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Hybrid hydrogen PEM fuel cell and batteries without DC–DC converter

Jinlei Shang[1]*, **Kevin Kendall**[2] **and Bruno G. Pollet**[3]
[1]*Electric Vehicle System, Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB, UK;* [2]*Centre for Hydrogen and Fuel Cell Research, School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK;* [3]*HySA Systems Competence Centre, South African Institute for Advance Material Chemistry, The University of the Western Cape, Private Bag X17, Bellville, Cape Town 7535, South Africa*

Abstract

Concerns about greenhouse gases as well as the price and security of oil supply have acted as a spur to sustainable automobile development. The hydrogen fuel cells electric vehicle (HFCEV) is generally recognised by leading automobile manufacturers and scientists as one of the optimum technologies for long-term future low carbon vehicle. In a typical HFCEV power train, a DC–DC converter is required to balance the voltage difference between the fuel cells (FCs) stack and batteries. However, research shows that a considerable amount of energy generated by the hydrogen FCs stack is deplete during this conversion process as heat. This experiment aims to improve the power train efficiency by eliminating the DC–DC converter by finding the best combination of FC stack and batteries, matching the size and capacity of the electrical components.

Keywords: hydrogen fuel cell hybrid vehicle; battery electric vehicle; DC–DC converter

*Corresponding author.
jinlei.shang@coventry.ac.uk

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1 INTRODUCTION

The large number of automobiles in use worldwide has caused and continues to cause a series of major challenges in our society [1, 2]. Greenhouse gases and other emissions from vehicles' tailpipes affect not only the climate but also humans, especially the particulate emissions from the increasing numbers of diesel vehicles on the road [3–7]. In addition, rapid oil depletion, issues with energy security, dependency on foreign sources and population growth make the challenges posed by automobiles even greater [8, 9].

The hydrogen fuel cells electric vehicle (HFCEV) is generally recognised as one of the optimum technologies for long-term future low carbon automobiles [10–13]. This combines the proton exchange membrane (PEM) fuel cells (FCs) with a battery- and electric-driven train to optimise the starting time, operating temperature and efficiency of the vehicle [14]. Using PEM FCs to generate electricity from high-purity hydrogen; the electricity is then either used to drive the electric motor of the vehicle or stored in an energy storage device, such as a battery or ultra-capacitor. Since FCs generate electricity from chemical reactions, they do not combust fuel and therefore do not produce pollutants and generate much less heat compared with an internal combustion engine. The by-product of a hydrogen FC is only water [15]. FC stack itself has no moving parts (apart from its auxiliary components) and are fabricated by stacking repeatable components together; hence, they have the potential for high reliability and low manufacturing cost.

PEM FCs are best operated at a constant load in order to achieve peak efficiency and maximum lifespan [16], whereas the power required for the automobile varies substantially, because of the variety of accelerations and decelerations under real-life driving conditions. However, the battery can accommodate these dynamic power changes perfectly, while also capturing the braking energy using electromagnetic deceleration [17]. Hence, the HFCEV not only solves the problem, but also offers additional benefits:

- Smaller FC stack therefore lower cost;
- FC stack can operate at optimum efficiency most of the time;

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- FC stack lifetime is extended;
- The FC stack designer is able to optimise the cells for power and efficiency rather than cycle life;
- Deep discharging from the battery is eliminated, therefore improving the batteries' lifetime;
- Fast start-up of the FC stack;
- Improves power train efficiency through capture of regeneration energy.

In general, there is a difference between the FC stack voltage and battery voltage, and a DC–DC converter is required in this hybrid system. According to previous study of the Micro-Cab HFCEV, nearly 20% of energy generated by the FCs was depleted through the DC–DC converter currently used in this vehicle [18], mainly because this kind of DC–DC converter obtained only its peak efficiency at full load, which is rarely achieved in real driving cycles, especially under urban drive cycles which involve many stops. To minimise this power loss in the DC–DC converter, the present project aimed to match the FCs, the battery pack and the electric motors, in a 48 V system without a DC–DC converter. Advanced DC–DC converters have wider high efficiency range; however, it will still deplete considerable amount of energy, as well as add cost in addition.

2 EXPERIMENTAL METHODS

The experiments comprised bench tests to examine the PEM FC hybrid with both lead-acid (PbA) batteries and Li-Ion phosphate (LPBs) batteries with a battery managing system (BMS) under different state-of-charge (SoC) and load conditions. In order to investigate the FCs performance, rate of battery charging, SoC of batteries and power distribution character from both batteries and FCs, the bench test was developed with three electric loads to simulate the electric motor.

Figure 1 shows the bench test configuration of the hybrid system. The FCs stack and batteries were connected in parallel. The FCs stack may not only supply power to electric loads but also charge batteries at the same time where needed. The batteries may also assist the FCs stack to supply extra power to the electric loads when required. The power flow relies solely on the voltage difference. The current flow between them will be examined. Table 1 shows the equipment used and its specifications.

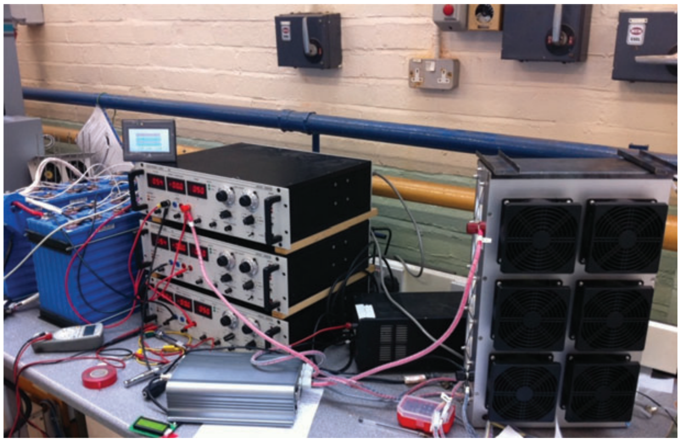

Figure 1. *Configuration of the FCs and batteries hybrid system.*

Testing procedures:

(1) Charge/discharge the batteries to the required SoC;
(2) Turn on the FCs, start to withdraw current from it after it is fully started;
(3) Increase the electric load by 50 W with every 15 s interval;
(4) Record the voltage, current and temperature of electric loads, FC and batteries where applicable.

3 RESULTS

3.1 Hybrid with 4 × 12 V lead-acid batteries

First, the 3 kW Horizon PEM FCs was connected with 4 × 12 V valve-regulated lead-acid (VRLA) batteries, connected in series to provide the nominal voltage of 48 V and total energy capacity of 1 kWh. The lead acid battery has high specific power and is capable of producing high power for short periods of time (e.g. during maximum acceleration in an automobile). In addition, its low cost, reliability and highly recyclable character make it a good option as peak power source, despite its heavy weight [19].

Figure 2 shows the FC stack output against the electric loads when hybridised with these batteries at different SoC from 20 to

Table 1. *Bench test components and specifications.*

Equipment	Specifications
FCs Stack	3 kW PEM, Self-humidified, rated performance 43.2V@70A, low voltage protection is 36 V and over current protection is 90A
Load	3 × 1 kW Electric Loads
Batteries	4 × 12 V 22Ah Sealed Lead Acid batteries 16 × 3.4 V 180Ah LPBs with BMS 15 × 3.4 V 180Ah LPBs with BMS
H2 Supply	99.999% purity H2 at 0.55 Bar

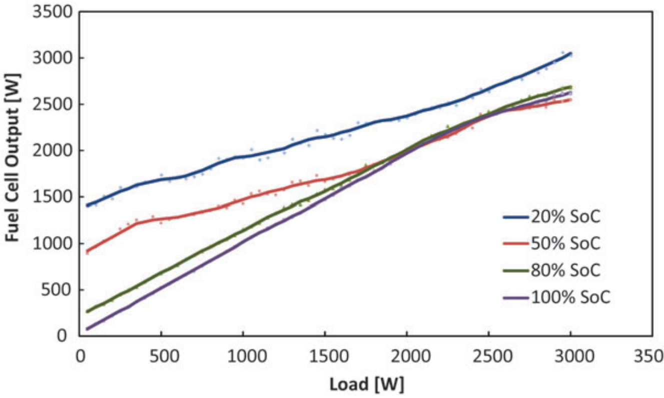

Figure 2. *FC stack output against electric load when hybrid with 4 × 12 V lead acid batteries.*

100%. (The PbA battery SoCs were estimated by measuring the cell voltage after the batteries had cooled down, therefore an error range is ± 5 V or ± 10% may exist.) It can be seen that different SoC of batteries share a similar trend; the FC stack output gradually increases along with the electric load increase, at the same time, the FC stack charged the lower SoC batteries more rapidly than higher SoC batteries.

For instance, when the battery's SoC at 20%, the FC stack charged the batteries up to a rate of 25.88 A at the beginning of the experiment, then steadily decreased as the electric load increased, to ~1 A at the end of the test (see Table 2). In this experiment, no current flowed from the batteries to the electric loads during whole process; the FC stack not only supplied the required power to the electric loads, but also charged the batteries continuously. This was because the battery's voltage was too low to provide any electrons to the electric loads, compared with the FC stack at the same point. As a result, the battery pack had been charged 164.8 W by the FC stack during the 15 min experiments and the SoC increased by 16%.

When battery's SoC is 100%, the FC stack provides power to the electric loads by itself until the load is >1300 W, then the battery pack starts to provide a small amount of power to assist the FC stack, see Figure 3. This is not because the FC stack cannot supply the extra power, but because the battery's voltage is now higher and be able to share some of the load; the batteries shared 370 W out of 3000 W when approaching the end of this experiment. Consequently, the battery pack reduced 9.8 W h of energy and its SoC decreased by 1%. The FC stack output was lower in this test and therefore the temperature change was relatively small too.

Not surprisingly, most results from 50 and 80%SoC are between low 20%SoC and high 100%SoC discussed above; they had both been charged by FC stack at the beginning while the electric load was small, and both assisted the FC stack when the electric load was high.

3.2 Hybrid with 16 × 3.4 V LPBs

Lithium-ion batteries are the fastest growing and most promising batteries for automobiles [20]. Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest energy density by weight. There are many types of lithium-based batteries with different cathode materials, such as lithium cobalt oxide, lithium manganese oxide, lithium nickel oxide and lithium-ion phosphate. It is believed that the LPB is the best option for automobile application owing to its high safety factor. In addition, it does not include noble elements such as cobalt, hence the price of raw materials is lower and both phosphorus and iron are abundant on earth which lowers raw material availability issues. Nevertheless, this battery's cathode is heavier and its capacity is ~25% less than that of other lithium batteries per unit weight [21, 22]. However, for automobiles, the top priority is safety rather than capacity. The LPB cells used in this experiment have a nominal voltage of 3.4 V per cell and 180 A h capacity, and with 16 cells the LPB pack could supply >9 kW h energy at 54.4 V. This capacity is much higher than that of the PbA batteries, which were capable of producing high power for longer periods of time.

With the BMS, this LPB pack can be tested at any precise SoC: for comparison purpose, 5, 20, 50, 80 and 100% SoC have been tested. At the beginning of the testing for low SoC, it was observed that the voltage potential between the FC stack and LPB pack is large enough to make the FC output its >3 kW power and charge the batteries at the rate of 62.5A. Although the LPB could take such a high current, heat would build up quickly and the battery's life would be affected, and with such high demand from the FC stack, its temperature increased dramatically at the beginning of the test; hence this circumstance should avoided if possible. While approaching the end of this low SoC test, unlike the PbA batteries, the LPB could assist FCs stack to provide a small amount of power to electric loads.

When testing the higher SoC, from 20 to 80%, it can be seen from Figure 4 that the LPB have a similar charge/discharge character, with the FCs stack constantly running at the range of 1500 to 2500 W, which is within its high efficiency range. In all cases, the batteries provide a reasonable amount of power to electric loads when the requirement is above 2.1 kW. After the tests, the batteries SoC increased moderately by up to 1.7%.

A fully charged battery was also has been tested; from Table 3 it can be observed that the FCs stack still charges the LPB in the beginning, but at a much lower rate of 13.65A. This is because the FCs stack has a high voltage of 64 V when the electric load was small. Once the electric load was >0.85 kW, the batteries assist the FCs stack to provide power to electric loads. As a

Table 2. *Results from FC stack hybrid with 4 × 12 V PbA batteries at 20, 50, 80 and 100% SoC.*

Batteries SoC	20%	50%	80%	100%
FC maximum charge (+)/discharge (−) rate	+25.88 A	+16.64 A	+3.43 A	+0.5 A
Battery minimum charge (+)/discharge (−) rate	+1.02 A	−8.16 A	−6.06 A	−9.8 A
Charge/discharge turning point	N/A	Load to 2100 W	Load to 1800 W	Load to 1350 W
Change of capacity	+164.8 W h	+64 W h	+13.6 W h	−9.8 W h
Change of SoC	+16%	+6%	+1%	−1%
Change of voltage[a]	54–48 V	55–49 V	61–50 V	64–50 V
FC Temperature	24°C–42°C	22°C–39°C	22°C–38°C	21°C–36°C

[a] True voltage under load condition, not open-circuit voltage, data from electric load display.

result, the SoC decreased 0.2% after the test. By estimation, in a real-life vehicle, the power required is normally >0.85 kW most of the time; hence the SoC should further decrease.

3.3 Hybrid with 15 × 3.4 V LPBs

After testing the 16 × 3.4 V LPB pack, one battery cell was removed and the nominal voltage lowered to 51 V. From the previous test, it was proved that lower SoC, such as 5%, should be avoided due to the high current at the beginning. By removing one cell, the voltage difference further increased, causing higher current flow at the beginning. The 5% SoC test was therefore not conducted in this experiment, as well as 100% SoC to avoid LBP over charging. Again from the previous test, it was shown that even when the battery pack was full, the FC stack still charged the LBP at the beginning.

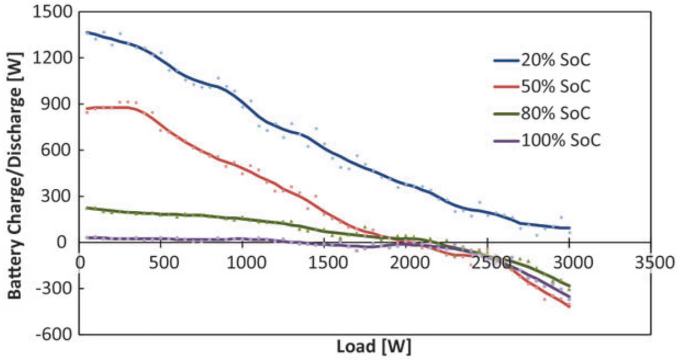

Figure 3. *Change of battery power distribution against electric load with 4 × 12 V lead acid batteries.*

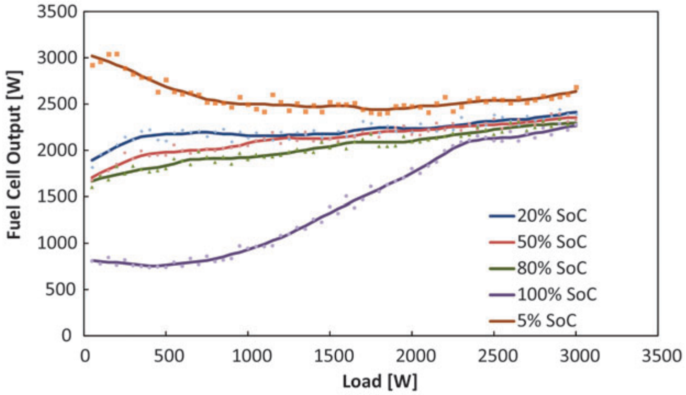

Figure 4. *FCs stack output against electric load when hybrid with 16 × 3.4 V Li-Ion batteries.*

For these reasons, only 20, 50 and 80% SoC have been tested, yet the results were not satisfactory. This was because for all three cases, the FC stack not only charged the batteries at high current at the beginning, but also over its rated output for most of the time, see Figure 5. Furthermore, the batteries were charged from start to end, and were not able to assist the FC stack throughout the whole process. The worst case was at 20% SoC; the FC stack operated over its rated power at all times, and the stack's internal temperature reached its highest point across all tests of 49°C, see Table 4. This would reduce the efficiency as well as shorten the stack life span. However, Table 4 shows that 443.7 W h of energy was transferred to the batteries in 15 min when battery SoC at 20%, the maximum charging rate around 0.3°C which would not give any impact to battery.

4 DISCUSSION

From the test results of hybrid FCs with PbA batteries and different LPBs, it is clear that the absence of a DC–DC converter in this hybridisation is not a problem. However, the type, voltage and capacity of the batteries have to be carefully selected for a defined FC stack. As most commercial PbA batteries are either 12 or 24 V, the flexibility is narrower than for LPBs with 3.4 V. For example, developing a PbA battery with nominal voltage of 54.4 V (with ∼26 individual cells), the curve shown in Figure 2 would be more constant like that of the LPBs. In other words, the voltage of the batteries and their ability to keep on this voltage would directly determine the FC stack output.

Comparing the FC stack output when hybridised with 15 and 16 LPBs at 20, 50 and 80% SoC (Figures 4 and 5), it can be seen

Table 3. *Results from FC stack hybrid with 16 × 3.4 V LPB at 5, 20, 50, 80 and 100% SoC.*

Batteries SoC	5%	20%	50%	80%	100%
FCs maximum charge (+)/discharge (−) rate	+62.6 A	+36.68 A	+31.97 A	+30.25 A	+13.65 A
Battery minimum charge (+)/discharge (−) rate	−5.85 A	−11.28 A	−11.81 A	−13.15 A	−13.18 A
Charge/discharge turning point	Load to 2600 W	Load to 2250 W	Load to 2300 W	Load to 2150 W	Load to 850 W
Change of capacity	270 W h	+117.2 W h	+155.7 W h	+131 W h	−22.2 W h
Change of SoC	+3%	+1.3%	+1.7%	+1.5%	−0.2%
Change of voltage[a]	46–48 V	51–50 V	53–52 V	53–52 V	64–50 V
FC temperature	34 −39°C	26–39°C	24–37°C	24–37°C	19–36°C

[a] True voltage under load condition, not open-circuit voltage, data from electric load display.

that the curves give a similar trend but in a different range. These LPBs have a stable performance from 20 to 80% SoC when hybridised with this 3 kW PEMFC stack. In terms of the FC efficiency and lifespan, the 16-cell pack is superior to the 15-cell pack, because with 16 cells, the FC output power is maximised at 2.5 kW, irrespective of the SoC.

It is proved that 16× LPB pack is the best possible solution; this is shown by Figure 4 and Table 3. Except in the low SoC condition <20%, the FC stacks and batteries work perfectly at all others times. It can be speculated that the battery's SoC may hardly ever be <20% in real life conditions. Because in the low battery SoC situation, the FC stack would provide most of the power before the batteries when the power need is >2.6 kW, while when the power need is low, the FCs would replenish the battery at a slower rate than the bench test. Of course, it would be recommended that the batteries are always kept at a higher SoC.

To summarise, this 3 kW FC stack is likely achieve the best efficiency and a longer life span if hybridised with 16× LPBs.

4.1 Limitations

- The PbA battery SoCs were estimated by measuring the cell voltage after the batteries had cooled down; therefore, the error range is ±5 V or ±10%.

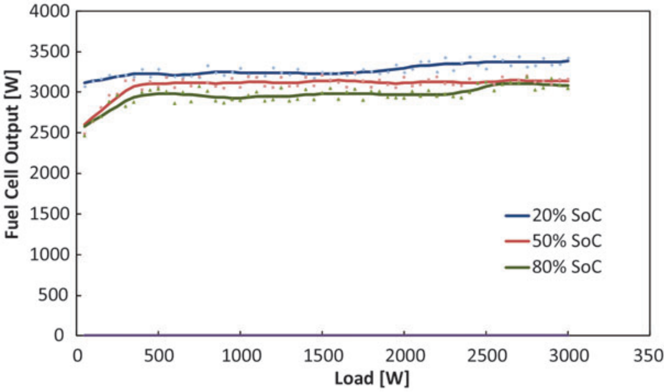

Figure 5. *FC stack output against electric load when hybrid with 15 × 3.4 V Li-Ion batteries.*

- The experiment only demonstrated that the FC and batteries could hybridise without a DC–DC converter to reduce energy losses. The power needed in a real vehicle is more complex than this simulation; hence the behaviour of the FC and batteries may different.
- The effects on the life cycle in both the batteries and the FC were not investigated.
- This study is limited to a DC power train only, a DC–AC converter will be needed for an AC drive.
- The number of batteries can affect the performance and thus the durability of the components. Further investigation is needed into the component-level design. This system will be trialled on a hydrogen FC hybrid vehicle.

5 CONCLUSIONS

Improving the energy flow efficiency of HFCEV is crucial, especially whilst all the elements such as hydrogen, the FC stack and batteries are still very expensive, compared with conventional vehicles. The efficiency of electrical flows within the system is paramount in electric power train design; eliminating components such as the DC–DC converter not only reduces the cost, but also improves the overall efficiency by simplifying the power train. In addition, fewer components mean less can go wrong in term of reliability. However, the absence of this voltage-controlling device not only requires matching the voltages of the FC stack, batteries and electric motors, but also requires the components to work effectively with each other. For example, the batteries need to have a matching nominal voltage, as well as an appropriate charge/discharge curve for the FC discharge curve; then this matching system will work as a whole to supply the power to the motor effectively.

In this study, all the components were commercially available and carefully selected to suit this experiment. There is still room for improvement in terms of suitability, because the components could have been designed specifically for automobile use. Optimising the compatibility of both FCs, battery and motor components could further improve the power train efficiency. To conclude, this simplified approach to an HFCEV without a DC–DC converter is workable, and could lead to further improvements in the future.

Table 4. *Results from FC stack hybrid with 15 × 3.4 V LPB at 20, 50 and 80% SoC.*

Batteries SoC	20%	50%	80%
FC maximum charge (+)/discharge(−) rate	+60.93 A	+55.82 A	+53.36 A
Battery minimum charge (+)/discharge(−) rate	+9A	+4.63 A	+1.55 A
Charge/discharge turning point	N/A	N/A	N/A
Change of capacity	+443.7 W h	+398.2 W h	+367.5 W h
Change of SoC	+5.3%	+4.8%	+4.4%
Change of voltage[a]	50–49 V	51–49 V	51V–50 V
FC temperature	29–49°C	20–46°C	20–45°C

[a] True voltage under load condition, not open-circuit voltage, data from electric load display.

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