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Design of an energy management technique for high endurance unmanned aerial vehicles powered by fuel and solar cell systems

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ABSTRACT

A hybrid electric propulsion system with a power switching technique is tested in flights of long endurance unmanned aerial vehicle, interchanging power supply between fuel and solar cell systems. A fuel cell system consists of a sodium borohydride-based hydrogen generator, a 300 W scale proton-exchange membrane fuel-cell stack that is connected with a battery and a customized controller. The solar cell system consists of a maximum power point track device, a battery and 80 W solar arrays on each wing. These two power sources are controlled by a power switching technique using solid-state relays, which selectively permit either one of the two power sources, or both, to meet the load variation during flight. Using this method, both power sources are independently operated to deliver necessary power to satisfy the load demand, which means that it can extend flight endurance by alternating between solar and fuel cells with high-system reliability. The flight test is conducted over a period of 1.5 h to evaluate the designed hybrid power system by switching from fuel cell power to solar cell power, and vice versa, thereby proving system reliability as well as extending the operational time for flight.

Introduction

Alternatives to internal combustion engines, such as reciprocating engines and gas turbines, are continually being developed to satisfy the high demand for clean and renewable energy sources. This is attributed to the fact that fossil fuels have been causing environmental pollution and exhaustion issues for a long time. To minimize these problems, the electric energy generated from fuel cell power or solar cell power is attracting more attention as alternative energy sources because they do not cause issues like fossil fuels, and they have low operational costs, especially the electric propulsion for small vehicles, such as UAVs, which are less than 25 kg, provide a route for lower capital cost [1].

The fuel cell is an electrochemical device that produces direct current based on the chemical reaction between hydrogen and oxygen in the presence of an electrolyte [2]. Both hydrogen and oxygen are abundant elements in nature. In turn, the fuel cell can convert the chemical energy of a

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reaction directly into electrical energy without moving parts, thereby achieving high efficiency [3]. There are several types of fuel cell systems available depending on the operating temperature, power capacity, or mobility. Among them, proton-exchange membrane fuel cells are extensively adopted for mobile applications, especially for unmanned aerial vehicles owing to their wide range of power capacities without a concomitant increased thermal heat release.

Moreover, the recharge of a proton exchange membrane fuel cell (PEMFC) system is almost instant as compared to a lithium battery that requires a considerable amount of time [4]. In this way, the fuel cell system can provide electric power to the load continually as long as hydrogen is fed into the fuel cell stack.

Hydrogen is an interesting fuel that does not produce CO_2 emissions during its combustion, and contains three times more energy than petroleum. Additionally, it can be regenerated in the form of water or hydrocarbons [5]. However, it is not a free element and its process is still under development stages. Extraction of pure hydrogen from natural resources requires advanced technologies [6]. However, pure hydrogen for operating PEMFCs can be easily obtained from the hydrolysis of $NaBH_4$. The reaction of hydrolysis is expressed in accordance to Eq. (1).

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 + 217\ kJ \tag{1}$$

According to this reaction, the hydrolysis is exothermic, and the only gas product is pure hydrogen after separating the byproduct, $NaBO_2$. Thus, the supply of stored hydrogen to our fuel cell engine in UAVs is achieved using a catalytic hydrolysis scheme of sodium borohydride ($NaBH_4$). This scheme was adopted herein, instead of using a compressed tank, because the former has an increased hydrogen content and is easier to control in the presence of catalysts [7]. Additionally, both Co–P/Ni foam and Co/γ-Al_2O_3 were utilized in this case as justified by findings in our previous research [8]. Moreover, sodium borohydride is melted in stable, aqueous, alkaline solutions that can be stored in flexible containers, such as fluid bags, which volumetrically occupy a small space in the fuselage. Thus, the fuel cell power could be readily regulated in accordance to the load conditions during the flight by adjusting the flow rate of the $NaBH_4$ solution, thereby saving fuels.

Similar to fuel cell systems, the solar power is considered as soaring renewable energy source that converts sunlight into electrical energy that can be utilized for numerous applications. One popular application is the mobile sector, including UAVs. This is because the solar-powered aircraft is driven by an electric-based propulsion system with power supplied by the limitless solar energy that is low-cost, environmentally friendly, and energy efficient [9]. In addition, solar systems do not require extra materials, such as fuel, or gas, for their operations, thereby resulting in lower UAV gross weights. However, a solar power system cannot generate power during cloudy weather, or at night. Consequently, the available power from photovoltaic arrays depends on the outer environmental conditions that can limit flight periods. To minimize this limitation, a battery can be integrated through a maximum power point tracking device (MPPT) to provide compensation during periods of insufficient solar power since hybridization in using renewable energy is necessary, and since no single source currently matches the capability of fossil fuels in terms of both energy and power density [10].

To achieve long endurance missions for the flight, a fuel cell system should be integrated with a solar cell system to provide uninterrupted high-quality power [11]. In this proposed hybrid systems, it could overcome the drawback of low-power density from renewable energy sources as well as improve the energy density in terms of the operational time using hybrid power sources.

However, the primary challenge encountered in the system integration is how to balance two different characteristics of electric power sources to meet load variations during the flight. In other words, it is imperative to understand how quickly the fuel system can support the electric load transients in the instances when the solar cell system cannot completely meet the load demand and vice versa. To achieve this control logic, solid-state relays were used, which they were electronic switching devices activated by an input signal. They were connected in a microprocessor controller to control the two main power sources by simply turning them on or off, based on the calculated power requirements. For instance, if the fuel cell system supplied the necessary power to satisfy the load demand for the cruise flight, the control logic could decouple the solar power system by placing it in a standby mode, and allow the concurrent charge of the battery. A similar process can be executed when the solar cell system supplies the necessary power to meet the load demand. In addition, both systems could be operated simultaneously to meet high-load variations when an unexpected maneuvering of the UAV is required. Consequently, successful hybridization of the fuel and solar cell systems was achieved through the ground test using this power switching technique.

Subsequently, the flight test was conducted to evaluate if our hybrid electric propulsion system for the UAV could operate according to the system's control logic. In summary, the flight was successful by the effective integration of two electric power plants via a power switching technique which has the potential to extend the flight endurance by strategically alternating between the supply of fuel and solar cell power.

Flight mission profile and main features for the UAV

Our flight test model, known as Falcon II, was designed to test and prove the power switching technique between the fuel and solar cell systems, achieving long flight endurance by alternating between two electric power sources. It has a trapezium-like wing shape, designed based on the SD 6080 airfoil, which is appropriate for a low-speed mission. Its wingspan is approximately 4.2 m, and its maximum gross weight is 11.0 kg. NACA intakes were equipped on both front sides of the fuselage to supply air to the fuel cell stack, and cool the fuel cell system. The exhaust and heated air from the fuel cell were routed to vent out at the outlets in the empennage. The flight control computer was on board to

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