

Development of a Fuel Cell Hybrid Electric Vertical Takeoff and Landing Aircraft Power Train

Mengxuan Wei^a, Maohang Qiu^a, Shuai Yang^a, Xiaoyan Liu^a, Jeff Taylor^b, Dong Cao^a

a. Electrical and Computer Engineering Department

University of Dayton, Dayton, OH

b. Event 38 Unmanned System, Richfield, OH

dcao02@udayton.edu

Abstract—This paper proposed the development of a fuel cell and battery hybrid electric vertical takeoff and landing (eVTOL) aircraft power train to address the dramatic power requirement difference during the cruise, takeoff and landing of the eVTOL aircraft. During the eVTOL aircraft cruise mode, the fuel cell would serve as the main power source due to its high energy density feature. During the eVTOL aircraft takeoff and landing mode, the power requirement could be about 7~10 times higher than the cruise mode. The Lithium-polymer (Li-po) battery has high power density feature and can provide high power surge during a short period of time. Therefore, both fuel cell and battery must provide the power simultaneously during the takeoff and landing in the proposed hybrid eVTOL power train. A GaN based DC-DC converter has been utilized to interface the fuel cell and the battery to serve as a voltage regulator and a battery charger. The proposed GaN DC-DC converter design and control strategy is described, a hardware prototype has been developed. The simulation and the experiment results of the hardware prototype are also demonstrated.

Keywords—Hybrid eVTOL, Fuel cell, Li-po battery, DC-DC converter

I. INTRODUCTION

The demand of eVTOL aircraft has dramatically increased due to its wide application areas, such as mapping, monitoring, photography, and warehousing [1]. Therefore, high mobility, long endurance and all-weather accommodation are the future design targets for next generation of eVTOL aircrafts [2]. To design the aircraft to achieve the target, the suitable energy source should be built. The design target is a power train system have both high energy density that can support longer endurance and the high power density which can fast response to the power consuming during take-off and landing. Traditional aircrafts from “Boeing Condor” and “Aerosond” utilizing the conventional fossil fuel as the single power source. However, the flight range will be limited by the fuel that carries. The tradeoff of the weight of the fuel and the flight length is needed.

Moreover, due to the recent lightweight, high compactness and the environmental protection design goals for the eVTOL aircrafts, the usage of the new energy source such as fuel cell, Lithium battery and ultra-capacitor becomes a new trend in eVTOL aircraft power train system. However, as shown in Fig.1, these new energy source cannot have the high

energy density and high power density at the same time, which means the energy storage capacity and fast power response requirement cannot be met when using single new energy source. Fuel cells have the relatively high energy density, high efficiency and cleanness features that meets the requirement of the eVTOL aircraft energy source. But the low power density, slow dynamic response speed and the difficulty during the cold start need to be solved. [3] The most popular fuel cell in the experimental aircraft platform is Proton Exchange Membrane Fuel Cell (PEMFC), which power range up to 1000kW and the power density range is 300-1000mw/cm². [4] The lithium battery and ultra-capacitor have a higher power density compare with fuel cell and the dynamics response is faster than fuel cell. But, the energy density of these two components are relatively low, the corresponding working hour just using these two components will not be long enough.

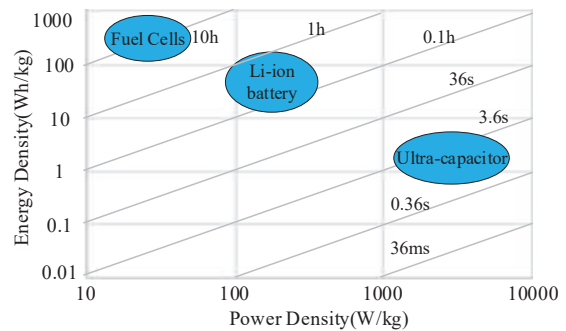


Fig. 1: Fuel cell, lithium battery and ultra-capacitor power density and energy density comparison

Thus, the hybrid system using the combination of fuel cell, Lithium battery and ultra-capacitor as power source has a better performance both on energy density, dynamic response speed and the working duration. Some research has been done in the hybrid aircraft area. In [5], a fuel cell battery hybrid aircraft is developed targeting long endurance and small size. By presenting the high level system architecture, the simulation model for the aircraft system is built. Also, the hardware-in-the-loop testing is done. But the design process only considers the take-off, cruise, and landing without operation in disturbance circumstance. A fuel cell and battery hybrid aircraft is proposed in [6] with the peak power 1kW. The fuel cell and the battery are connected to the same DC bus through a uni-direction DC-

DC converter and a bi-direction DC-DC separately. The cold start and the overload condition are also discussed. But the system size can be further reduced. Another PV/ rechargeable fuel cell/ rechargeable battery hybrid aircraft system is proposed in [7]. The PV panel can reduce the weight issue cause by the conventional fossil fuel, the fuel cell can replace the PV panel during the night flight and the battery can provide power when needed. However, the system peak power deliver ability is only 1500W with 800W take-off power. The optimization of the system weight and EMS based on state-machine are presented in [8]. The hybrid power system consists of fuel cell, lithium-ion battery, a uni-direction DC-DC converter and an EMS processor. The modeling of each component is built, and the optimized system weight is achieve based on the power requirement of total flight profile. However, both fuel cell and battery need a DC-DC converter to regulate the power. The system architecture can be optimized to achieve the smaller weight at same operating power.

This paper presents a fuel cell and battery hybrid power train for the eVTOL aircraft when considering the influence of the air disturbance. The fuel cell will provide power during the whole operation period of the aircraft. The battery will provide the difference of the burst load and the output power of the fuel cell during the climbing and descending. Additionally, the battery can recycle the extra energy from the fuel cell during the cruise. The charging process of the battery is following the battery charging profile. The system architecture and operation principle are demoed in section II. The GaN based DC-DC converter design and control are discussed in section III. The simulation and the experiment result are also demonstrated in section IV.

II. SYSTEM DESIGN

A. System Architecture

The hybrid fuel cell battery aircraft power train is shown in Fig. 2. The system configuration consists of a fuel cell, a DC-DC converter, a Li-po battery and inverter motor sets. The DC-DC converter works as both a voltage regulator for the fuel cell and a charger for the battery. It transfers the power from the fuel cell to the load. Also, the DC-DC converter will charge the battery in certain stage. The output of the DC-DC converter and the battery are connected to the same DC bus. The inverter motor sets can be divided into two groups. One VTOL system

group work when the aircraft is climbing or descending and stop during forward flight, the other is the pusher system for aircraft fly forward [9].

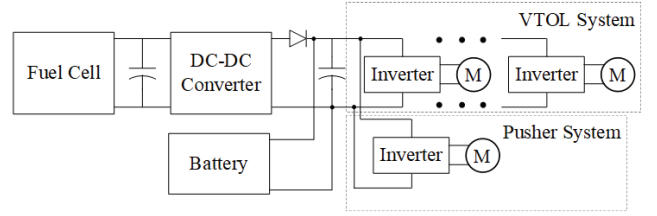


Fig 2: Hybrid fuel cell battery VTOL aircraft power train

B. System Operation Principle

Fig. 3 shows the designed aircraft power train system power flow profile for the presented fuel cell powered aircraft. The load profile (P_{ld}) is build based on the demand power of flight profile. The P_{con} is the converter processing power which is the same as the fuel cell output power, the P_{batt} is the power processed by the battery.

- Stage1 [t_0 to t_4]: During the take-off stage, both the fuel cell and the battery deliver power to the load. From t_0 to t_1 , the aircraft is in the accelerate climbing mode. The power drag from the fuel cell and battery are increasing. In t_1 to t_2 , the aircraft will enter a short period of cruise then will accelerate climbing again in t_2 to t_3 . Fuel cell reaches the peak output power. During t_3 to t_4 , the aircraft is in the decelerate mode and the power drag from fuel cell is decreasing. Meanwhile, fuel cell will start charging the battery.
- Stage2 [t_4 to t_6]: At the start of the cruse mode t_4 to t_5 , fuel cell deliver power to battery and load. From t_5 to t_7 , the battery is fully charged, the output power of the fuel cell will decrease to the power consumed by the load.
- Stage3: [t_7 to t_{12}] In this stage, the aircraft will cruise and descending in the unstable air condition. This results in the disturbing power consumption of the load. In t_8 to t_9 , the battery will provide the disturbing power to since the fuel cell is in the full power mode. From t_9 to t_{12} , the aircraft is descending without disturbing, and the power consumption is even smaller. Thus, at some point, both fuel cell and battery will not output any power.
- Stage4: [t_{12} to t_{15}] This is the landing stage of the aircraft. Basically, the reverse of take-off.

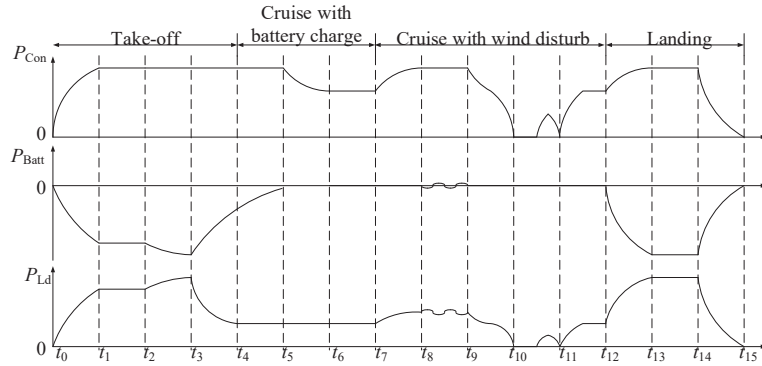


Fig 3: Designed aircraft power train power flow profile

III. DC-DC CONVERTER DESIGN AND CONTROL METHOD

A. DC-DC Converter Design

Fig. 4 shows the proposed two stage DC-DC converter circuit with a boost first stage and a buck second stage using GaNFETs. The boost stage can boost up the fuel cell output voltage level and the buck stage can be controlled to charge the Li-po battery following the charging profile. To accommodate the wide operating range of the fuel cell and the GaNFETs current rating [10], an interleaved boost DC-DC converter is used for the first stage. The input voltage of the DC-DC

converter V_{in} should cover the same range of the fuel cell output voltage. Since the second stage is selected to be an interleaved buck converter to charge the battery, the V_{Link} should be selected high enough to cover the maximum voltage of the desired battery pack. The popular 48V output voltage bus is selected as an example to charge the li-ion battery. The DC link voltage (V_{link}) is set as 50V. Besides, the power rating of both buck and boost DC-DC converter should be designed corresponding to the maximum fuel cell power. And a diode is put on the output side of the DC-DC converter to prevent the negative power flow of the DC-DC converter as an additional safety factor.

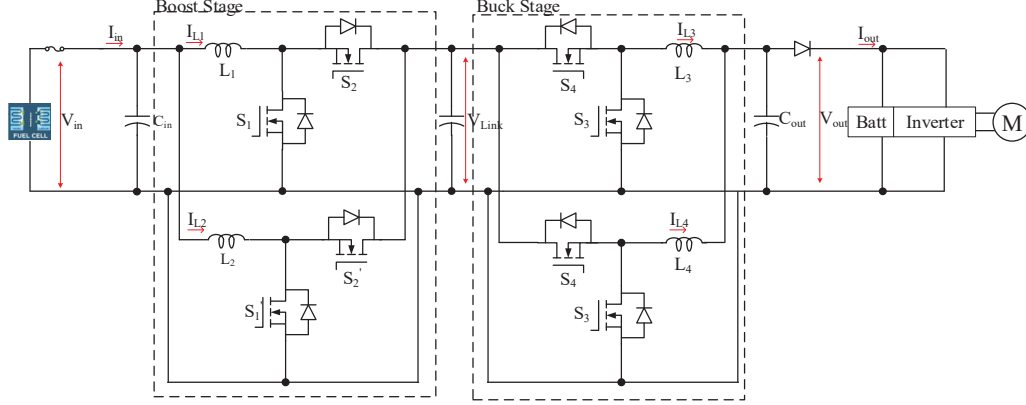


Fig 4: DC-DC converter circuit

To achieve a small footprint, the converter operates at around 150kHz. Several EPC GaNFET are selected, and the converter total device power loss breakdown is shown in Fig.5. The EPC2218 has the smallest power loss but the EPC2021 is selected since the modularized Dr.GaN is available with EPC2021. The Dr.GaN can help eliminate the assemble of the small footprint components. Besides, the input capacitor bank (C_{in}) and output capacitor bank (C_{out}), and dc link capacitor size can be reduced when the two-phase design is adopted. Moreover, due to the interleaving operation and well-designed converter layout, the converter can operate without an extra heatsink.

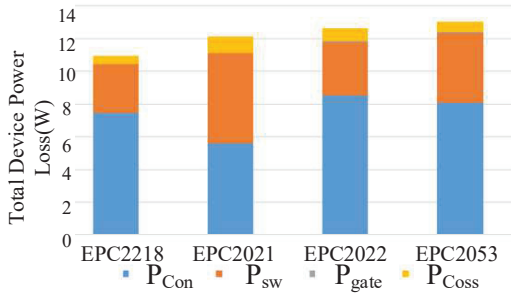


Fig. 5: Powe loss analysis for several GaNFET

B. System Control Method

The control strategy for the boost stage and buck stage is displayed in Fig 6 (a) and (b) respectively. The boost stage close loop control is realized by controlling the V_{link} and inductor current (I_L) and the buck stage is controlled to realize the CC, CV charging for the battery.

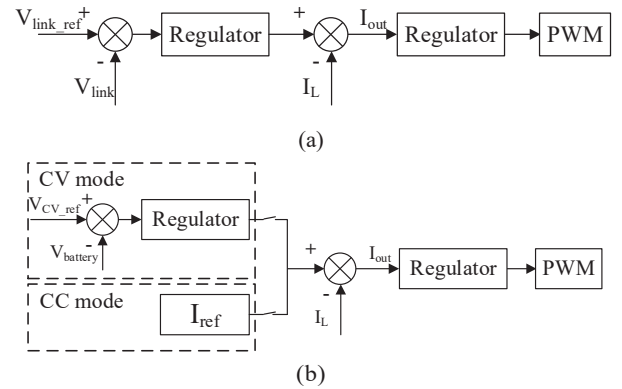


Fig 6: (a)Close loop control diagram for boost stage (b) Close loop control diagram for buck stage

The average model of interleaved boost can be expressed as equation (1), (2)

$$L \frac{d\langle i_L \rangle}{dt} + \langle i_L \rangle R_L = \langle v_{in} \rangle - (1-d) \langle v_{out} \rangle \quad (1)$$

$$C \frac{d\langle v_{out} \rangle}{dt} = -\frac{\langle v_{out} \rangle}{R_{out}} + 2(1-d) \langle i_L \rangle \quad (2)$$

Linearize equation (1), (2) with small signal perturbation, and small signal equation can be expressed as equation (3), (4)

$$L \frac{d(I_L + \tilde{i}_L)}{dt} + (I_L + \tilde{i}_L)R_L = \langle V_{in} + \tilde{v}_{in} \rangle - (1-D - \tilde{d})(V_{out} + \tilde{v}_{out}) \quad (3)$$

$$C \frac{d(V_{out} + \widetilde{v_{out}})}{dt} = -\frac{(V_{out} + \widetilde{v_{out}})}{R_{out}} + 2(1 - D - \widetilde{d})(I_L + \widetilde{i_L}) \quad (4)$$

Ignore second order items then the equation (5) can be deduced

$$\left. \frac{\widetilde{i_{L_{total}}}}{\widetilde{d}} \right|_{\widetilde{v_{in}}=0} = \frac{2sCR_{out}V_{out} + 4V_{out}}{s^2LCR_{out} + s(L + CR_{out}R_L) + R_L + 2(1-D)^2R_{out}} \quad (5)$$

Set cut-off frequency as 20 kHz (about 1/10 of switch frequency), and phase margin as 45 degree. Then equation (6), (7) can be deduced

$$\left. \frac{\widetilde{i_{L_{total}}} k_p s + k_p}{\widetilde{d}} \right|_{s=2\pi \times 20k} = 1 \quad (6)$$

$$\left. \angle \left(\frac{k_p s + k_p}{s} \right) \right|_{s=2\pi \times 20k} \approx -45^\circ \quad (7)$$

IV. SIMULATION AND TESTING RESULT

The simulation result for a typical eVTOL aircraft operating in cruise mode while battery is not charged is shown in Fig 7 (a). Both the boost stage and buck stage is operating as designed. Fig 7 (b) shows the simulation result of a representative example of the aircraft take-off at peak power and followed by the charge of the battery during the cruise and ended by the landing.

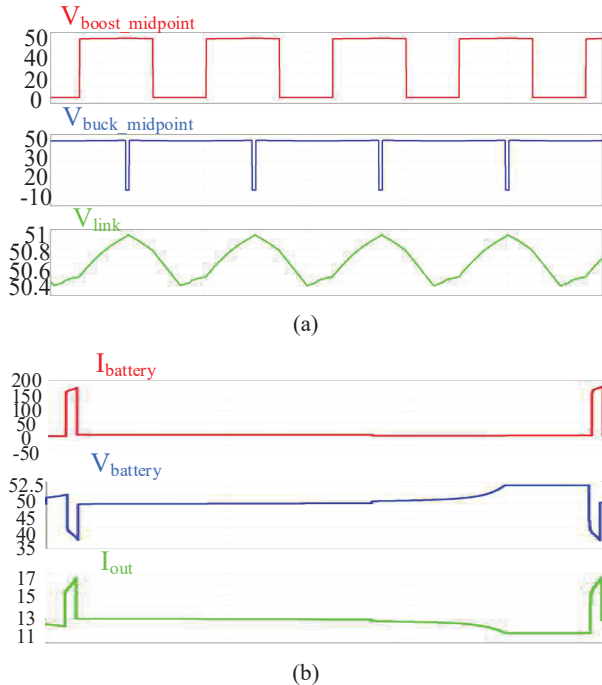


Fig 7: (a) Simulation result of aircraft cruise state without battery charging (b) Simulation result of take-off, battery charging during cruise and landing

Fig.8 shows an example of a typical eVTOL aircraft ideal power flow profile to evaluate the performance of the proposed DC-DC converter and control assuming 400W cruise power and

3700W take-off and landing power. And assume the DC-DC converter can provide continuous 600W during the flight. Fig. 9 shows the corresponding experimental test result. The testing result meets the typical ideal power flow profile. The DC-DC converter prototype is shown in Fig.10 and the temperature performance of the converter without any extra cooling is shown in Fig.11. The testing platform is shown in Fig.12.

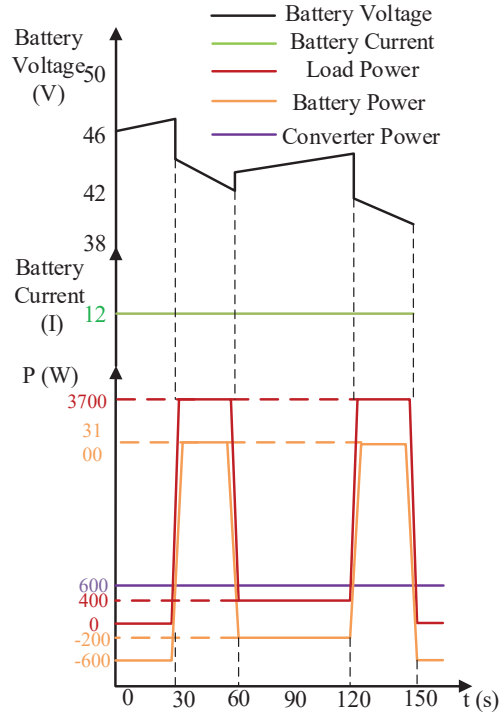


Fig 8: Ideal profile example for designed system

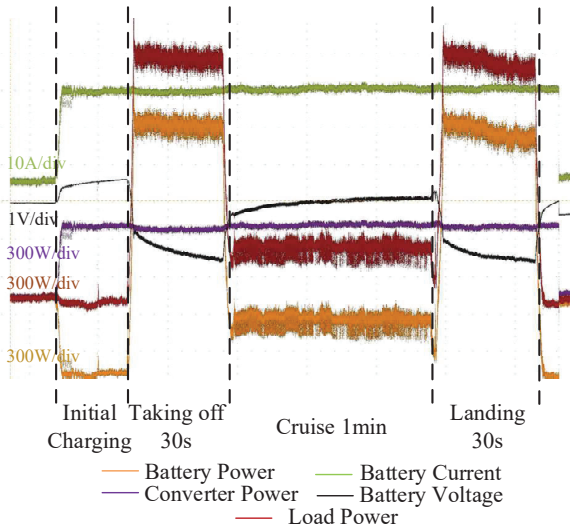


Fig 9: Testing result for designed hybrid power train system

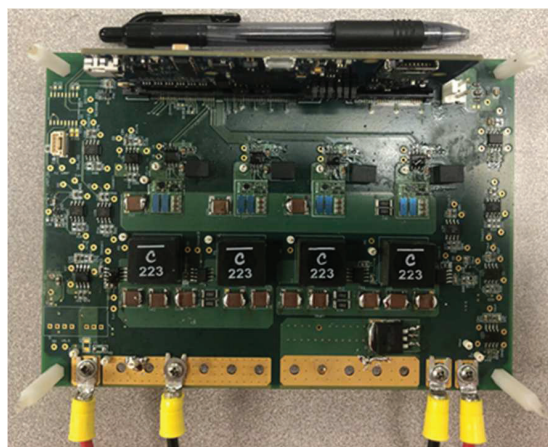


Fig 10: DC-DC converter prototype

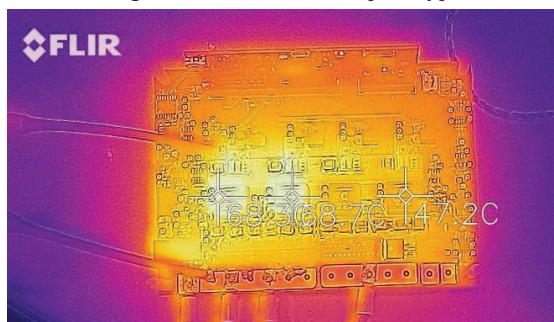


Fig 11: DC-DC converter thermal performance

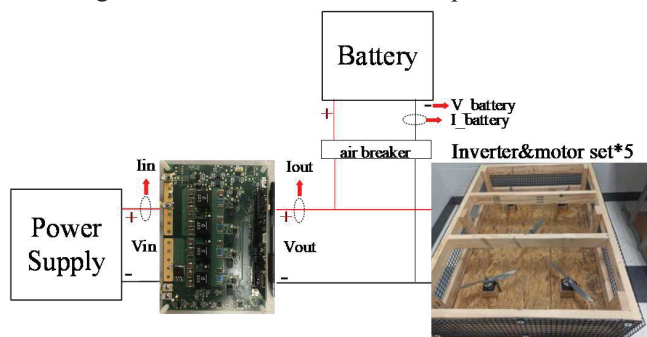


Fig 12: Testing platform for designed system

V. CONCLUSION

In this paper, a hybrid power train for the eVTOL aircraft is built. By using the new energy source such as fuel cell and li-po battery to replace the conventional fossil fuel, the designed eVTOL system reached can reach very high operating power.

The fuel cell always provide power during the eVTOL aircraft operation. The Li-po battery provide power when there is a difference between the load power and the fuel cell output power, also it can recycle the power from fuel cell when needed. The DC-DC converter operate as a voltage regulator to regulate the fuel cell output voltage and a battery charger to charge the Li-po battery.

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