Powerpath controller for fuel cell & battery hybridisation

This item was submitted to Loughborough University's Institutional Repository by the/an author.


Additional Information:

- This is an Open Access Article. It is published by Elsevier under the Creative Commons Attribution 4.0 Unported Licence (CC BY). Full details of this licence are available at: http://creativecommons.org/licenses/by/4.0/

Metadata Record: https://dspace.lboro.ac.uk/2134/20481

Version: Published

Publisher: © The Authors. Published by Elsevier

Rights: This work is made available according to the conditions of the Creative Commons Attribution 4.0 International (CC BY 4.0) licence. Full details of this licence are available at: http://creativecommons.org/licenses/by/4.0/

Please cite the published version.
Powerpath controller for fuel cell & battery hybridisation

Simon Howroyd, Rui Chen*
Aeronautical & Automotive Engineering, Loughborough University, LE11 3TU, United Kingdom

Abstract
Proton Exchange Membrane (PEM) fuel cells are a chemically fuelled power supply which generally have a higher energy density than Lithium-Polymer Battery (LIPOs) but a much lower power density. In order for PEM fuel cells to increase the endurance of an in-service battery power supply, without decreasing the peak power, it should be hybridised with a battery. It is key for the market that the overall switch to hybrid technology is low cost in terms of size, weight and money.

Hybrid technology tends to be generically designed to suit any power system, using regulators to ensure voltage matching, and diodes to control the direction of electrical flow. Many electric motors are controlled by speed controllers which can regulate the thrust provided by the motor, accounting for fluctuations in voltage usually found in a depleting battery. Using diode and regulator based hybrids for electric motor applications is therefore inherently inefficient even if complicated synchronous DC–DC converters are used due to the increased cost, size and weight.

This paper demonstrates the ability to use ideal diodes to control the flow of electricity through the hybrid and that voltage regulation is not needed for a motor in this case. Furthermore, this paper explores the natural balancing strategy created by duty cycling the PEM fuel cell to different points within its polarisation curve, removing the requirement for DC–DC converters to match it to the battery voltage. The changes made improve the efficiency of the hybrid power electronics to over 97%.

Copyright © 2016, The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications, LLC. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Introduction
There are many types of fuel cell available, all of which are applicable to this research, however, in this paper we will consider a Proton Exchange Membrane fuel cell, usually abbreviated to ’PEM fuel cell’ [1–3]. This is a power supply that converts hydrogen and oxygen gas into water and electricity. Unlike a battery which has a finite capacity due to its self-contained nature, a PEM fuel cell will keep supplying electricity as long as the fuel is continually supplied. Oxygen is often provided from using air from the surrounding atmosphere and the hydrogen can be supplied from pressurised tanks or a reformer. This also gives the advantage that a PEM fuel cell’s voltage does not change over time as does a battery when it is depleting.

Conversely, every fuel cell’s voltage does vary with load. The three mechanisms for losses in a PEM fuel cell which...
govern the voltage relationship with load are activation, ohmic and mass transport losses [3–6]. The load and voltage relationship is well known as a polarisation curve and is constructed using steady state loads. This does not account for is a pulsed load, such as Pulse Width Modulation (PWM), which creates a duty cycle on the load [7]. Using this technique it is possible to change the perceived load; for example, a 50% duty cycle on a 50 A load may only appear to be a 25 A load if the switching frequency is high enough. This will be important in a hybrid by allowing the partial load on the PEM fuel cell to be controlled, therefore allowing the voltage of the PEM fuel cell to be matched to the battery voltage.

In this paper we will consider a LIPO battery (a Lithium-Ion Battery (LIB) in a flexible polymer case), which is well known to be much smaller, lighter and is able to be cycled considerably more than the other battery types such as lead acid and NiMH [8–10].

In comparison to a PEM fuel cell, a LIPO has considerably higher power density but has a much lower energy density. This lends itself to a hybrid design, as is being used in many applications today [11–21].

The LIPOs being used have a safe operating range of 3.2 to 4.2 V/cell. A 3 cell and 4 cell LIPO will be considered due to their similarity to the operating voltages of the Horizon H100 PEM fuel cell.

Power electronics in hybrids have three main purposes; balancing, protection and regulation. Balancing is required to ensure that both supplies can be connected and is typically achieved using a DC–DC regulator on the PEM fuel cell output, set to match the varying LIPO voltage as it reduces during depletion [22–25]. Protection is required to ensure each of the supplies only power the output and not each other, achieved using solid state diodes, in order to block any back (EMF), downstream capacitor discharge or any situations where once supply becomes higher than the other (usually voltage spikes when supplies are initially connected). Regulation is required to match the output voltage to what is required by the load. Again, a DC–DC regulator may be used [26,27]. A traditional electronic hybrid is shown in Fig. 1a.

Regulator efficiency depends greatly upon the type of regulator being used and the difference between the input and output voltages. For low power devices, linear low-dropout (LDO) regulators provide a simple solution to reduce output voltage however their efficiency reduces greatly the more current is drawn through the device. Higher power systems use more efficient switched mode regulators to either reduce or increase voltage (buck–boost) or reduce only (buck). With regard to switching regulators, the synchronous type remove the inefficient solid state diode found in non-synchronous types and replace it with a Metal Oxide Semiconductor Field Effect Transistor (MOSFET), greatly improving efficiency, but both still require inductors to smooth the pulsed current output found in even the most capable regulators (such as Single-ended primary-inductor converter (SEPIC)). However, all types of switching regulator have complex circuits and are not easily scalable. Inductors also create a secondary issue of electromagnetic interference, which is not desirable in many applications today using wireless communications, including Remote Controlled (RC) aircraft.

![Diagram](Image1)

**Fig. 1** – Hybrid strategies – Fuel cell with battery hybrid powertrain strategies using traditional regulators and diodes.

Due to inherent inefficiencies in both types of regulator they require heatsinks and/or fans to remove the lost energy dissipated from the electronics as heat, which in turn use up energy to power and control, increasing the system losses. In particular, linear regulators are not traditionally suited to high current applications such as RC aircraft which typically require 50 A [23,24,26–29].

Reverse current protection is traditionally handled with simple solid state diodes [24,28,30]. Solid state diodes typically induce a 0.5–1.5 V drop, therefore their efficiency is proportional to the load current using Joules’ First Law. This provides a large source of inefficiency, heat, size and weight for high current applications.

Ideal diodes have been proposed before [31,32] and are being used in a few low power devices such as mobile phones, however are yet to progress into high power applications outside of active AC–DC rectification [33,34]. The knowledge from switching regulators can be used to control the flow of current more efficiently than semiconductor diodes by using transistor switches. It is well known that current will only flow from a high potential to a low potential, therefore we can use this principle along with a highly efficient Power MOSFET to switch a supply on or off depending on the voltage gradient between the input and output. In this case, if the output has a higher potential than the input, the switch will be off, and vice versa, but without the pronounced voltage drop experienced with a semiconductor diode.

The ideal diode MOSFET is controlled by a comparator and amplifier embedded within an integrated circuit such that it’s
operation is completely autonomous with no user intervention. Moreover, multiple MOSFETs may be used in parallel to either increase efficiency or peak power capability, making the ideal diode system easily scalable. Using the discussed principles it may be possible to hybridise a PEM fuel cell with a battery without the need to force voltages to balance using a regulator, this will be defined as natural balancing.

There are three common hybrid strategies which can be used for linking two electrical power sources to a motor; series, parallel and combined. These strategies have been discussed at length in the following papers, with a summary provided below; [12,35–37].

The parallel hybrid shown previously in Fig. 1a is simple and will provide power if either supply fails, and may have a peak power of the sum of the individual supplies. If using a mechanical linkage it requires a complex gearbox and with an electrical linkage it needs a regulator and diodes which, as discussed, can be a large source of electrical inefficiency. It also does not allow for recharging of the battery this system may be more suited to lead acid batteries which are less sensitive to varying input currents where the diodes can be removed to allow charging (e.g. between a car alternator and battery), with the disadvantage being a much lower power density battery as previously discussed.

A series hybrid (Fig. 1b) uses a battery as the direct power source to the motor, and the secondary supply as generator to recharge the battery. A series hybrid has mechanical simplicity but at the expense of added electrical complexity with battery charging circuitry. Battery chargers are also relatively low current devices due to the limitations of how quickly the chemistry within the battery will safely accept charge, meaning that the nominal load must be below the peak charge current for maximum endurance. Peak power is the sum of the battery output and the charger output, therefore may be much less than that of a parallel hybrid.

Finally, a combined hybrid (Fig. 1c) includes the complexities of both strategies by implementing allowing the secondary supply to power the load and recharge the battery simultaneously, providing greater system flexibility. The added electrical complexities traditionally introduce inefficiencies with the power regulation and reverse flow protection, however the peak power is the combined output of the two supplies as in the parallel case.

When exploring system optimisation, if one supply is a high energy density PEM fuel cell and the other a high power density LIPO, it is found that different strategies are needed for different load cases. In a high load situation it would make sense to have a parallel hybrid to allow for power sharing and therefore an overall increase in peak power compared to having a series hybrid. However, in a low load situation, a series hybrid may be more favourable to allow battery recharge or a complete passthrough from the fuel cell to the load if the battery is charged. In many applications, the design power of the system will be above that of the charger capability, so a combined hybrid solves the excess overhead issue as previously mentioned, to ensure the system can still be optimised for endurance.

Using regulators does not exploit the PEM fuel cell ability to operate in a wide voltage window. By duty cycling the load experienced by the PEM fuel cell is might be possible to naturally balance the voltage to the battery without forcing it with a regulator, improving the system output by reducing circuit complexity and the inefficiencies that go with it. Furthermore, using Power MOSFET switches in a dual ideal diode setup would greatly improve system efficiency and voltage output by removing the traditional diodes from the circuitry.

The aim is to develop and demonstrate an efficient, naturally balanced fuel cell hybrid powertrain. The objectives are to:

1. Develop a model to test the theory of natural balancing.
2. Test the electronic hardware to prove the plausibility of natural balancing.
3. Demonstrate a naturally balancing PEM fuel cell battery hybrid.

Theory of natural balancing

Using a dual ideal diode the possibility to link two power supplies together safely without losses is achieved efficiently. However, without forced regulation there is no guarantee that both power sources can have an opportunity to power the output. Careful specification and understanding of the power sources is therefore more important in a naturally balancing hybrid.

Fig. 2 shows the usable region of the Horizon H100 PEM fuel cell polarisation curve for this paper. This has been obtained from test data and has had a best fit line equated to it, the equation of which will form the model explained in Section Modelling. Overlaid on this curve are the typical LIPO voltages which show the potential naturally balanced regions of the hybrid for a 3 cell or 4 cell battery. It can be seen that with a 3 cell LIPO the naturally balanced region allows a PEM fuel cell partial load of 3.75 to 5.25 A (depending on the battery state of

Fig. 2 — Hybrid natural balancing regions — Horizon H100 PEM fuel cell partial load ranges for different LIPO battery cell counts.
charge). However, with a 4 cell LIPO this partial load is reduced to 1.6–3.75 A, but at a higher voltage.

Analysing the two LIPO cell counts on Fig. 2, it can be seen that if a 4 cell LIPO is used the range at which the two supplies may balance is across the majority of the operational range of the PEM fuel cell from 12.8 to 16.8 V. With a 3 cell this is confined to the high current end of the polarisation curve (corresponding to peak power) from 9.6 to 12.6 V. In this paper a 3 cell was chosen in order to allow the PEM fuel cell to operate at its peak power whilst the battery is still at around 50% charge, whereas if a 4 cell was used the battery would be almost flat before peak power is achieved. It is important to note that going below the “flat” voltage of a LIPO, by dropping into a current region below 3.2 V/cell, would cause irreversible damage to the battery so is not considered here.

**Dynamics**

The powerpath controller, shown at the centre of Fig. 3, has been analysed from an electrical flow perspective to understand the operation of the system as a parallel hybrid. In order for either of the supplies to safely power the load, it must have a higher voltage than the other supply (or the output). Therefore there are three potential outcomes; FC only, battery only or both. Both transistor switches “on” can only occur if the two supply voltages are equal, i.e. balanced, otherwise reverse flow would occur from one supply into the other. It is this logic that provides the diode functionality of the system by preventing a reverse voltage which would result in a reverse current flow.

Analysing the expected dynamics of the system under normal operation gives the following. We are assuming that the current capacity of the PEM fuel cell is exactly 10 A for simplicity.

When under no load, the PEM fuel cell voltage will be highest at just over 20 V, and the battery will be fully charged at 12.6 V. Therefore the PEM fuel cell transistor switch will be turned on, and the battery transistor switch will be off. If a load is applied to the PEM fuel cell, it will initially supply the current for a very short time due to its internal capacitance, however its voltage will quickly collapse below 12.6 V, at which point in time the switching will be reversed. At this point the battery will be under the large load and the PEM fuel cell under zero load. LIPOs have a very stable voltage under load so the voltage will hold with little reduction and the full load will be delivered to the motor electronics. A short time after this the PEM fuel cell voltage will recover to within 100 mV of the battery voltage, which will be slowly decreasing in proportion to the state of charge of the battery. Therefore the logic will change to the balanced state with both transistor switches on. At this point the PEM fuel cell will be part loaded, in share with the battery, causing its voltage to drop and the PEM fuel cell transistor switch to turn off. Now not under load, the voltage will recover and switch back to the balanced state and so on.

This load and recovery cycling will create a duty cycle for each power supply. In this case the LIPO has a 100% duty cycle meaning it is connected to the output all of the time. The PEM fuel cell, however, may have a 50% duty cycle due to it recovering and then being in the balanced state for an equal amount of time. This will mean that the PEM fuel cell voltage measured will be at some point between the open circuit and loaded voltage as defined by the polarisation curve, assuming steady state. The higher the load, the faster the PEM fuel cell discharges when switched on, however recovery takes the same amount of time as driven by the PEM fuel cell chemistry, this therefore reduces the duty cycle. Conversely, if the load is low the PEM fuel cell voltage will be high and sustained thus creating a 100% duty cycle.

The duty cycle will determine the load sharing ratio between the two supplies and allow the PEM fuel cell to contribute to the output power even when the output is above the capability of the PEM fuel cell. The voltage of the battery corresponds to the balancing voltage of the system, which has been plotted on the polarisation curve in Fig. 2 to determine the peak current deliverable by the PEM fuel cell in that state. Regulation of the PEM fuel cell voltage is not achieved, however, so the output of the system must be capable of handling up to the open circuit voltage of the PEM fuel cell but this will only ever be for very low load situations at low power. Typically brushless motors used in RC aircraft can handle a wide voltage range, e.g. 9.6 to 25.2 V allowing for anything from a 3 cell to 6 cell LIPO to be used.

**Efficiency**

Power MOSFETs have a typical “on resistance” of 2 mΩ which gives a theoretical transmission efficiency of 99.83% for the PEM fuel cell power path and 98.33% for the battery power path when under a maximum source load of 10 A and 100 A respectively (calculated using typical datasheets). This is clearly a vast improvement on the efficiency experienced when using any type of DC–DC regulator, so, it is worth investigating further. Moreover, DC–DC converters in the order of 100 A are not easily available and very expensive. It is also important to note that this requires no protection diodes, due to the switch severing the connection between a high and low voltage supply, which would typically incur an additional 5 to 15% loss plus any demand from cooling fans and a cruise power increase due to the weight of the heatsinks.

---

**Fig. 3** — Dual ideal diode – Simplified parallel hybrid schematic using a dual ideal diode powerpath controller and two transistor switches.
Modelling

System description

Models of the power supplies and electronics have been created in SIMULINK to explore the dynamic behaviour of a powerpath controller when the sources are a PEM fuel cell and a LIPO battery. The schematic for which can be seen in Fig. 4.

Fuel cell

To determine the output of the PEM fuel cell the steady state voltage needs to be calculated from the imposed load. This is calculated using an approximation of the PEM fuel cell polarisation curve which has been derived from the equation of the best fit line for Fig. 2. Using this approximation we have the steady state voltage at any given load is the following:

$$V_{fc(t)} = a_3 \cdot I_{req}^3 + a_2 \cdot I_{req}^2 + a_1 \cdot I_{req} + a_0$$

(1)

Where:

- $V_{fc(t)}$ is the steady state fuel cell voltage now
- $I_{req}$ is the current load demand/output
- $a_0 = 19.3358$
- $a_1 = -1.3112$
- $a_2 = -0.2169$
- $a_3 = 0.0223$

The voltage is then filtered to simulate the slow dynamic nature of a PEM fuel cell. The filter only applies when the voltage is increasing, i.e. recovering, as observed from lab tests:

$$V_{fc} = V_{fc(t-1)} + k \cdot (V_{fc(t)} - V_{fc(t-1)})$$

(2)

Where:

- $k = 0.1$, is the filter gain (based upon experimental data)
- $V_{fc(t-1)}$ is the fuel cell voltage at the last timestep
- $V_{fc}$ is the fuel cell voltage output from the model

At this point, if the calculated voltage is below that of the battery, then the battery voltage is used to back calculate the current that would be output by the PEM fuel cell. This simulates the binding phenomena of the PEM fuel cell to the battery voltage when in a loadsharing mode.

Battery

It has been assumed that the capacity of a LIPO is linearly proportional to voltage which ignores the steep dropoff in the first and last 0.2 V of the LIPO range. The difference between steady state output and dynamic output of a LIPO are negligible in comparison with a PEM fuel cell and therefore no low pass filters are required. The equations for voltage and current output of the LIPO are given as the following:

$$V_{batt} = V_{batt(t-1)} - \frac{I_{req} \cdot \Delta t}{C}$$

(3)

Where:

- $V_{batt}$ is the battery voltage output from the model
- $V_{batt(t-1)}$ is the battery voltage at the last timestep
- $\Delta t$ is time since the last step (hours)
- $C$ is the battery capacity (Amp hours)

Power electronics

Since the controller operates on two transistor switches, binary logic is used. This can be replicated in simulation to create the system as previously explained in Section Theory of natural balancing.

Simulation results

To test the theory and the model, a triangular ramp test has been used to understand how the hybrid reacts in the two major modes of operation; PEM fuel cell only and naturally balanced. The former mode will have a wide voltage range and should follow the polarisation curve of the PEM fuel cell and there should be no contribution from the battery. The latter mode should be at the voltage of the battery and the PEM fuel cell voltage should balance at this voltage. Increasing the load in the naturally balanced mode will alter the duty cycle and therefore the load sharing ratio between the two power supplies. The PEM fuel cell output should be constant with the battery filling in the remaining partial load.

The simulation results of the natural balancing hybrid strategy are shown in Fig. 5. Firstly it can be seen that for low loads, the only contributor to the output is the PEM fuel cell and it follows the polarisation curve as the load increases and most importantly, the battery current is not negative, showing the ideal diode setup works. Once the two voltages balance the partial load provided by the PEM fuel cell remains constant and the partial load from the battery increases in proportion to the demand. When the demand reduces, the opposite occurs, and at the point where the PEM fuel cell voltage raises above that of the battery, the battery output it reduced to zero.

As explained in the maths, the battery is modelled to show it's depletion and can be seen by the natural balance voltage reducing with respect to the batteries discharge curve, in this test we are starting with a charged 3 cell LIPO. Since the reduction in balancing voltage alters the position on the PEM fuel cell's polarisation curve we actually get an increase in the partial load supplied by the PEM fuel cell as we move towards...
its peak power. Clearly, a battery with a higher capacity would deplete slower and delay this shift towards peak power.

**Summary**

Simulation results have shown that the dual ideal diode powerpath controller setup with a PEM fuel cell and battery allows both power supplies to be on at the same time, but only when there is a positive potential difference between the source and the output, ensuring that there is no reverse current flow which might damage the power supplies. This occurs in load situations above the battery voltage shown on Fig. 2. When the load is below the respective battery voltage then the PEM fuel cell is the only supply connected to the output and the LIPO goes unused.

As the battery depletes, the balance voltage reduces and so the potential PEM fuel cell contribution naturally increases as the balance point moves to the right on Fig. 2. At no time is a DC–DC regulator or traditional diode required.

**Experimental testing**

**System description**

**Fuel cell**

The PEM fuel cell being used is the Horizon H100, a 100 W hydrogen fuel cell. The hydrogen is fed at 0.5 bar(g) and the air is atmospheric as per the datasheet [38]. The stock controller has been removed and a new custom one fitted; however, for this paper it is set to mimic the purging strategy used by the stock controller (0.5 s purge every 30 s). The controller is powered by the hybrid output, rather than a separate battery, so the system is fully closed and not dependent on any external mains supply thus capable of long endurance running. This extra load, in parallel with the output load, is variable and up to 10 W dependant upon processor load at any given time.

The controller is also the datalogger and user interface for the whole system. It is responsible for safely controlling the PEM fuel cell, recording results and sending the instantaneous load requirements to the digital loadbank via TCP (or motor controller via PWM) at each timestep.

**Battery**

The battery being used is a Hyperion G3, 3 cell, 3300 mAh, 35C LIPO. This has a potential difference range as previously discussed of 9.6 to 12.6 V, is well worn in and fully charged and balanced to 4.2 V/cell.

**Power electronics**

The power electronics have been custom designed and incorporate Power MOSFETs as the main switches and the Linear Technologies LTC 4416 dual ideal diode controller as the powerpath controller. The battery powerpath only requires a single MOSFET, however the PEM fuel cell powerpath has two in series in opposite polarisations to overcome the body effect of the semiconductor. The only practical difference here is that the resistance of that powerpath will be double that of the other, leading to a slightly lower overall efficiency. The power electronics have shunt resistors on the two supplies in order to measure current through a 16-bit analogue-to-digital converter (ADC). The sensor readings are taken and saved in the datalogger which is a Raspberry Pi computer.

**Load**

A digital loadbank is being used to realise the demand from the system which is sent from the user interface on the Raspberry Pi computer to the loadbank over the University network. It is configured to demand a given current rather than power to mimic three-phase brushless motor controllers used in hobbyist remote control applications. It has also been used to help calibrate and verify the ADCs measurements.

**Test results**

Three tests have been designed in order to fully verify the dynamics of the system proposed in Sections Theory of natural balancing and Modelling.

1. The first test explores the high speed switching behaviour using a bench Power Supply Unit (PSU) on one powerpath and a LIPO on the other. This will help verify that the hybrid can operate along either powerpath independently, or with both on simultaneously, whilst ensuring no reverse flow, thus still acting as a diode.

2. Test two endeavours to prove that the system does naturally balance if the two supply voltages are the same. This is achieved by using two LIPO batteries at the same state of charge, therefore the same voltage, connected one after the other.

3. The final test integrates the PEM fuel cell into the system, with it’s previously discussed voltage dynamics, and a 3 cell LIPO battery. This test will show that the hybrid works as expected from the basic model developed in Section Modelling.
Test 1 – ideal diode switching results
In order to protect both power supplies, the controller must ensure that the potential difference from the supply to the output is always positive when the respective transistor switch is on, otherwise it must be off to protect against reverse current flow. Using a stable voltage from a LIPO and an adjustable voltage from a bench PSU, Fig. 6 shows the switching logic of the powerpath controller as the voltage output to the gates of the MOSFET switches. The MOSFETs being used are p-channel so as the gate-ground voltage reduces, the gate-source voltage becomes negative and the switch turns on.

Initially the LIPO is a higher voltage than the PSU and as such the battery transistor switch gate is ’low’ (therefore on), and the PSU gate the opposite, proving that the negative voltage across the PSU transistor switch caused the controller to turn it off to provide reverse current protection. As the PSU voltage is increased there is a point at which the system is balanced before the PSU holds a higher voltage and the switching logic is completely flipped compared to the start to protect the LIPO. After a brief pause, the PSU voltage is ramped down and following a slightly longer balanced period (due to output capacitance in the PSU) and the logic is switched again in favour of the LIPO taking up the full load and the PSU being protected.

Test 2 – balancing results
Test two explored the balanced mode of the hybrid, shown in Fig. 6 when both switches are on together at 60 to 120 μs and 295 to 380 μs. Using two batteries at the same state of charge (therefore same voltage), with just battery 1 connected, it can be seen that battery 1 transistor switch gate is biased on, and battery 2 transistor switch gate is off. After 15 ms battery 2 is connected and Fig. 7 shows it takes the full load as battery 1 transistor switch gate is immediately switched off. This is due to the output load (2 A) causing battery 1 voltage to be slightly reduced, whereas, at the initial point of connection battery 2 is under no load so holds a higher voltage. Once the internal capacitance effect of battery 2 is depleted at 21 ms, battery 1 is switched back on as they are now within 100 mV of each other as defined in Section Theory of natural balancing.

Test 3 – hybrid test results
Using the Horizon H100 PEM fuel cell and Hyperion 3 cell LIPO, Fig. 8 shows the results of running a triangular ramp test as previously done in simulation in Section Modelling and depicted by Fig. 5. Of particular interest is that the battery did not discharge as much as expected but a slight voltage dip can be seen when the LIPO is loaded, an effect which was ignored in the battery model approximation.
Initially, as the load is applied, the PEM fuel cell takes up the load and its voltage reduces in line with its polarisation curve. At the point the battery is not contributing at all. When the load increases to a point at which the PEM fuel cell voltage matches that of the LIPO, the load sharing situation begins as the system is now naturally balanced as explained in Section Theory of natural balancing without any forced voltage regulation (e.g. DC–DC converter). As the load continues to increase, the load sharing ratio increases in favour of the LIPO however the PEM fuel cell output remains constant, as does its voltage.

As the load is reduced, the reverse happens where the PEM fuel cell unlashes itself from the LIPO voltage and takes full control of the load with respect to it’s polarisation curve. All voltages and loads in the test would typically be accepted by a brushless motor and speed controller combination as discussed in Section Theory of natural balancing.

The peak power experienced by the Horizon H100 72 W (plus the ~10 W overhead to power the datalogger and controller which is not accounted for on this graph). It is important to note that the deficit from peak power (100 W) of ~18 W is not due to losses, it just isn’t generated due to the balancing voltage with respect to the polarisation curve in Fig. 2, thus the fuel is not wasted. Also, it is interesting to note that a PEM fuel cell under part load may be more efficient than when it is at peak power in terms of chemical efficiency [39].

Efficiency

By measuring the voltage drop from input to output of the two power paths at different loads, the efficiency of the system can be determined. Results for this are shown in Table 1. The main sources of inefficiency in the hardware are the Power MOSFET switches, the shunt resistors and the PCB tracks. In principle, these inefficiencies will increase with load due to the internal resistance of the components, which will cause these components to become warm. This limits the maximum load for the PEM fuel cell powerpath to 10 A and the LIPO powerpath to 100 A for this particular hardware design. Temperature impacts the internal resistance of the components and for this test no forced or passive cooling was applied, it was only just warm to the touch. Notably, to increase the power capabilities of this hardware only thicker copper PCB tracks, more MOSFETs in parallel and higher power rating shunt resistors would be required. All these modifications would serve to either preserve efficiency or may even improve it, meaning the hardware is easily scalable to larger power applications unlike traditional regulator and diode hybrids.

Summary

Test results show that the powerpath controller with dual ideal diode acts as an efficient parallel hybrid. In particular, the theory of natural balancing between a PEM fuel cell and a battery has been proven and shows that traditional diodes and regulators are not required. This allows for a highly efficient hybrid using only MOSFET switches as the link between input and output, resulting in reduced losses, size, heat generation and weight. It is also known that the system is scalable with no reduction of efficiency due to simple electronics knowledge of MOSFETs in parallel.

Conclusion

Developed a new hybrid strategy

In this paper we identified that using regulators to hybridise a PEM fuel cell with a battery does not exploit the natural ability of a motor and PEM fuel cell to operate over a wide voltage range. Moreover, the use of solid state diodes to protect one supply from being powered by the other results in not only power losses; but an increase in mass, size and temperature of the power electronics.

When at loads that would cause the (PEMFC) to have a voltage below the battery, the PEM fuel cell latches to the battery voltage and the battery supplies the current deficit. The voltage is held high by enforcing a high speed duty cycle on the PEM fuel cell output to match it to the battery voltage. By choosing a battery whose nominal voltage aligns with the peak power voltage of the PEM fuel cell, in this case a 3 cell LIPO at a nominal 11.1 V, the PEM fuel cell can contribute more to the output than a higher voltage battery. The system is compatible with a more powerful 4 cell LIPO at a nominal 14.8 V however the PEM fuel cell contribution will be lower, reducing the overall system endurance. In this case you would also need to increase the cell count of the PEM fuel cell to match the battery and modify the power electronics as previously explained in order to recover the system efficiency but at a higher overall power.

Developed new hybrid electronics hardware

We have realised a new control strategy to switch highly efficient Power MOSFETs using a dual ideal diode powerpath controller in a high current powertrain, with considerably less losses than traditional regulators and the same protection capabilities of solid state diodes. This methodology also exploits the natural ability of the PEM fuel cell to operate at different voltages and the wide operating range of a brushless motor.

The system is also completely self-contained by using power from the output rail to run the PEM fuel cell controller (including fans/valves), datalogger and communications. This makes the system completely off-grid, allowing for use in

<table>
<thead>
<tr>
<th>Load/A</th>
<th>FC powerpath efficiency/%</th>
<th>Battery powerpath efficiency/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>98.92</td>
<td>99.70</td>
</tr>
<tr>
<td>6</td>
<td>98.52</td>
<td>99.89</td>
</tr>
<tr>
<td>10</td>
<td>97.63</td>
<td>99.93</td>
</tr>
<tr>
<td>12</td>
<td>97.16</td>
<td>99.92</td>
</tr>
<tr>
<td>30</td>
<td>n/a</td>
<td>99.72</td>
</tr>
<tr>
<td>50</td>
<td>n/a</td>
<td>99.59</td>
</tr>
</tbody>
</table>
transport applications or anywhere where mains power is not available. Importantly, the results shown in this paper include the full power requirements of the system, so are not invalidated by needing an external power supply for any part.

Acknowledgements

The author would like to thank EPSRC for funding the project through the Doctoral Training Centre in Hydrogen, Fuel Cells and Their Applications (EP/G037116/1), Thomas Coggins for his assistance in designing the printed circuit board and to SMS Electronics Ltd. for manufacturing the circuit board.

REFERENCES


