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Short communication

Electronic integration of fuel cell and battery system in novel hybrid vehicle

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HIGHLIGHTS

- ▶ 8 Microcab H2EV hydrogen-electric hybrid urban vehicles officially launched on 1st July 2011 as part of CABLED project.
- ▶ Use of high temperature PEM Hydrogen Fuel Cell.
- ▶ Use of LiFePO₄ technology as main secondary battery energy store.
- ▶ Integration by SME was by using off-the-shelf components where possible.

GRAPHICAL ABSTRACT



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ABSTRACT

The objective of this work was to integrate a lithium ion battery pack, together with its management system, into a hydrogen fuel cell drive train contained in a lightweight city car. Electronic units were designed to link the drive train components using conventional circuitry. These were built, tested and shown to perform according to the design. These circuits allowed start-up of battery management system, motor controller, fuel cell warm-up and torque monitoring. After assembling the fuel cell and battery in the vehicle, full system tests were performed. Analysis of results from vehicle demonstrations showed operation was satisfactory. The conclusion was that the electronic integration was successful, but the design needed optimisation and fine tuning. Eight vehicles were then fitted with the electronically integrated fuel cell-battery power pack. Trials were then started to test the integration more fully, with a duration of 12 months from 2011 to 2012 in the CABLED project.

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1. Introduction

The CABLED [1–3] project (Coventry and Birmingham Low Emission Demonstrator) started in 2009 to test 100 electric city cars driven by commuters around the Birmingham/Coventry area in the UK. Five different electric cars: Mitsubishi i-MiEV, Tata Indica Vista EV, Smart fortwo electric drive, Landrover Range-e and Microcab

H2EV were made available to a diverse range of local people. Data were collected to answer questions about performance, range, driver behaviour and battery charging infrastructure. As electric vehicles have zero carbon and low noise emissions at the point of use, the local environment should be enhanced significantly by their increased widespread application, leading the way for the reduction of UK total carbon emissions, as defined by the UK government in a number of papers [4]. A number of other manufacturers and research projects have developed prototypes using battery technology as well as a limited number using Hydrogen Fuel Cells (HFC) [5–10].

The only Hydrogen Hybrid vehicle in the project was the Microcab H2EV shown in Fig. 1. This was developed from a 2005

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Fig. 1. One of the 8 new Microcab H2EV.

design of lightweight city car which included an electric drive train, lead acid batteries, a Ballard hydrogen fuel cell and 0.6 kg of hydrogen stored in a composite tank at 350 bar. Four of the previous Microcab design were built in 2008 and tested for 3 years on the University of Birmingham campus [11–15].

The main advantage of the Hydrogen-Electric Hybrid vehicle is that it has the performance of larger and more costly pure fuel cell (FC) or pure battery vehicles but with a much reduced cost and weight advantage. This is because the range is largely derived from the capacity of the hydrogen tank that feeds the FC. The tank can be filled in 5 min, which is comparable to conventional road vehicles, whereas full battery charging of EV vehicles in the project takes 6–8 h [1]. The FC itself only has to deliver the *average power* required for the journey. The battery on the other hand only has to supply the peak demand of the system not the total energy. The peak demand is mainly that required by the motor particularly while accelerating, until the cumulative net output from the FC can catch up by recharging the battery.

Three problems were recognised in the earlier Microcab experiments [11–15]:

- The Ballard fuel cell was too small (1.2 kWe) to satisfy the power requirement of the ECE15 urban drive cycle.
- The Ballard fuel cell was not thermally integrated with the vehicle, so that the windscreen required an electric heater.
- The Ballard fuel cell demanded expensive 99.999% pure gas and was not tolerant of industrial grade hydrogen fuel.

In order to overcome these problems the Serenergy serenus 390 high temperature Polymer Electrolyte Membrane Fuel Cell (PEMFC) was selected for the Microcab H2EV. This supplies a nominal 3.2 kWe, hot air at 150 °C, and is tolerant of only 95% pure hydrogen see Fig. 2. The purpose of this paper is to describe the integration of this new fuel cell into the vehicle drive train, which included a new battery and two new motors.

2. Vehicle propulsion motor system architecture

2.1. General overview of system requirements

The previous vehicles were built as a steel frame with an aluminium floor and Glass Reinforced Plastic (GRP) sides to give a kerb weight of 677 kg [15]. One of these vehicles was built as a Postal delivery van for which the 1.2 kWe Ballard PEM (Proton Exchange

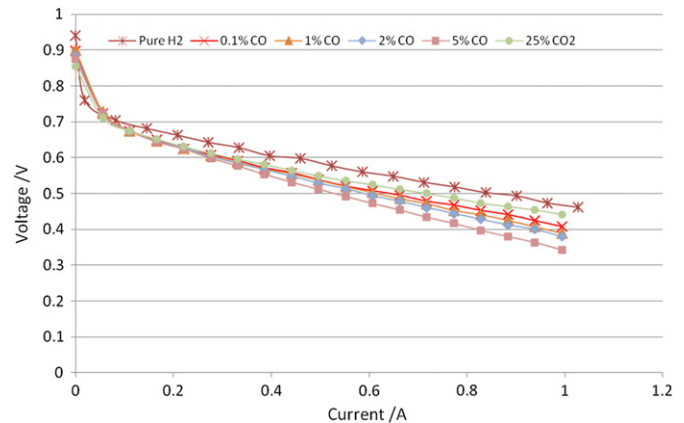


Fig. 2. The polarisation performance curve of a cell in the serenus 390 fuel cell stack (showing data extracted from publicity material received from Serenergy).

Membrane) HFC (Hydrogen Fuel Cell) was sufficient. The postal drive cycle around campus gave a low average power requirement and allowed the low capacity HFC to recharge the battery for each movement. The maximum speed achievable was 30 mph (50 kph). However to achieve ECE15 the stops are shorter and more power is required overall to accelerate to that speed. The Extra Urban Drive cycle (EUDC) for low power vehicles requires a top speed of 56 mph (90 kph), with the sustained duration of this entirely dependent on the output power of the HFC. Allowing for some auxiliary and hotel power use, an HFC of 3–5 kWe was specified in the requirements. Low temperature PEM HFC have quick start capability (seconds) and are mechanically rugged because the ambient temperature of operation introduces very little stress. However a very pure hydrogen supply is demanded to avoid poisoning of the platinum catalyst normally used. Generally available SOFC (Solid Oxide Fuel Cell) technology was not considered due to slow starting and the fragile nature of the cells. High temperature PEM is considered a good middle ground and Serenergy in Denmark were releasing the first production items in time to incorporate their 3.2 kWe unit into the design. The specification of the major components chosen is given in Table 1. In order to achieve a lightweight roadworthy vehicle a GRP and adhesive bonded aluminium chassis was designed for the Microcab H2EV project to meet simulated crash test requirements.

2.2. Fuel cell system

This new HFC has a start up time in the order of 10–30 min with an operating temperature of 80–160 °C. The start temperature (80 °C) is achieved by electrical heaters within the insulated HFC enclosure. The high temperature allows the catalyst to shed carbon deposits that would otherwise poison a PEM HFC. This permits the use of cheaper, lower grade hydrogen available from fossil sources (normally from steam methane reformation) which is more widely available, reducing some of the hurdles for general hydrogen vehicle uptake that exists when requiring high purity hydrogen (more easily available, when required, from an electrolyser source preferably using green electricity). Comparing grid natural gas (methane) prices with electricity prices, particularly green electricity, it is not difficult to appreciate the reason for the higher cost of high purity hydrogen, if it has to be produced from this energy source. The current grid mix, the cost of renewables and fossil fuel shortages may change this ratio in the future. Higher purification may be also possible from fossil fuel sources but costs, and environmental pressures, generally restrict its feasibility, and the types of impurities contained are generally less desirable.

Table 1
Specifications of major components.

	Motor	Motor controller	Fuel cell	Main battery
Manufacturer	Lynch motor Company	P&G drives	Serenergy	LiFeBATT
Website	lemcoltd.com	pgdt.com	serenergy.com	Lifebatt.co.uk
Type	Permanent Magnet DC motor	Sigmadrive	Phosphoric acid based High Temperature PEM Hydrogen Fuel Cell	LiFePO ₄ 'Energy' Cells
Model	D127	PMT835M	Serenus 390 with dedicated DCDCs	X-2E 40166 4*24cell bank
Nominal	12.56 kW 200A	120A	3.2 kWe 140 V 140 °C 23A	15 Ah 3.3 V/cell 60 Ah 79.2 V/bank
(Absolute) Maximum	25.38 kW 400A	350A	200 V (267 V) 175 °C 5%CO in H ₂	10 C discharge to 48 V 3 C charge to 87.6 V 3 mΩ/cell 18 mΩ/bank
Weight	2*11 kg	4.1 kg	22 kg +DCDC converter	96*470 g = 45.12 kg +controller

2.3. Battery system

Lead-acid batteries were used in the previous vehicles due to their low cost, availability, recyclability and ease of use. This led to one of the inefficiencies encountered due to the difference in charging and discharging voltages in order to use the capacity rated by current and time. A typical 24 cell lead-acid battery (48 V nominal) charges at 50–60 V and discharges at 40–52 V; typical energy efficiency stands at 74% with an example optimised system achieving 83% on average [16]. Lithium battery technology however has a much reduced voltage range between charge and discharge and therefore a much improved efficiency. LiFePO₄ technology was chosen because of its performance characteristics, including safety and maturity. Lithium technology has higher energy density than Pb-Acid but has immediate availability compared to ZEBRA batteries from cold [17]. An Open Circuit Voltage (OCV) of 3.2–3.6 V per cell is normal for the LiFePO₄ type used. The charge and discharge voltage closely follow the OCV except at very high currents due to the very low internal impedance of the cells. A higher voltage of 80 V was chosen to further reduce the losses associated with high currents. The main disadvantage is the increased risk of electric shock to maintenance workers; a non-earthed system with automatic (double poled) main contactors was chosen to mitigate the risks.

A LiFeBATT Ltd battery was chosen consisting of 24 'X-2E' 15 Ah cells (giving 76.8–86.4 V) per series set. Four such units are connected in parallel to achieve a bank of 4.8 kWh. Direct control and protection is provided by LiFeBATT's on board control unit. Separate contactors (heavy duty relays) are provided on positive and negative lines (on the provided battery board) out to the vehicle, with limited direct access such that only one contactor is required during charging but both for discharging.

2.4. Motor system

In the previous vehicles the 3HP (2.25 kWe) separately excited GE motor would appear under rated compared to the sustained peak power it was capable of. The rating is a 60 min average due to the thermal mass of the motor. The battery and HFC combination ensured this limit was never met. The separate excitation however meant power always had to be fed to the field winding disproportionately to the armature 'drive' current. It also meant the GE controller could reduce the field current to increase the speed for the same armature voltage. The overall conclusion however was that the motor was under powered and less efficient than was otherwise available.

In order to achieve the acceleration to and sustain at least 50 mph (80 kph) two 12 kWe permanent magnet motors were chosen. The Pancake type Lynch motors are capable of a 25 kWe

peak each however this can only be sustained for 5 s due to the low thermal mass of the motor. Each motor output is connected via a toothed belt and pulley system as a fixed step down ratio to its front wheel. Moving the driving wheels to the front was primarily due to the available space.

2.5. Fuel storage system

The HFC and tank would therefore sit in the normal tank and 'spare wheel' space keeping all the hydrogen gas components together. The hydrogen tank was of the same type used in previous Microcab vehicles, but larger with capacity of 1.8 kg to give a predicted range of 190 miles (300 km), manufactured by Dynetek, with a nominal storage pressure of 350 bar.

2.6. System operation

Due to uncertainties in the design process associated with the new fuel cell, it was decided at an early stage that the vehicle must be capable of running as an electric vehicle (EV) without requiring the operation of FC components including the Vehicle Control Unit (VCU) required to operate it; this required capability of normal operation with the split as shown in Fig. 3. The 'I/O interface' therefore required a maintenance feature that would facilitate the switching between modes.

The 4.8 kWh of battery was considered both to be sufficient to get started on a journey during FC warm-up, and to have sufficient energy to allow short non-FC journeys or 'get me home' limp mode should a problem arise with the FC. The battery, when fully charged was calculated to allow up to about 15 miles (24 km) use in ideal conditions; 13 miles (21 km) was experienced in practice though this would be limited by any battery imbalance. The FC was calculated to be able to support both average continuous urban use, and allow some support for hotel functions such as cabin heating in winter; both of these were considered lacking in the previous vehicles, requiring frequent rest periods etc. Thermal management and possible use of the heat from the HFC to directly heat the cabin will be described in a later report.

3. Electrical system integration design

Bespoke electrical interface systems were designed in house in order to electrically integrate the fuel cell, battery, and motor systems in order to satisfy the requirements of the overall design, referring to the information supplied with each of the main components. The resulting interface system was constructed using standard automotive relays mounted on a custom Printed Circuit Board (PCB). The PCB incorporated jumpers to allow programming of the function of each of 5 relays, with an LED (Light Emitting

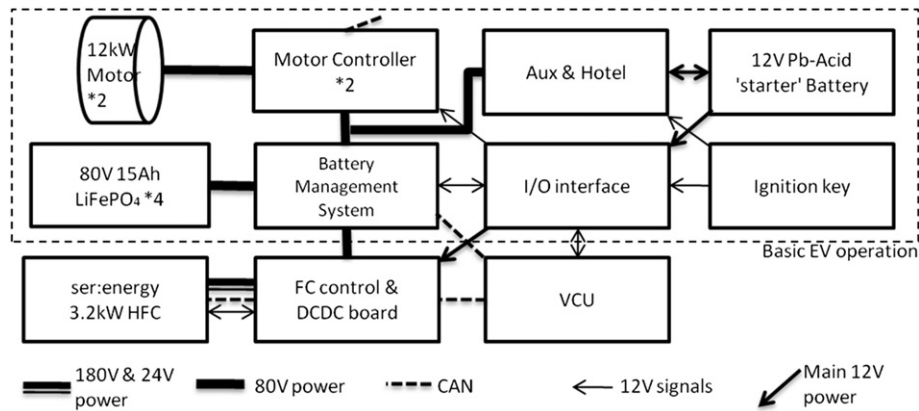


Fig. 3. The system architecture detailing main power flows and lines of communication, with explanations of individual systems given in the text: Sub-systems visible include the Serenergy fuel cell with its controller, the battery with its controller and the two Lynch motors with controllers.

Diode) output to indicate status. The PCB design could therefore be frozen and manufacture started, allowing finer details of the system design and the function of each relay to be finalised at a later stage.

An additional safety related circuit was designed to check the torque output from the motor, and to isolate the motor from the power should a fault be detected. These examples show the process by which the integration was carried out, with other circuits designed and implemented in a similar way.

3.1. Electrical power and control integration

An 'I/O interface' PCB box as in Fig. 4 was designed to facilitate the primary integration and allow the key switch to operate the vehicle directly as an Electric Vehicle for testing purposes. Integration allowing the VCU to operate the vehicle could be carried out at a later stage, with minimal wiring, when the VCU was ready.

The design of the box was such that the inclusion of a software-driven VCU could easily be added that would take charge of both the Fuel Cell and battery systems. As the PCB used jumpers to control the connections to the relay under the PCB, the function could be switched to an alternate input with ease. Both inputs and outputs were connected directly between the box and the VCU to facilitate the control of the vehicle. The VCU also facilitated some integration through CAN communications. For speed of development different

team members were given charge over different parts of this system, but the switchable design allowed testing to progress prior to full integration. A brief outline of the software function and operation of the VCU with the interface box and vehicle system is given in Fig. 5.

3.1.1. Communications

The main integration issue was getting the 3 (battery, HFC and VCU) controller units to communicate. In order to integrate the motor controller with the battery system a common mode suppression circuit was designed. This consisted of capacitors and high value resistors connected between chassis ground and each of the battery terminals. This meant the main battery voltage would be seen as +/- 40 V floating relative to chassis.

3.1.2. Human machine interface inputs

The accelerator pedal chosen was of an integrated design rated for 5 V and 12 V use, with a Hall sensor allowing an ingress protected design, with an isolated switched output activated upon the start of pedal travel. A DAC (Digital to Analogue Converter) derived analogue voltage output allowed a proportional control of the motor controller and motor. In order to connect the pedal to the motor controller a circuit board containing a simple operational-amplifier (op-amp) buffer with protective 6.8 V zener diodes was

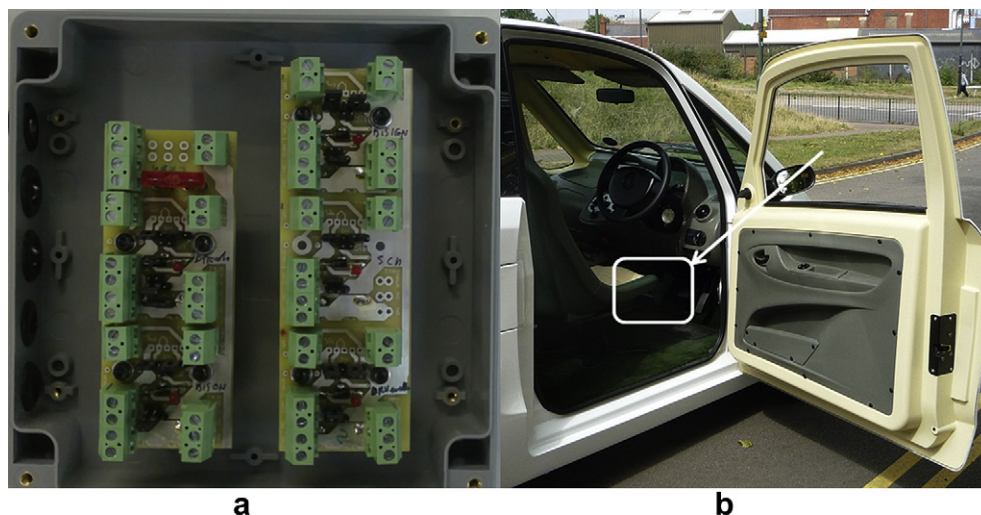


Fig. 4. (a) The I/O interface box with (b) its location in the vehicle under the dash containing integration circuits.

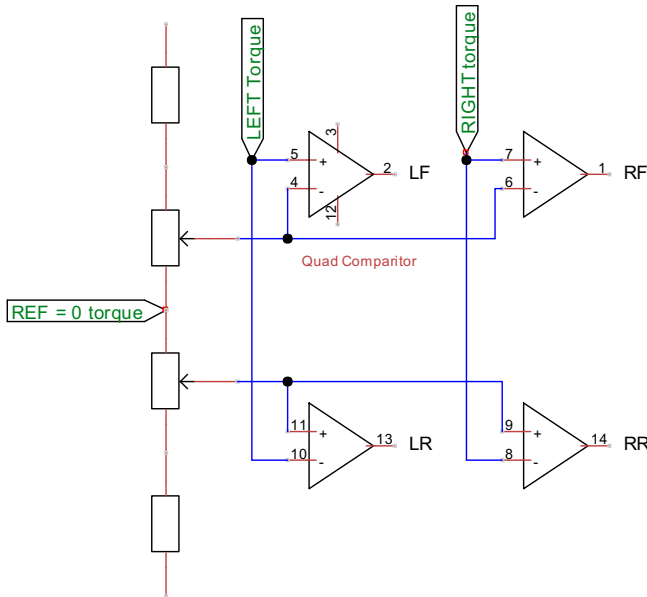


Fig. 7. Preset references and comparators in the principle analogue circuit.

achievable together as required in two stages with suitable resistor values. The durability of components and determinability of failure modes was also considered a major role in choosing which logic type to use. The final orientation of the logic was determined by the output relay requiring to failsafe (contact open) if the board did not receive power or if the driving circuit (transistor) was not receiving the right signals. The open collector output of the quad comparator integrated circuit also suited this logic type. The logic orientation of the comparator output could be switched by swapping each pair of inputs if this was required. The current design of the circuit does not allow for the use of regenerative braking, as this feature was not turned on by the time of the launch; although an important efficiency gain is achievable by an electric motor with regenerative braking, it was not activated due to experiences with the previous vehicles [15].

	LF	RF	RR	
LF	1	1	0	0
LR	1	0	0	1
acc	RF	RR		
0	1	1	CE CE CE CE	
0	1	0	CE F 1 T	
0	0	0	CE 1 ok 1	LF.FR.RF.RR (1)
0	0	1	CE T 1 R	
1	0	1	CE T 1ok Rok	acc.LF.RF (2)
1	0	0	CE 1ok ok 1ok	
1	1	0	CE Fok 1ok T	acc.LR.RR (3)
1	1	1	CE CE CE CE	

- CE Comparitor circuit Error
- T Twisting torque, opposing motors
- 1 only 1 motor has significant torque
- F Forward drive
- R Reverse drive
- ok no error to report

Fig. 8. Truth table logic for the torque monitoring circuit, with switch input 'acc' from the accelerator being pressed and 4 torque detection outputs from Fig. 7 (LF Left Forward, LR Left Reverse, RF Right Forward, RR Right Reverse) giving 3 boolean expressions.

3.3. Testing of systems

All circuit boards after the assembly and soldering process were initially tested for continuity. The standard continuity test involves attempting to pass 1 mA from a source limited to about 2 V. All tracks on each circuit board were checked for short circuit faults. The test also proved the function of diodes in the circuit as these show open circuit in reverse but 0.5–0.7 V in the forward direction.

By applying the required 12 V power to the board, any on-board function indicating LEDs were checked visually. Including LEDs on circuit boards in the design stage to show basic functionality aided the fault finding process during assembly, installation and later as prototype and small production run vehicles were whole system tested. In the I/O interface, the jumpers were used to force a relay function on the interface board echoed with LED indication. An LED in the torque monitoring circuit, with protective resistor, in parallel with (so as not to be relying on the function of the LED for the function of the circuit) the pull up resistor, was included for each of the logic expressions in Fig. 8. Each LED therefore indicated an input removed from the following OR gate and therefore the output stage; the three LEDs indicated (1) current detected, (2) forward drive and (3) reverse drive; a combination of (2) and (3) indicated no accelerator pedal input. Current detected by (1) in this 'no accelerator' mode caused all three logic circuits to remove their signal from the OR gate and therefore to the transistor and relay. Whilst an output LED parallel to the relay coil showed the transistor drive functions, an audible click and a continuity-check between the relay contacts confirmed the output function.

Digital signals such as the accelerator pedal switch input were tested by applying the appropriate voltage supply or a ground connection. Analogue inputs such as a current sensor input or the buffer circuit were similarly stimulated by a 5 kΩ potentiometer connected across the supply. This analogue input was swung across all possible values and the limits or switching points of the circuit noted. Thus all the inputs, intermediate parts and outputs of the circuits were tested according to their type and logic, so that function was assured without necessarily iterating though every single logic combination. Once installed, the systems were first tested whilst the driven wheels were raised so that the range of drive could be checked without moving the vehicle or needing a completed vehicle to use on a road or track space. Thus speeds exceeding 55 mph (88 kph) were simulated and observed on the driver display; similarly varying torque were applied by testing the braking system at the same time, the threshold for the torque detection was confirmed without brakes on a level factory floor, to just obtain motion.

Some of the initial testing produced less than favourable results; however these minor prototype assembly errors were simple things such as solder bridge short circuits. All errors were then fixed and the simple tests repeated to prove the problem had been solved satisfactorily with final results as shown in Table 2.

The 8 Microcab vehicles were then tested for electrical performance before road testing with nearly 600 miles (960 km) across the fleet by the end of June 2011, before handing over to users in the CABLED demonstration project.

4. Future developments

Once the demonstration period is completed, more conclusions can be drawn about the design of the integrated system.

Notable system improvements include the use of regenerative braking; this requires an upgrade to the torque monitoring system. Two significant factors with regenerative braking are:

First the current and torque are in the opposite direction to the motor voltage and speed;

Table 2
Tests applied to the various circuits.

Circuit	Continuity	Analogue	Digital	LED
I/O Interface	PASS	N/A	PASS	PASS
Buffer	PASS	0.4–4.6 V PASS	N/A	N/A
Torque monitoring	PASS	PASS	PASS	PASS

Second this torque is applied with no accelerator pedal input. Regenerative braking will be implemented with an extension to the logic.

The CAN bus offers far more potential in this vehicle. By dedicating different CAN buses to different priority signals, safety related functions can still be kept separate from less critical functions. Relocating current sensors and speed sensors to CAN will allow a different approach to both 'must have' as well as 'nice to have' functions. Diagnostics type monitoring and programmable logic units could operate independent of the VCU using data available on the CAN bus. Such a unit may compare the expected and measured torque including: acceleration and regenerative, ramp up and ramp down. Dynamic reduction of maximum motor power available is possible by integrating the CAN on the motor controllers (shown not connected in Figs. 3 and 6). The increased use of CAN based sensors would also reduce some of the frustration encountered finding faults in wiring looms. The use of the CAN features on the dash display would also assist in giving the driver more relevant information.

The current HFC system initially takes a lot of power from the 12 V starter battery to operate the heaters to attain the starting temperature (connections seen in Fig. 3). This will be replaced by the 80–12 V battery charger, which is currently not of sufficient power to prevent some discharge of the starter battery. Monitoring the starter battery voltage for regulating heater use could be another option.

Each new main battery pack needed to be taken to full charge a number of times to allow the battery pack to do its internal balancing operation. Due to limitations in the number of times the HFC was able to be shut off instantly and reliably restarted without manufacturer intervention, the level of charge in the main battery pack was limited to 80% before HFC shutdown was initiated. A proportional ramp down of the power with increasing main battery pack state of charge, along with allowing a secondary route to the Pb-Acid 12 V starter battery could be a better solution; this would then allow the main battery to be 100% charged from the HFC.

5. Discussion on technique

Eight vehicles now fitted with this system are now being tested in the CABLED project. Whilst the Microcab H2EV is acknowledged as not being a perfect vehicle, requiring further work with major points outlined in Section 4, Microcab Industries Ltd is not a large company with the capability of well known large automotive manufacturers. Let us examine the technique by which the Microcab H2EV was achieved.

Most of the automotive components used are off-the-shelf items used in other cars: items such as the steering wheel, stalks, wing mirrors, lights, alarm, radio etc. This allowed a fast development time by a small company. The wiring between these standard components however required designing carefully, as well as including the non-standard wiring required for the integration of the power train components described in this paper. RDM automotive¹ provided great assistance in the assembly of the looms for

the standard components listed above but much of the power train wiring had to be completed separately once the circuits had been fully designed.

Disadvantages experienced with this approach however meant that without a time tested thorough knowledge of each component, certain ambiguities in the component design portrayed had to be guarded against. A number of features designed into various components are beyond the needs of this application, components that required their own programming and configuring connector and programmer or software. If these components were either manufactured in-house or more fully integrated, then either the same software could be used to program them or at least the same CAN bus port could be used on the vehicle and computer.

6. Conclusions

The integration of fuel cell, battery and electric motors has been studied and achieved in practice. This was achieved using off-the-shelf components as far as possible to enable a short development time.

The key integration issue was communication, between the driver, the VCU, the lithium ion battery pack, the motor controller unit and the fuel cell system. Circuits were designed, built and tested to allow communication between these drive train components; three of these circuits have been reported in this paper. After installation in the vehicle, the whole system was tested and operated according to expectation. The eight Microcab H2EV vehicles are now being tested over a 12 month period in the CABLED project.

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Glossary

BMS	Battery Management System
CABLED	Coventry And Birmingham Low Emission Demonstrator
CAN	Controller Area Network
Comparator	circuit drives output low when inverting input (–) is higher than the non-inverting (+) input
Contactors	heavy duty relays
CR	Capacitor Resistor electronic network – used for simple timing circuits
DAC	Digital to Analogue Converter
FC	Fuel Cell – may/may not be fuelled by hydrogen
FPGA	field programmable gate array
GRP	Glass Reinforced Plastic
HFC	Hydrogen Fuel Cell
Jumper	a short between two pins on a PCB acting as a manual switch
LED	Light Emitting Diode
op-amp	operational-amplifier – like a comparator but drives high as well as low allowing use over a continuous range
PCB	Printed Circuit Board
PEM	Proton Exchange Membrane
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
VCU	Vehicle Control Unit

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¹ RDM Automotive is a trading name of Richmond Design & Marketing Ltd. As per <http://www.rdmautomotive.co.uk/contactrdm.aspx> (accessed 13.03.12).

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