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Hybrid Propulsion System to Power Unmanned Aerial Vehicle in Worst Case Scenario

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Abstract The present fuel cell systems have demonstrated a high degree of efficiency for automotive applications. Currently the technology is under considerations as potential power source for Unmanned Aerial Vehicles (UAVs). This paper presents an investigation of the fuel cell/battery hybrid propulsion system for PiperCub J3 aircraft in worst case scenario (battery low state of charge) by using the fuzzy logic controller. The hybrid propulsion system consists of a 1.2kW Nexa PEMFC, three 12V batteries, DC/DC converters, and an electrical engine. The fuzzy logic control the output powers of the batteries through the bidirectional DC/DC converter to assisted and maintain the fuel cell operates at optimal point with high efficiency as a main power supply to achieve the desired power for different phases of flight. After completing the test of first flight scenario, the batteries had been operating for a long time. The test was then repeated without charging the battery to investigate fuzzy logic controller performance during the worst case scenario when the battery cannot supply power to assist the fuel cell. The controller implemented in hardware-in-the-loop.

Keywords: hybrid system, fuel cell, energy management, UAV.

نظام الدفع الهجين لتشغيل طائرة بدون طيار في اسوا سيناريو

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الملخص أظهرت أنظمة خلايا الوقود الحالية درجة عالية من الكفاءة لتطبيقات السيارات. هذه التكنولوجيا قيد النظر حاليا كمصدر للطاقة للمركبات الجوية بدون طيار. تقدم هذه الورقة استقصاء لنظام الدفع الهجين لخلايا الوقود وبطارية لطائرة صغيرة في أسوأ السيناريوهات (حالة شحن البطارية منخفضة) باستخدام وحدة تحكم المنطق الضبابي. يتكون نظام الدفع الهجين من خلية كهربائية وثلاث بطاريات ومحولات و محرك كهربائي. نظام التحكم يتحكم في الطاقة الخارجة من البطاريات من خلال محول نائي الاتجاه لمساعدة الخلية الكهربائية لتعمل بكفاءة عالية كمصدر رئيسي للطاقة لمراحل مختلفة من الطيران.

الكلمات المفتاحية: النظام الهجين، خلية الوقود، إدارة الطاقة، *UAV*.

1. Introduction

Conventional aircraft use gas turbines or piston engines for propulsion. Nowadays there is an increasing pressure to reduce the environmental impact of all modes of transport including air-travel. The aim is to reduce fuel burn and increase efficiency thus reducing CO_2 and NOx emissions by jet-powered aircraft per passenger km. In addition to this there are also operational restrictions, especially in Europe with regards to aircraft noise. Noise has historically been the principal environmental issue for aviation. It remains high on the agenda of public concern [1].

Current technological advancements in aviation are pushing towards the more electric aircraft. It is one of the proposed solutions to make aircraft more efficient and subsequently reduce emissions and the environment impact. Fuel cells are among the proposed advances in technology which are under consideration for supplying power to the back-up hydraulic circuit and ailerons on large commercial aircrafts [2]. In the case of smaller aircraft such as UAVs, fuel cells could potentially power the entire aircraft. In 2008, Boeing successfully performed flight tests of the first small two-seater FC powered airplane [3]. Motor glider of a Super Dimona HK36TTC from Diamond Aircraft Industries was replaced by a proton exchange membrane fuel cell (PEMFC)/ Lithium battery hybrid system. It supplies power to a brushless DC electrical motor to drive a variable pitch propeller. The FC acted as the primary power source with the assistance of a battery during take-off and climb. Other types of fuel cell technology could be implemented for replacing other aircraft systems such as the emergency power systems and the Auxiliary Power Unit (APU). This would significantly reduce further the noise and emission levels in and around airports.

Fuel cells are an electrochemical power plant, that takes hydrogen and oxygen as inputs and produce 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 into electricity but 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 [4], [5]. In this

investigation a Proton Exchange Membrane Fuel Cell (PEMFC) was chosen as the type of fuel cell to act as the main power source, with an assisting 12V sealed lead acid batteries in order to achieve the desired power at different phases of flight.
The advantage of PEMFCs is that they operate at relatively low temperatures around 80 ^{0}C, which allows them to start up quickly without warming time. Furthermore, PEM fuel cell could deliver high power density up to 1-Acm^{-2} or more and the thinness of the membrane electrode assemblies gives them the advantages of low weight and volume [5], [6]. Hence, it means that compact fuel cell can be manufactured, which make them suitable for the type of application we are interested in.

2. Experimental set-up

2.1. Nexa fuel cell system

The Nexa power module is a small, low maintenance and fully integrated system that produces unregulated DC power [7]. It contains a Ballard fuel cell stack, as well as all the ancillary equipment necessary for fuel cell operation. Ancillary subsystems include hydrogen delivery, oxidant air supply and cooling air supply. Onboard sensors monitor system performance. The control board and microprocessor fully automate operation. The Nexa system also incorporates operational safety systems for indoor operation.
The Nexa fuel cell output voltage level can vary from 43V at no load to about 26V at the full load. The designed operating temperature in the stack is around 65 ^{0}C at the full load. The stack is composed of 46 cells, each with a 110 cm^2 membrane. The system is auto-humidified and air-cooled by a small fan. Regarding the hydrogen feeding of the fuel cell, the fuel is 99.99% hydrogen with no humidification, and the hydrogen pressure to the stack is normally maintained at around 1.8 bar g. The maximum Nexa system efficiency is about 50% at part load and drop to 38% at full power [7]. A PC was used for the acquisition of the measured values, and in order to simulate a variable power demand, the energy produced was delivered to an electronic load Fig. 1 shows hybrid power module system set-up in Cranfield university lab.

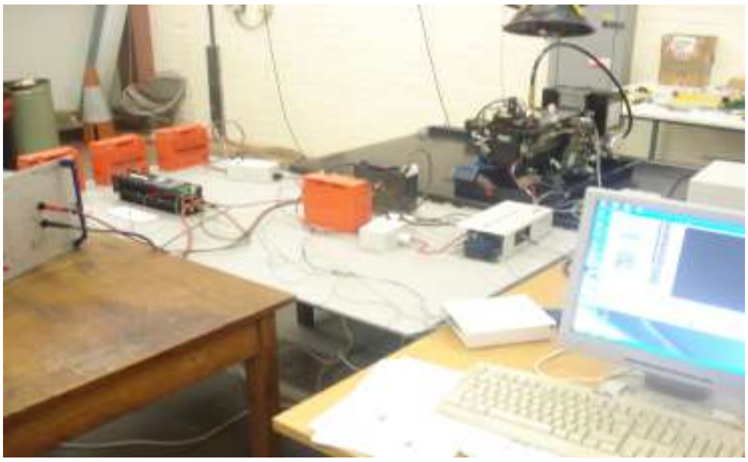

Fig. 1: Hybrid fuel cell/battery system set-up

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

FC hybrid system consists of a 1.2kW Nexa PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter connected to the Nexa FC, a bidirectional DC/DC converter connected to the batteries and programmable electronic load. The bus voltage between the two converters is 27V. The schematic diagram of hybrid system is shown in Fig. 2. This architecture enables us to achieve both the high-energy density from the fuel cell and the high-power density from the batteries [8], [9], [10] to satisfy desired power for different phases of flight. In the experiment, 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 data acquisition device via 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 and the readings were then scaled back in the software. The current flowing through the various devices was sensed using numerous AMP25 Linear-to-60A Hall sensors.

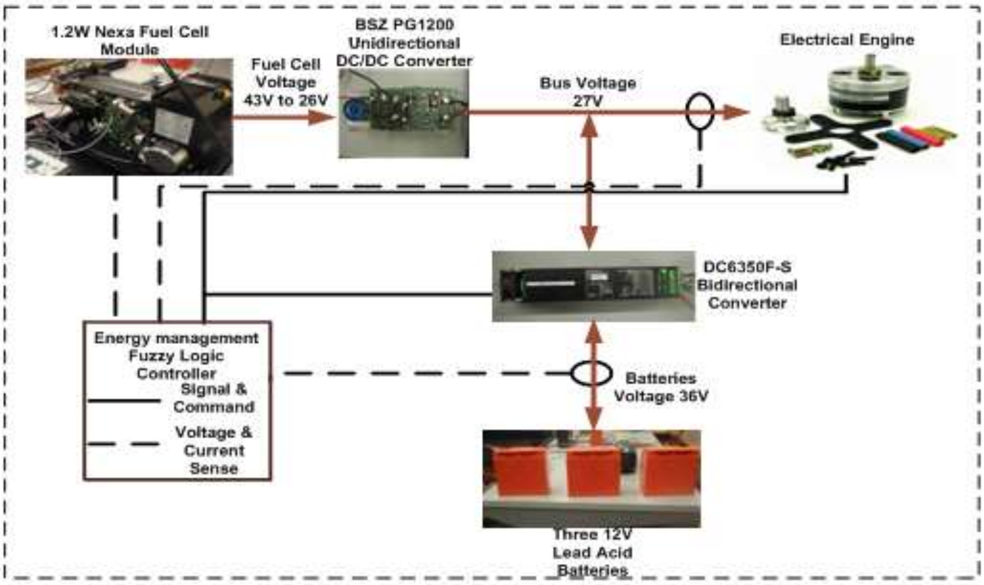

Fig. 2: Fuel cell/battery hybrid propulsion system

The simulation model of the hybrid system consisting of a 1.2kW Nexa PEMFC [11], three 12V lead acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter [12], [13], [14] and electrical engine was developed in MATLAB/Simulink. For aircraft model, a non-linear 6 degree-of-freedom model with conventional high wing, positive dihedral configuration of the PiperCub J3 aircraft has been developed by Thomas [15] and de Lomas [16] with the intention to emulate accurate flight dynamic characteristics of the aircraft was used. The model has been subject to modifications with the replacement of the piston engine by an electrical motor. A specification of 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.

3. Case study of worst case scenario

In this flight scenario of the case study, the aircraft taxing in beginning of flight scenario then takes off at t = 150 seconds to climb to a height of 20m and performs a circuit with a radius of 1550m in cruise phase for 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 the 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 demand of the electric motor for each phase of flight. 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 if the total battery voltage was less than 30V the battery needed to be charged. Here 33V and 36V (or more) correspond to 50% and 100% SoC, respectively [17].

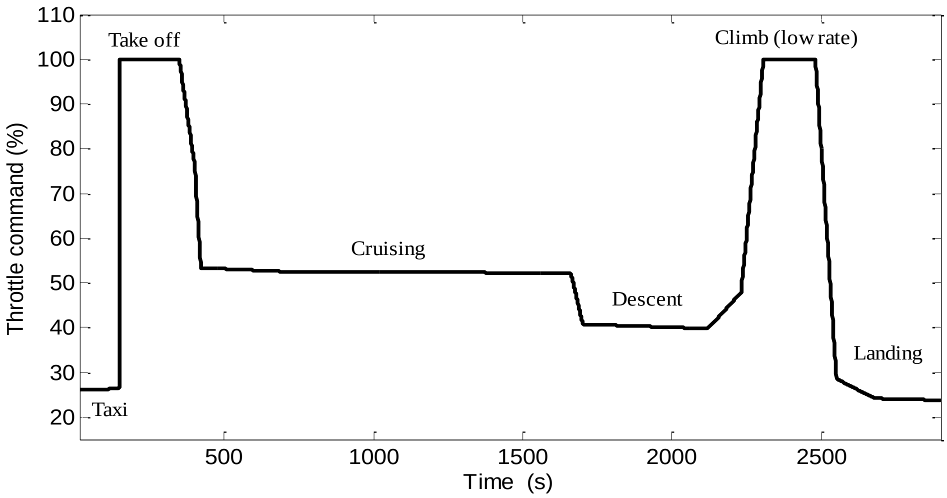

Fig. 3: Throttle commands during different flight phases

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) while maximum power demand occurred during take-off and climb with 100% throttle. For the other two stages (cruising and descent) the required power is 470W and 215W, respectively.

Table 1: Power demands of flight phases for case study

Throttle command (%)	Phases of flight	Require power (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

4. Results and discussion

After completing the test of scenario in first running experimental, the batteries had been operating for a long time. The test was then repeated without charging the battery to investigate fuzzy logic controller performance during the worst case scenario 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, during this time the FC provides current to both the engine and for charging the battery in nominal operating conditions as shown in Fig. 4. Once again the negative current values in Fig. 5 correspond to the battery being charged, and also from Fig. 5 it can be seen that during this charging period battery voltage is 38.5V.

During take-off the current demand reading is 46.5A, see Fig. 4. In this stage the FC stack current increase from 9.4A to 28A. Instantaneously the fuzzy logic controller sent signal to the bidirectional converter to make up the current shortage from the batteries. The battery's current sharply increases from about -4.64A to 16A in line with throttle changes, while the battery voltage drops from 38.9 to 35V in one step and decreases gradually to about 30.8V before the take-off stage finishes, see Fig. 5. Due to low battery voltage the controller takes less current from the battery and the FC provides more current.

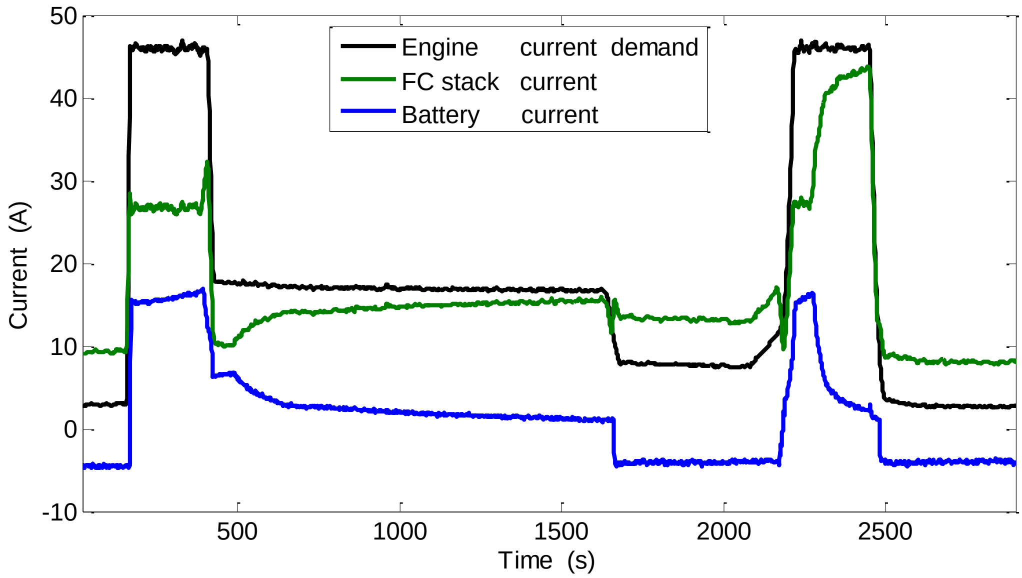

Fig. 4: Engine current demand, FC current and battery current during different flight phases

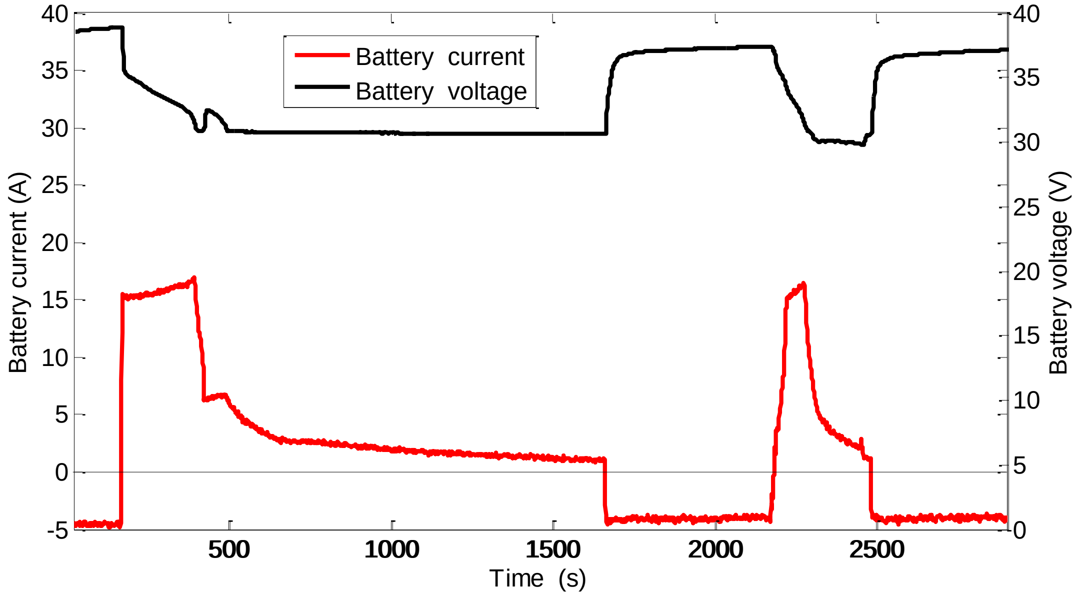

Fig. 5: Battery voltage and current during different flight phases, scenario with low SoC

At 421 seconds the aircraft starts cruising and typically requires 16.8A on average in phase of the flight. Initially the FC supplies 10.12A and takes 6.8A from the batteries, but 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 and in Fig. 4 the battery and FC stack currents can be seen moving in opposite directions.

After cruising for 1658 seconds during which the FC stack was supplying an increasing current there followed by descend for 466 seconds, during which 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 for charging the battery with maximum efficiency, see Fig.4 and 5.

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 drives the controller to take less and less current from the battery, see Fig. 5 and FC current takes over, see fig.4. 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. 5.

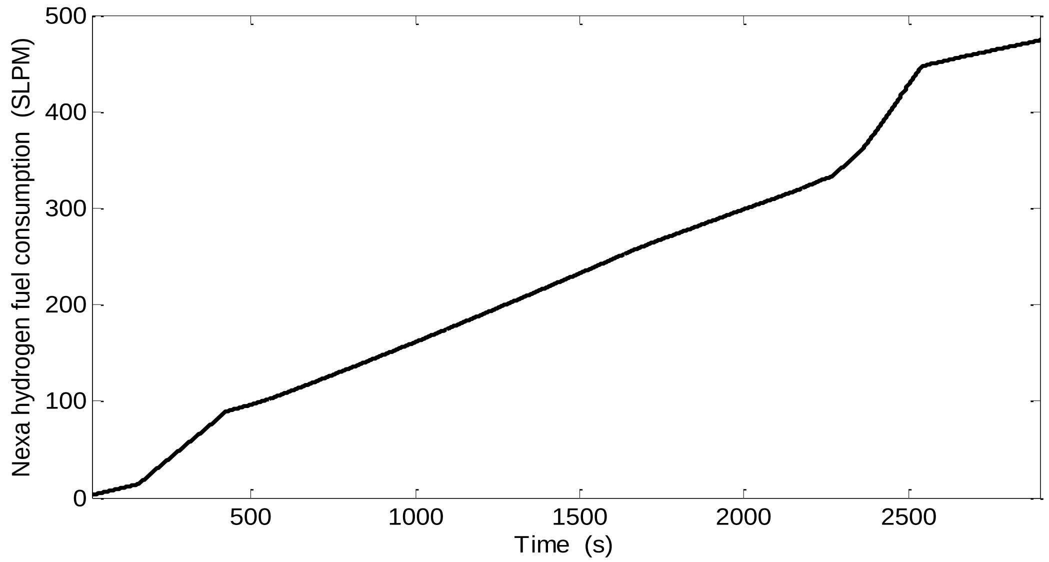

Fig. 6: Nexa fuel consumption during different flight phases, scenario with low SoC

The flight successfully completed in the same time as previously running. Fig. 6 shows how much hydrogen the FC needed to satisfy the power requirements of the aircraft during the flight:

take-off, climb, cruise, descent and landing. The Nexa PEMFC (1.2kW) had consumed 473 liters of hydrogen at the end of the flight scenario.

5. Conclusion

This paper has presented an investigation into the feasibility of using an electric hybrid system to power a small aircraft in worst case scenario. In case study, the FC hybrid system 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 electrical engine. During the experiment, engine load profile was implemented via a programmable electronic load. Power management between two sources was achieved by implementing feed-forward fuzzy logic controller in both simulation and hardware-in-the-loop to manage the power flow between two sources. The flight successfully completed in on time, but the FC was working at very low efficiency when maximum power demands occurred during the end of the take-off and climb (about 40%). The results show that fuzzy logic controller performance could deal with the worst case scenario when the battery cannot supply power to assist the FC. The Nexa PEMFC (1.2kW) had consumed 473 liters of hydrogen at the end of the flight scenario.

6. Abbreviations

APU Auxiliary Power Unit
SoC Battery State of Charge
CO_2 Carbon Dioxide
NOx Nitrogen Oxides
DAQ Data Acquisition
DC Direct Current
FC Fuel Cell
FLC Fuzzy Logic Controller
PC Personal Computer
BAR g Bar Gauge Pressure
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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