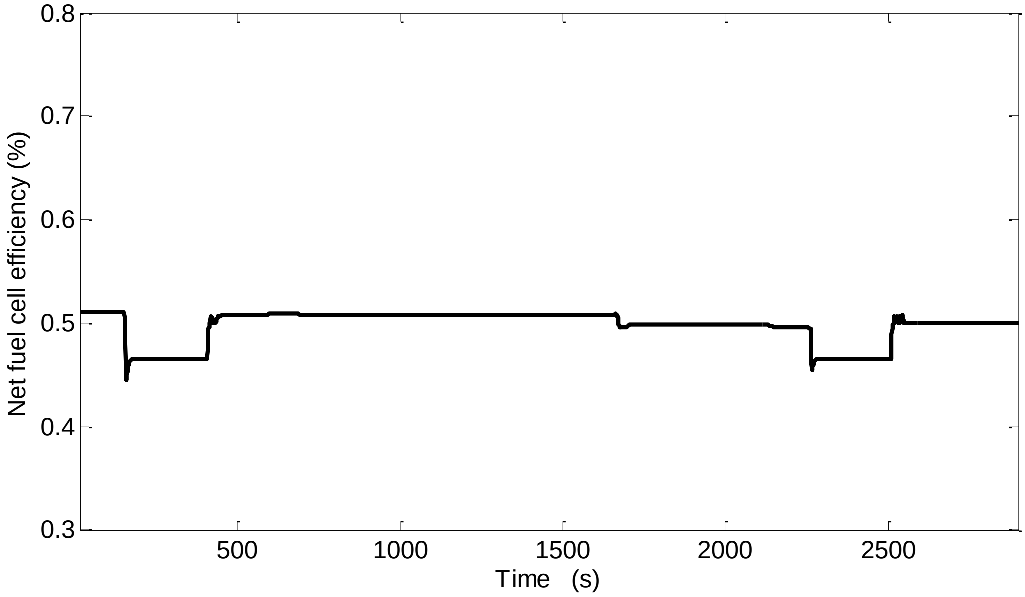

Figure 9. different flight phases for fuel cell efficiency.

At the end of the descent (2124 seconds), the aircraft began to climb slowly, which lasted for 356 seconds. The engine required a total of 1285W from the FC and the battery combined. This climb is simulated in the case study to emulate real flight go around scenarios. The battery current increased to 14.8A, and the battery voltage decreased. After the slow climb came, the last phase of the flight is landing. The required power was 74W, the FC supplied 245W, and the additional power was used to charge up the batteries with a current of -4.3A, see Fig. 7. The results are from the experiment, and the simulation shows good agreement. Fig. 10 shows the hydrogen consumption to meet the aircraft's power demand during the flight: taxi, take-off, climb, cruise, descent, and landing. At the end of the flight, the hydrogen consumption of the nexa PEMFC (1.2kW) was about 378 litres.

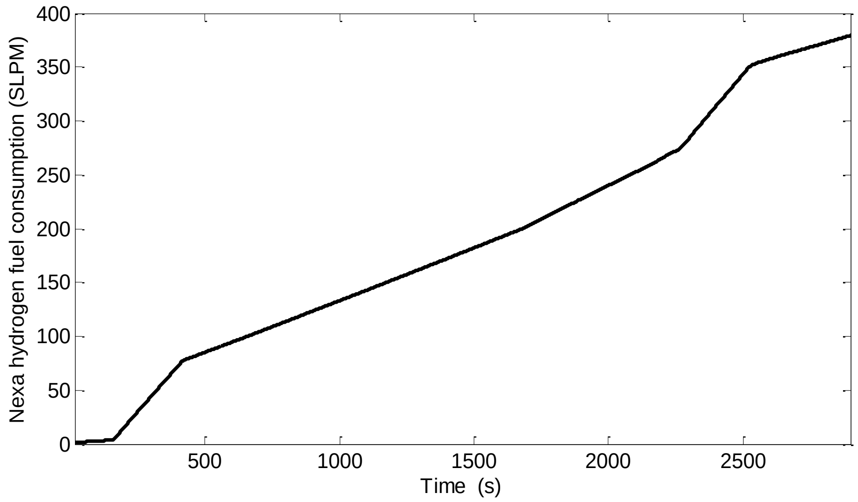

Figure 10. Nexa fuel consumption during different flight phases.

2. Second journey without charging up the battery

After completing the flight scenario test in the first running experimental, the batteries had been operating for a long time. The test was repeated without charging the batteries to investigate fuzzy logic controller performance when the battery cannot supply power to assist the FC. For the first 150 seconds, the aircraft is taxiing, and the engine requires 2.8A. The FC provides current to the engine and charges the battery in nominal operating conditions, as shown in Fig. 11. Once again, the negative current values in Fig. 12 correspond to the battery being charged. Also, from Fig. 12, it can be seen that during this charging period battery voltage is 38.5V.

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During take-off, the current demand reading is 46.5A, see Fig. 11. In this stage, the FC stack current increase from 9.4A to 28A. Immediately, the fuzzy logic controller sent the bidirectional converter signal to make up for the current shortage from the batteries. The current increases significantly from about -4.64A to 16A in line with throttle changes. The battery voltage drops from 38.9 to 35V in one step. It decreases gradually to about 30.8V before the take-off stage finishes; see Fig. 12. The controller takes less current from the battery and the FC provides more current due to low battery voltage.

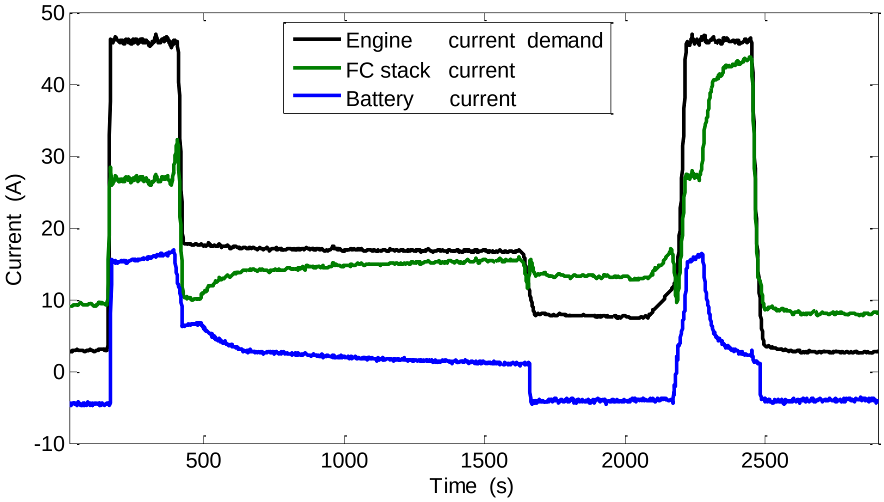

Figure 11. Engine current demand, FC current and battery current during different flight phases, the scenario with low SoC.

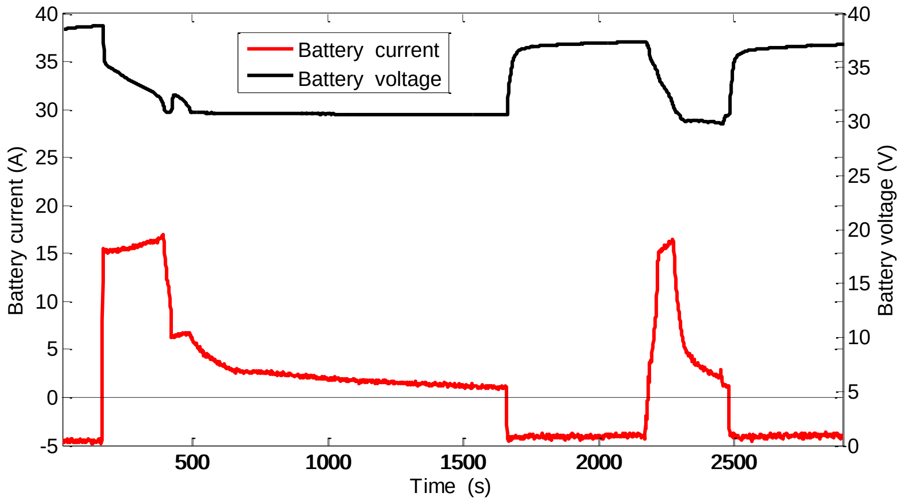

Figure 12. Battery voltage and current during different flight phases, the scenario with low SoC.

At 421 seconds, the aircraft starts cruising and typically requires 16.8A on average in the flight phase. Initially, the FC supplies 10.12A and takes 6.8A from the batteries. However, after about a minute of cruising, at 485 seconds, the battery current started to decrease and gradually faded until it reached 1A. Simultaneously battery voltage decrease from 32.44V to 30.6V. The FC had to supply the current shortfall from the battery. In Fig. 11, the battery and FC stack currents can be seen moving in opposite directions.

After cruising for 1658 seconds, during which the FC stack supplied an increasing current, followed by a decrease of 466 seconds, the current demand dropped to 7.6A. The battery voltage was low (30V or less), and the controller switched the DC/DC converter to charging mode. The FC then provides current to both the engine and charges the battery with maximum efficiency, see Fig.11 and 12.

At 2124 seconds, a slow climb was commenced that required 46A from both FC and battery to meet the engine power demand. The battery current increased to 15A. The battery voltage remains at about 37V until about 2179 seconds when it starts to drop. At 2300 seconds, the battery voltage reaches 30.32V and then drops slowly to 29.82V. This condition drives the controller to take less and less current from the battery; see Fig. 12 and FC current takes over, see fig.11. In the last phase of the flight, the required power is 2.7A, The FC supplies this, and the additional current is used to charge up the batteries again; see Fig. 12.

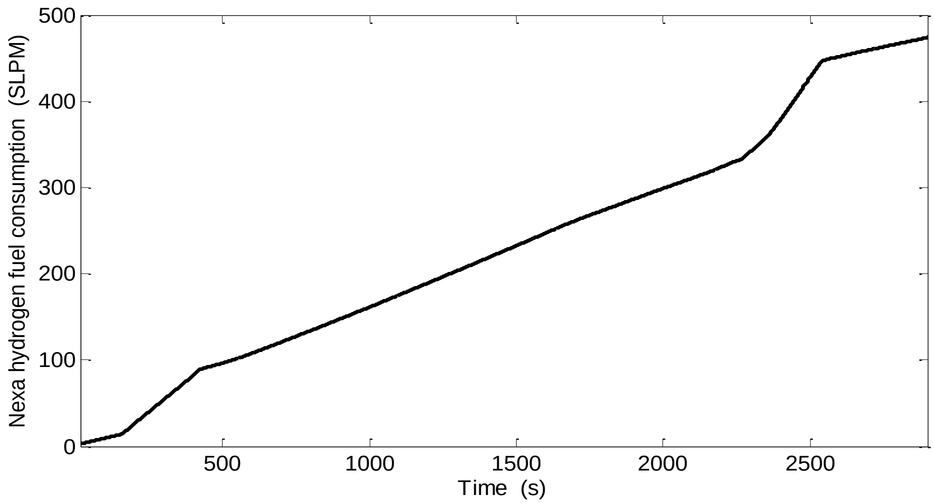

Figure 13. Different flight phases for Nexa fuel consumption, the scenario with low SoC.

The flight completed at the same time as the previous journey. Fig. 13 shows how much hydrogen the FC required to satisfy the required power during the flight: taxi, take-off, climb, cruise, descent and landing. At the end of the flight, the consumed hydrogen of the Nexa PEMFC (1.2kW) was about 473 litres. The FC consumed 95 litres more than the previous flight journey because of the low battery SoC. In this case, the FC operated at low efficiency.

CONCLUSION

This paper has presented an investigation of an electric hybrid system to power a small aircraft in two scenarios. The FC/battery hybrid system in the case study consists of a 1.2kW Nexa PEMFC, three 12V lead-acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter, and an electric engine. Programmable electronic load implemented the engine load profile during the experiment. Power management between two sources was achieved by implementing a feed-forward fuzzy logic controller in hardware-in-the-loop and simulation to manage the power flow. The flight was completed in the same manner in two journeys. During the first journey, the FC tended to operate at high efficiency (50%). Sources supplied for different flight phases to meet the desired power (taxi, take-off, cruising, descent, climb and landing). At the end of the first flight journey, the consumed hydrogen of the Nexa PEMFC (1.2kW) was about 378 litres. In the second journey, the FC worked at low efficiency and consumed more hydrogen when maximum power demands occurred during the end of the take-off and climb phases. At the end of the second flight journey, the consumed hydrogen of the Nexa PEMFC (1.2kW) was about 473 litres. It can be seen that the FC consumed 95 litres more than the previous flight journey because of low battery SoC and in this case, the FC operated at low efficiency. The battery state of charge (SoC) represented by the battery voltage. The fuzzy logic control system included the condition (worst case scenario). If the total batteries voltage was less than 30V, the batteries needed to be charged. Here 33V and 36V (or more) correspond to 50% and 100% SoC, respectively.

ABBREVIATIONS

APU	Auxiliary Power Unit
SoC	Battery State of Charge
CO2	Carbon Dioxide
NOx	Nitrogen Oxides
DAQ	Data Acquisition
DC	Direct Current
FC	Fuel Cell
FLC	Fuzzy Logic Controller
PC	Personal Computer

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SLPM	Standard Litre per Minute, measured at 1 atm, 0°C
PEMFC	Proton Exchange Membrane Fuel Cell
UAV	Unmanned Aircraft Vehicle.

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