879. Dynamic evaluation of a mini train powered by the hybrid fuel cell

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Abstract. Fuel cell system is widely used in the mobile devices and USA space program. This project studies the feasibility of powering a small train with a hybrid fuel cell system by employing electric power integration technology. Specifically, this study performs the dynamic tests on a mini train powered by Proton Exchange Membrane Fuel Cell (PEMFC). The original 12 V, 100 AH lead-acid battery, which can provide 12 V, 0.5 Hp for the locomotive and carry 9~12 people, is replaced by a hybrid Proton Exchange Membrane Fuel Cell. After an oval railroad and a low-pressure metal hydrogen storage canister recharging station are built, the mini train is tested on weekend and holidays at the outdoor park of National Science and Technology Museum, Taiwan. The dynamic performance of the PEMFC system is analyzed and the feasibility of applying this system to mini trains is evaluated. After one year of running, the mini train has been operated over 1,200 hours and has been transported over 30,000 passengers. The hybrid PEMFC system works perfectly and meets the original goal. Results also indicate that the temperature significantly affects system performance.

Keywords: dynamics, fuel cell, mini train, proton exchange membrane.

Introduction

Although the advancement of human technology has promoted the economic growth and has provided a convenient lifestyle, the consequences of over-exploitation and energy consumption are causing environmental pollution that endangers sustainable living and for following generations [1]. This induces the global warming effect, fossil energy exhaustion, and other problems. Therefore, it is an urgent and world-wide goal to educate people and develop clean energies including solar energy, wind power, biomass energy, and hydrogen energy, etc. that do not destroy the environment [2]. Hydrogen energy is a shining star in this new energy area. It can produce not only heat energy by direct burning, but also electric power through reaction between fuel cells and oxygen. Since this reaction emits only heat and water, hydrogen energy does not cause pollution problems [3]. Furthermore, hydrogen is storable and is an important solution to the traditional fossil fuel problems of energy safety and environmental sustainability.

Many studies report on PEMFCs due to their advantages of low-operational temperature (20–100 ^{o}C), high power density, and lightweight. Chien [4] discusses a high temperature proton exchange membrane fuel cell (HT-PEMFC) at various temperatures and current loads, showing a low temperature activation phenomenon. Wang et al. [5] studies the effect of different assembly pressures on dynamic performance and the effects of contact resistance on efficiency in a PEMFC. Rao and Rengaswamy [6] develop a detailed current-voltage dynamic model for spherical agglomerates in PEM fuel cell. Hung [7] emphasizes systematic approaches to the modeling, design, and control of fuel cell systems to solve three important issues: hydrogen generation, hydrogen storage, and power generation. Chou [8] focuses on the design and operating conditions for a 2 to 200 W micro stack PEMFC, including air breathing, humidity, gas distribution of the main flow channel, and water flow. Wu [9] establishes a PEMFC stack model using algebraic equations to simulate the dynamic performance of the fuel cell.

To generate new fuel cell knowledge, promote education on energy saving and sustainable development, and spark public interest in environmental awareness, the NSTM cooperated with Asia Pacific Fuel Cell Technologies to rebuild the mini train by combining entertainment and novel fuel cell technology. The original 12 V 100 AH lead-acid battery driven mini train is transformed into the first fuel cell powered train equipped with hybrid PEMFC and Ni-MH battery. This train is running on a 212 m long railroad in an outdoor park at NSTM (Fig. 1). The train's dynamic performance and entertainment draw the attention of many people, who are impressed with its zero pollution and clean energy technology. Thus, this fuel cell achieves the educational goal of preserving energy and protecting the environment. The dynamic performance of the pilot system is tested to evaluate the feasibility of applying the proposed system to larger vehicles. NSTM invests in re-designing streamlined fuel cell powered locomotives integrated with a transmission shaft and motor in one body. This gives the mini train a new look so that the second generation of fuel cell powered mini train can be even more effective and save more energy.

Fig. 1. Driving test of fuel cell powered mini train in NSTM

This study investigates the feasibility of employing electric power integration technology to power a mini train using a hybrid PEMFC and Ni-MH battery system, and analyzes the effects of different temperatures on system performance.

Design of fuel cell-powered mini train system

This study adopts an original 12 V 100 AH lead-acid battery powered mini train as the experiment platform. Leaving the motor and transmission system intact, the battery of the locomotive is replaced by a 250 W hybrid PEMFC as an add-on power system. This PEMFC provided 12 V 0.5 HP and a Ni-MH battery (24 V) for the extra 450 W power, making it a PEMFC-driven mini train. Figure 2 shows the electric power that is needed by the original 12 V 100 AH lead-acid battery powered mini train after an actual running test. This figure shows that when the train system accelerates from rest to running in a straight line stably, the electric current and power it required are 44 A and 528 W. When the train is backing up on a straight line, the maximum electric current needed is 10 A, approximately equivalent to 120 W. The fuel cell system of the mini train is designed according to this operation data curve, as Fig. 2 shows.

To satisfy the power and economic design requirements for the train, the add-on PEMFC and a Ni-HM battery are combined to form a fuel cell system that provided hybrid electricity for the locomotive. The fuel cell system is designed to output an average of 250 W to maximum 700 W of power. The main components of the system include an air-cooled PEMFC, add-on humidifier, hydrogen module composed of four metal hydride hydrogen storage canisters, air supply module, and remote control module. The system also includes several safety devices and signal lights to secure the train operation. Figure 3 shows a system functional block diagram of the PEMFC. The fuel-cell-powered mini train is designed to run normally on 250 W of power, which is entirely provided by the PEMFC. However, when the mini train is turning or accelerating, it requires approximately 700 W of output. In this case, the extra 450 W is provided by a secondary cell-Ni-MH battery [10, 11].

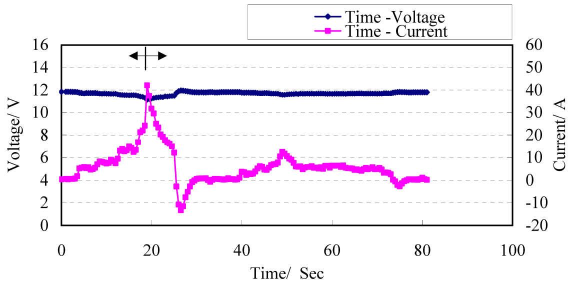

Fig. 2. Voltage and current variation with time of lead-acid battery

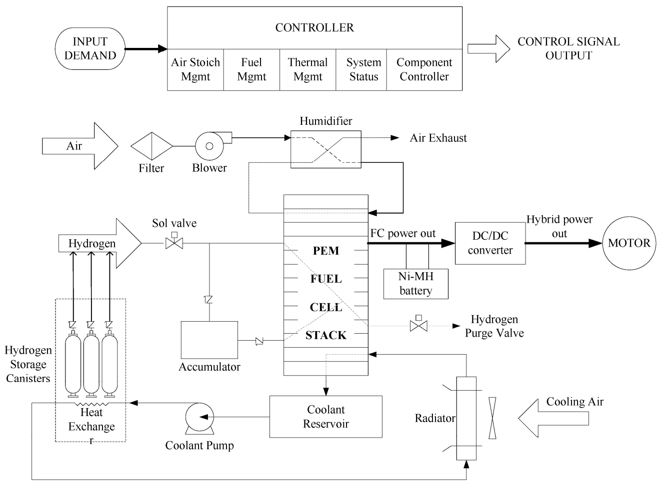

Fig. 3. Functional block diagram of the fuel cell system

Control logic

Figure 4 shows a control logic block diagram of the fuel cell system, described as follows:

1. Turn on the system: the battery power through diode and transformer to supply electricity to the fuel cell controller and then start PEMFC system.
2. The PEMFC discharges to the load when its voltage exceeds the safety voltage, and the small train starts working.
3. When battery voltage exceeds the safety voltage, the relay will be electrified. In this system discharge pattern, both the PEMFC and the Ni-MH battery provide hybrid electricity to the load.
4. When battery voltage is lower than 50 % of State of Charge (SOC, 24 V), the charge switch will be activated and the PEMFC will charge up the Ni-MH battery.
5. Turn off the system.

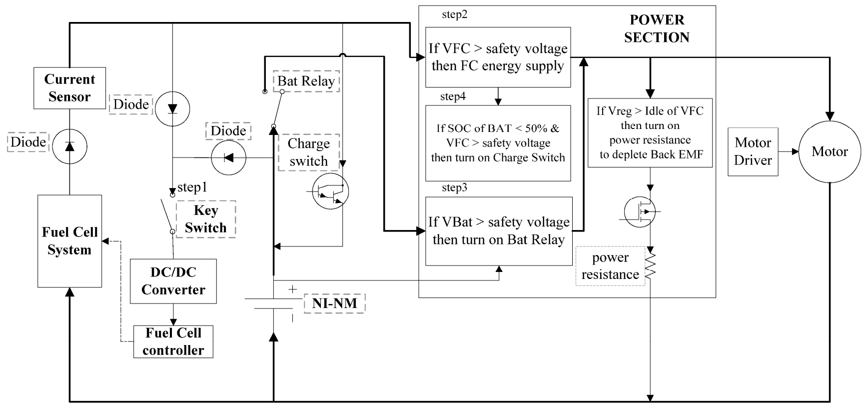

Fig. 4. Control logic block diagram of the fuel cell system

Fuel cell stack

A fuel cell stack consists of several single fuel cell (single cell) assembled together. The number of single cells needed depends upon how much power is required. These characteristics make it easy to manufacture modular fuel cell stacks. As for the characteristics of power provided by the fuel cells, the number of assembled single cell determines the voltage. The maximum current depends upon the response area of a single cell. If the negative/positive electrodes are supplied normally, a stable direct current can be achieved. Therefore, researchers have designed different fuel cell stacks for different applications [12]. The fuel cell stack used in this system is based on the needs of the mini train. The fuel cell stack consisted of 41 PEMFCs, each with an area of 40 cm^2 and length × width × height = 137×138×314 mm. The system's output power is 24 V, 250 W. Figure 5 shows the performance test results. The maximum operation current of the cell is 25 A and the maximum output power is 545 W. 10 A of rated current can output the power of 265.4 W. 20 A of rated current can output the power of 474.6 W. The system structure is almost identical to a general PEMFC system. However, a Ni-MH battery provides auxiliary power, making this a hybrid PEMFC power system.

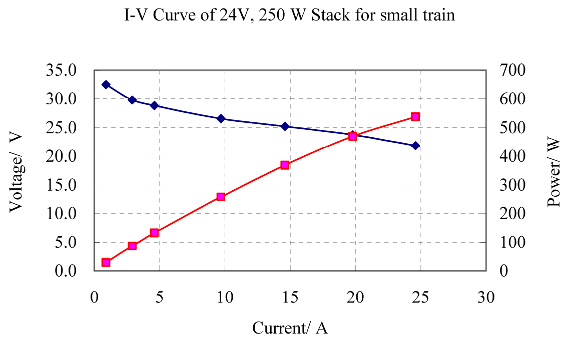

Fig. 5. Performance curve of fuel cell stack

Hydrogen supply system

Currently, most fuel cell-powered vehicles adopt high-pressure hydrogen, while motorcycles and automatic bikes utilize low- pressure alloy hydrogen storage canisters. The proposed system adopts alloy hydrogen storage canisters for storage and supply based on factors of activity and education safety, convenience, and shorter usage time, etc.

The metal hydrogen canisters used in this study weigh 4338.9 g full load and 4294.1 g empty, after 44.8 g hydrogen is released. The usability rate of hydrogen gas is 93 %. Based on 8.2 slpm of hydrogen flow in 30 °C ambient temperature, the hydrogen gas can be released continuously for up to 55 minutes under atmospheric pressure.

Humidifier

Since PEMFC uses hydrogen ions conductive solid polymer electrolyte (SPE), it requires an appropriate amount of water to humidify the sulfate in its chemical structure to transfer hydrogen ions. Thus, when reacting, it must increase humidity to the responded gas to ensure normal fuel cell operation. The higher its relative humidity is, the better the power generation rate will be, and the longer the battery life of the fuel cell stack can be ensured. Several studies report the fuel cells using hydrogen as fuel and air as oxidant. A test under natural humidity and temperature conditions shows that at 30 °C and relative humidity ranged from 100 %RH to 70 %RH the performance decreases when relative humidity decreases [12, 13].

A wet-film humidifier in this system is used together with PEMFC stack and is utilizing the recycled water from fuel cells to humidify inlet air. It also optimizes the fuel usage by heating the input dry air to 5~10 °C, which is cooler than the battery operation temperature, and humidifies the air to 90~100 %RH.

Cooling

The water evaporation speed of the membrane electrode assembly (MEA) increases when the PEMFC operation temperature exceeds 60 °C. The MEA's humidity and the power generation gradually decrease when the water evaporation speed is faster than its formation speed. Therefore, cooling and hear dissipation modules should be designed to cool the cell temperature effectively and increase power generation efficiently.

Heat dissipation methods in fuel cells are usually classified as water-cooled and air-cooled. Water-cooled fuel cells direct water into the cell and use a radiator outside the cell to decrease water temperature, whereas air-cooled fuel cells use fans to direct outside cooler air into the cell and bring out the heat. A fuel cell stack produces a great amount of waste heat when reacting. However, hydrogen will absorb heat upon release from storage canisters, thus reducing the ability to release hydrogen due to lowering storage can's temperature. As the result, the proposed system uses the air-cooled method to reduce the amount of waste heat produced during cell reaction. The system also redirects waste heat into the fuel supply module to heat up the canisters and release hydrogen stably.

Fuel cell performance also varies at different operation temperatures. Too low or too high of the temperature may cause poor cell performance and cell damage, respectively. In general, the low temperature range for fuel cell operation is from 50° to 70 °C. When the temperature rises above the 70 °C limit, a warning signal will light up and the system will turn off.

Test results and discussion

Dynamic test

After assembly was completed, the fuel cell system was run on the NSTM railroad. Figure 6 shows the test results. When the mini train is moving stably, the operation voltage is 25~38 V (the system's lowest voltage limit is at 21 V), and both fuel cells and Ni-MH battery output

3~11 A and 3~6 A current, respectively. This combined power is enough to provide the movement for the mini train, and the operation temperature of fuel cell remained at 55 °C. Due to additional electricity discharged from Ni-MH battery, the fuel cells do not reach the lowest protection voltage, 21 V, during the entire trial process. This indicates that the proposed design met the train's operational requirements. The maximum charge current of fuel cell to Ni-MH battery is 6 A in this system. Therefore, when the mini train stops and the system are idle, the fuel cells recharge Ni-MH battery at 6 A maximum.

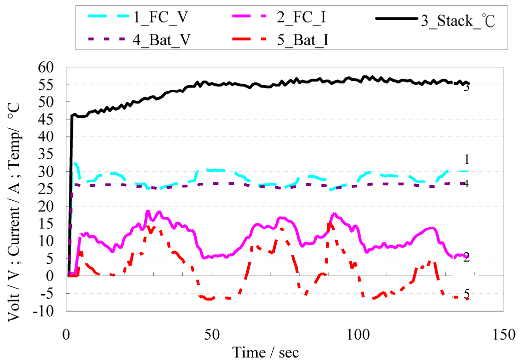

Fig. 6. Dynamic performance of the fuel cell mini train

DC/DC conversion test

Figure 7 and 8 show the results of multi-function meter measurement, confirming that the DC/DC converter has normal output, and DC/DC conversion efficiency is greater than 72 % and DC/DC output voltage is 11.5~13.6 V15. The symbols used in Fig. 7 and 8 are described as follows:

V_DC_in: DC/DC converter input voltage; V_DC_out: DC/DC converter output voltage.

I_DC_in: DC/DC converter input current; I_DC_Out: DC/DC converter output current.

P_DC_in: DC/DC converter input power; P_DC_Out: DC/DC converter output power.

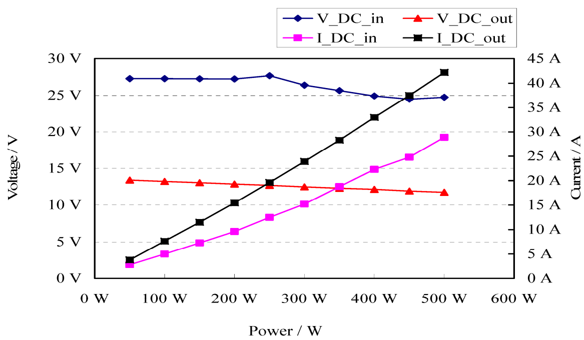

Fig. 7. Power-Current-Voltage curve of DC/DC conversion

Study on dynamic test

This study focuses on the effects of temperature on the performance of a PEMFC-Powered Mini Train system. In Kaohsiung, Taiwan, the average temperature is from 18 °C to 29 °C in whole year. Figure 9 shows that the performance of the fuel cell system tested in April, Kaohsiung, the first day of operation, is at the most optimal state. The highest voltage is 33.67 V, with voltages of 29.33 V and 26.25 V at 7 A and 14 A loads, respectively. The operation results for the first month indicate that even though the performance varied within 1 V due to the temperature and humidity slightly changed daily, it is within the normal range without error and the system is rather stable. Figure 10 shows another performance power diagram of the fuel cell system tested in May, Kaohsiung. In May 5th, the voltage was slightly lower at 10 A, ranging from 28 V to 26 V. The main reason for this low voltage may have been higher environmental temperature. In May 7th, the overall performance decreased for the same reason. Although high temperature causes a decrease in fuel cell performance, it does not cause any immediate damage to the fuel cells because the performance returned to the original level at the end of May. The performance of mini train continued to be lower, which is probably caused by the temperature and climate. Figure 11 shows that this phenomenon may be related to environmental change in June and July, Kaohsiung. After careful review of operation data of the same day, it is discovered that the temperature is as high as 41 °C and the fuel cell operation temperature reaches the upper limit of 55 °C. After adjusting and reinforcing the system's cooling ability, the system resumes its original performance in July and the voltage is 28.3 V at 10 A. Figure 11 also shows the system status in August. After the adjustment in July, system performance is not only stable, but also improved. The voltage is 27~29.8 V at a 10 A rated load. Figure 12 shows the mini train operation performance power diagram from September to December, indicating that the performance stays at 27~29.8 V at 10 A rated load in September and continues to maintain above 27 V in November and December. The performance of fuel cell mini train in April and in December indicates that the voltage is 31 A at 3 A, 28 V at 10 A, and even 24.8 V at 15 A. This shows that the fuel cell system does not show any obvious signs of recession.

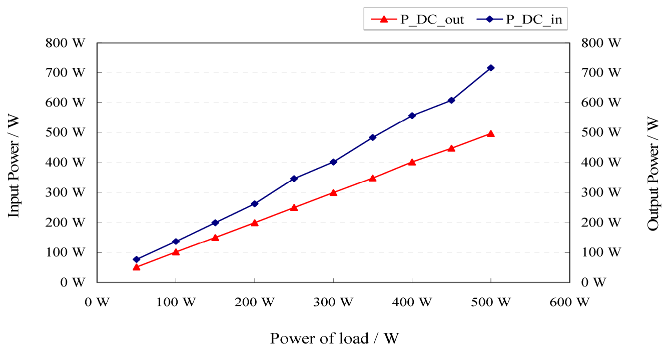

Fig. 8. The relationship between power load and Input/Output power

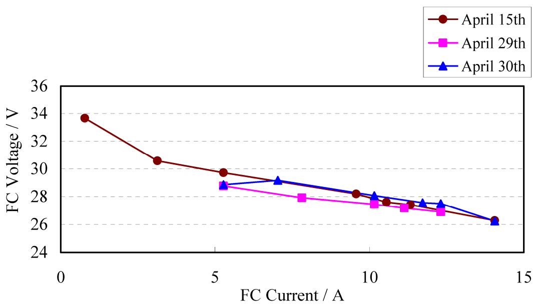

Fig. 9. The fuel cell mini train performance in April, Kaohsiung

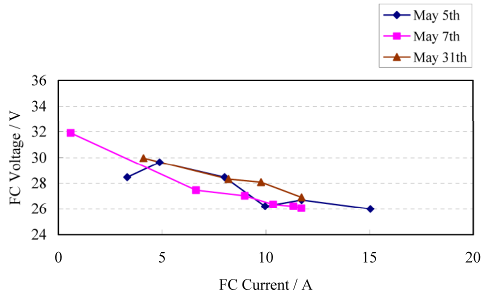

Fig. 10. The fuel cell mini train performance in May, Kaohsiung

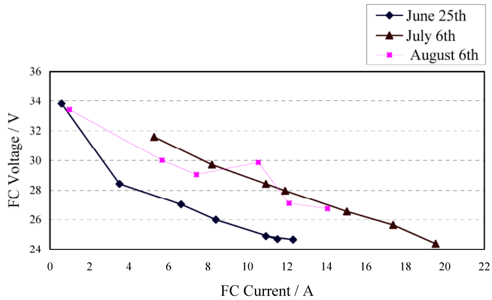

Fig. 11. The fuel cell mini train performance in June, July and August, Kaohsiung

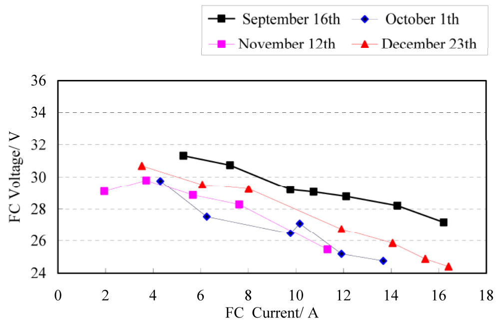

Fig. 12. The relationship between power load and Input/Output power

Lastly, to confirm the influence of environmental temperature on the fuel cell system, the system's operation data is analyzed. When the fuel cell operation temperature is lower than 47 °C, the voltage is approximately 31.2 V; when the temperature is higher than 50 °C, the voltage drops to approximately 30.1 V. This causes the voltage to decrease under a 6 A load, suggesting a decrease in fuel cell performance. This momentary recession may be caused by a decrease in battery humidity when the fuel cell temperature increases, which in turn causes the SPE's water content to decrease, and thus increases the impedance.

Summary

This study presents several interesting points that are summarized as followed:

1. The fuel cell is used to replace the traditional lead-acid battery power train system. Since the fuel cell is a primary power generation system and not a secondary energy system, a fuel cell-powered mini train does not have the problem of recharging. This system is equipped with four hydrogen storage canisters with approximately 180 g of hydrogen, and can provide power

for the train to operate for 10 hours without stopping. After the hydrogen in the system is depleted, the train can be restarted within a minute of replacing the canisters, without the problem of recharging.

2. Currently, fuel cells are still in the verification stage of system application. The actual operation of this mini train in Kaohsiung, Taiwan, shows that the system is affected by temperature. Thus, the performance is lower in June. Even so, the fuel cell system is sufficient for the mini train.

3. In the future, fuel cell systems will continuously be improved to automatically adjust and adapt to changes in temperature and humidity, stabilize fuel cell performance, reduce the risk of damage, and increase durability.

4. The mini train's hybrid fuel cell and Ni-MH battery power system can be expanded to enhance the power and the maximum power output can sustain operation for more than 30 minutes. Thus, it can be applied to trains, transportation vehicles, and other power equipment requiring more power.

Acknowledgements

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