HyLite Project - Development of a Fuel Cell Powered Hybrid Vehicle

Peter Treffinger, Andreas Brinner, Markus Gräf, Franz Philipps, Erich Ramschak, Peter Prenninger

Abstract

The HyLite Project is a joint project of 10 supplier companies and the German Aerospace Centre (DLR) to develop a fuel cell powered vehicle, which shall serve as a “technology carrier”. The majority of companies develops advanced components for the fuel cell system comprising essential components of air supply subsystem (e.g. advanced air compressor), heat and water management, hydrogen supply system and the control system. Some companies support DLR in the system integration. The basic vehicle for the integration of the PEM fuel cell system is a battery car, which was produced by a German manufacturer in a small scale production of nearly 150 vehicles. One objective of the project was to replace the battery pack of that base vehicle by an electrical power generation system with a fuel cell system. As basis for the development of the power supply system the battery vehicle has been characterized in a condensed measuring campaign. The paper reports about the results of the vehicle characterization, e.g. driving resistance parameters, performance curves and as well as NEDC characteristics. Based on the findings of the vehicle characterization it was decided to apply a hybrid fuel cell system, whereby the power distribution between battery and fuel cell system is realized by means of a bidirectional DC/DC converter. Further, the paper describes the layout of the fuel cell power unit and gives details about components - especially the fuel cell system. The vehicle management unit, which handles the overall vehicle control, and the energy management unit, which controls fuel cell system and battery, are explained in detail. Furthermore the packaging concept of the vehicle and the hydrogen safety concept are described. Recently, the integration of the system in the vehicle has been completed. The successful initial start up and first operation sequence of the vehicle on a test bench followed directly afterward.

Keywords: EV, fuel cell, control system, safety
1 Introduction

The automotive industry is the main driver for pushing the fuel cell technology to its present status. However, the role of the supplier industry, which has to develop innovative components and parts for the fuel cell system and the electrical drive train is also of crucial importance for the final success of fuel cell powered vehicles. The HyLite Project is a joint project of 10 supplier companies and the German Aerospace Centre (DLR) to develop a fuel cell powered vehicle, which shall serve as a “technology carrier”. The technology carrier helps the supplier industry in the development of advanced components for fuel cell systems. The basic vehicle, to be converted to a fuel cell “technology carrier”, is a battery car, which was produced by a German manufacturer in a small scale production of nearly 150 vehicles. It is a two-seat concept, designed for urban usage, mainly. Its total weight is about 830 kg, whereby the battery pack of 14 lead acid batteries takes 340 kg. The maximum speed comes to 100 km/h. In the following it is described in which way this vehicle has been converted to a fuel cell power train “technology carrier”.

2 Layout and characterization of the battery vehicle

2.1 Components of the power train

Figure 1 shows the power train of the battery powered vehicle. The battery powered drive train consists of a battery set, an inverter and an electrical engine.

![Figure 1: Scheme of the battery powered drive train](image)

The battery set of the vehicle comprises 14 lead-acid battery blocks (Hawker 12 EP 70). The open circuit voltage of a fully charged battery is around 12.8 V resulting in a bus voltage of approx. 180 V DC. The total weight of the battery set is around 340 kg. The dimensions of one battery block are 330 x 168 x 176 mm (Length x Width x Height). The manufacturer specifies that the battery can bear a current of 600 A over a period of 60 s [1]. Some indications on the capacity of the batteries are given in section “Results from the Base Vehicle Characterisation”. However, the maximum current of the motor inverter (BRUSA AMC 325, air cooled) can only be as high as 240 A. Consequently, the peak power could be theoretically more than 40 kWel. The control unit of the motor inverter - directly connected to the accelerator pedal - controls the vehicle operation. Its functions include power control of the inverter, discharge prevention of batteries, overcharge prevention of batteries and brake energy recuperation. The voltage of the BRUSA AMC 325 can go up to 216 V DC as a maximum.

The asynchronous motor of Thien has a continuous power output of 12 kW mech and in combination with the AMC 325 a theoretical peak power output of around 34 kW mech.


2.2 Results of the base vehicle characterisation

Table 1 includes the summary of technical and measured vehicle data. From coast down curves, measured on the test track, the driving resistance parameters and the air drag coefficient were calculated. Further, efficiency & power mappings, performance curves and the NEDC characteristics were measured on a chassis dynamometer. The inertia of the entire power train was calculated comparing the stationary measured torque mappings on chassis dynamometer (\(\frac{dn}{dt}=0\), \(n=\text{speed}\)) and full load acceleration curve on test track, where inertia has its highest influence (i.e. highest \(\frac{dn}{dt}\)).

<table>
<thead>
<tr>
<th>Techn. Vehicle Data</th>
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<tbody>
<tr>
<td>Tyres radius</td>
<td>0.2543 m</td>
</tr>
<tr>
<td>Top speed</td>
<td>104 km/h</td>
</tr>
<tr>
<td>Pn, rated power e-motor</td>
<td>12 kW</td>
</tr>
<tr>
<td>Speed @ Pn</td>
<td>5920 rpm</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>10.13</td>
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<tr>
<td>Vehicle tara weight</td>
<td>830 kg</td>
</tr>
<tr>
<td>Vehicle total weight (w/ driver and instrumentation)</td>
<td>1160 kg</td>
</tr>
<tr>
<td>Weight of batteries</td>
<td>338 kg</td>
</tr>
<tr>
<td>Vehicle front area</td>
<td>2.043 m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Driving resistance: const. param, (A_0) ((20^\circ\text{C}, 98.21\text{Pa}, 1160\text{kg}))</td>
<td>98.0 N</td>
</tr>
<tr>
<td>Driving resistance: linear coeff, (B_0) ((20^\circ\text{C}, 98.21\text{Pa}, 1160\text{kg}))</td>
<td>0.98 N/(km/h)</td>
</tr>
<tr>
<td>Driving resistance: quadratic coeff, (C_0) ((20^\circ\text{C}, 98.21\text{Pa}, 1160\text{kg}))</td>
<td>0.0225 N/(km/h)²</td>
</tr>
<tr>
<td>(c_w), air drag coefficient</td>
<td>0.34</td>
</tr>
<tr>
<td>(c_w \times \text{area})</td>
<td>0.69 m²</td>
</tr>
<tr>
<td>Efficiency of power inverter ((\text{NEDC}, 1160\text{kg}, 1st quadrant})</td>
<td>97.2%</td>
</tr>
<tr>
<td>Efficiency of e-motor ((\text{NEDC}, 1160\text{kg}, 1st quadrant})</td>
<td>72.5%</td>
</tr>
<tr>
<td>Efficiency of power train ((\text{NEDC}, 1160\text{kg}, \text{battery to wheel}))</td>
<td>67.8%</td>
</tr>
<tr>
<td>Torque of e-motor @ rated rpm</td>
<td>19.36 N</td>
</tr>
<tr>
<td>Inertia entire power train ((\text{ref. to wheel}))</td>
<td>0.13 kgm²</td>
</tr>
<tr>
<td>Performance 0-40km/h ((1160\text{kg}))</td>
<td>6.04 s</td>
</tr>
<tr>
<td>Elasticity: 40-70km/h ((1160\text{kg}))</td>
<td>10.66 s</td>
</tr>
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Table 1: Technical data of base vehicle

The baseline car was tested in the legislative NEDC cycle with two different power train operation strategies: first strategy with activated regenerative braking and the second one with mechanical braking, only. Without consideration of battery efficiencies, it can be concluded that more than 11 % (ref. to Table 2) of the energy drawn from the battery for acceleration and cruising can be regained during the braking events. Hence, these very initial tests already highlighted the importance of a fuel cell-battery hybrid power train concept even for such small vehicles.

<table>
<thead>
<tr>
<th></th>
<th>regenerative braking on</th>
<th>regenerative braking off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>energy discharging, Mj</td>
<td>5.287</td>
</tr>
<tr>
<td></td>
<td>energy charging, Mj</td>
<td>-0.589</td>
</tr>
<tr>
<td></td>
<td>relation discharging / charging energy</td>
<td>11.1%</td>
</tr>
<tr>
<td>Wheel</td>
<td>acceleration energy, Mj</td>
<td>3.568</td>
</tr>
<tr>
<td></td>
<td>deceleration energy, Mj</td>
<td>-0.887</td>
</tr>
<tr>
<td></td>
<td>relation energy deceleration / acceleration</td>
<td>24.7%</td>
</tr>
<tr>
<td>Power train efficiency</td>
<td>battery to wheel</td>
<td>67.8%</td>
</tr>
<tr>
<td></td>
<td>wheel to battery</td>
<td>66.4%</td>
</tr>
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</table>

Table 2: Energy balances of the NEDC

For the actual performance, the availability and reliability of a car, however, real driving cycles have to be taken into consideration. Hence, energy consumption of the baseline battery vehicle was investigated also under real city-, extra urban- as well as highway driving conditions. The duration of these real driving cycles was 2775, 1084 and 1104 s for the city-, extra urban and highway part, respectively. Parts of the velocity histograms are plotted in the top row of Figure 2.
The test results were combined with a simulation model of the entire car including the vehicle resistance characteristics. This approach allows an identification of the power and energy consumption as well as resistance to rolling between the wheels and the road. Average power consumption at the wheels was measured with power levels of 1.12, 6.47 and 11.1 kW within the investigated driving conditions (medium row of Figure 2). The diagram shows that during city operation, the fluctuations around the average power consumption are quite small (due to low speeds and therefore lower translational energies involved). In extra urban and highway operation, more pronounced acceleration as well as relevant brake events will occur, which require “boost-power” and recuperation capacity of the electrical power train for effective usage. Hence, a load following strategy for the fuel cell unit will lead to smaller electrical storage devices. Further, electric energy “has” to be consumed from the storage devices in order to provide sufficient capacity for subsequent brake events. Finally, considering the entire histograms of the three real driving cycles as investigated, the power demand for acceleration as well as deceleration can be classified according to their occurrence probability. The resulting power distributions are plotted in the lowest row of Figure 2. The electric power train of the baseline vehicle provides wheel power for acceleration with maximum 22 kW and about 12 kW for regenerative braking. With this layout of electric motor (in generator mode), inverter and battery, 94.8 % of all braking events in the city cycle are covered by the regenerative braking mode. Corresponding figures for the extra urban and highway cycle are 77 and 81 %, respectively.
3 Layout and characterization of the fuel cell vehicle

3.1 Components of the fuel cell powered power train

Figure 3 shows the structure of the fuel cell power train. A low-temperature fuel cell system with Polymer Electrolyte Fuel Cell stacks (PEFC) replaces the battery set.

![Diagram of fuel cell power train](image)

Figure 3: Scheme of the fuel cell power train

The installation comprises two “direct water injection” stacks from the manufacturer NUVERA, which are electrically connected in series. Both stacks have 120 cells, which yields to a common open circuit voltage of about 240 V DC. The maximum electrical power output of the fuel cell stacks comes to 20 kW. However, the available system power is reduced by electrical power consumed by auxiliaries like air compressor. Details on the fuel cell system are given in chapter 3.2. As a consequence, the maximum power of the fuel cell system is lower than the output of the original battery set. In order to compensate the lower fuel cell output a boost battery set is connected in parallel to the PEFC system. The boost battery has 4 Hawker lead acid batteries connected in series. Consequently, the power demand of the electric motor can be covered again by addition of the electrical power of the fuel cell system and the battery set. The allocation of power is determined by means of a bi-directional DC/DC-converter, which is also designed for brake energy recovery. The water-cooled bidirectional DC/DC-converter is of multi-phase type in order to reduce ripple current. It has been specially developed for application in the HyLite project. In combination with the lead-acid battery pack the DC/DC converter transfers in both directions around 10 kW. However, the power is limited by the current. If a higher voltage range is used, the converter can handle a higher power level. The parallel connection of a fuel cell system and an electric energy storage is motivated by the following reasons:

- The power addition makes it possible to downscale the fuel cell. This can be a financial benefit.
- The parallel connection is used to operate the fuel cell system in driving cycles as efficiently as possible.
- The additional storage for electrical energy is used for regenerative braking.
- Due to the power addition, higher vehicle performance is reached.
- The dynamic behaviour of the fuel cell system is relaxed in terms of transient response.

A more detailed view on the pro and cons of fuel cell hybrid systems for vehicles is available, from Pede et al. [2], for example.

Due to the higher fuel cell voltage level compared to the original battery set, the inverter of the battery vehicle had to be replaced. A water-cooled inverter from MES-DEA (TIM 600) was selected (input voltage range 80 – 400 V, rated output current 225 A, max output current 340 A for s). Testing this
inverter on the test bench strong electromagnetic interference with the electronic equipment was observed. This problem was reduced with additional filters and changes in the layout of the DC supply part of the inverter. Also it was necessary to install an additional electronic control unit, which controls the fuel cell system, the power split between battery and fuel cell system and finally the electric engine.

3.2 The fuel cell system

![Figure 4: Simplified scheme of the fuel cell system.](image)

In the fuel cell module, two stacks of the manufacturer NUVERA are installed. Every stack has 120 cells. The stacks are of the so called "direct water injection (DWI)"-type. The stack is fed with hydrogen, air and de-ionised water (DI), separately. Hydrogen/water and air/water mixtures leave the stack through common outlets. The DI-water cools the air and the hydrogen side directly in the cells. No external humidification of hydrogen and air is necessary. The two stacks are electrically connected in series and have a parallel media supply. Both stacks are equipped with a single cell voltage measurement unit. At nominal operating conditions ($T=75 \, ^\circ C; \lambda_{oxygen} = 2; p = 2.2 \, \text{bar}$) and a current of 140 A, the single stack power output is about $11 \, \text{kW}_{el}$.

The hydrogen module is fed from compressed $H_2$-gas storage with a nominal pressure of 200 bar. The hydrogen is supplied to anodic side of the stacks through a mechanical pressure-reducer device and an electric pressure control valve. The control valve follows the demands of an electronic PI-controller. The hydrogen pressure depends on the air pressure of the cathodic stack side, and follows with a positive difference of 0.2 bar ($p_{H_2} = p_{air} + 0.2 \, \text{bar}$). The fuel cell stacks are operated in the so-called "dead end" mode, which means that the hydrogen valve in the outlet line is most of the time closed. Therefore, the amount of feed is mainly determined by the actual consumption. For removing of water and accumulated gas pollutants, an electromagnetic valve is installed in the discharge line. This valve opens periodically for a short time interval, in order to reach a stack-internal hydrogen pressure drop of about 0.2 bar. During
this short-time opening of the valve the continuous pressure control is interrupted. These sequences are essentially for reliable and stable stack operation.

Air is supplied to the stacks by a compressor, whereby the air intake temperature is controlled by an air cooler. The air/water mixture from the fuel cell stacks is divided in a separator in to the gas and liquid phase again. The following electric control valve adjusts the cathode pressure, whereby also PI-controlling is used. The required air mass flow rate follows along of the compressor characteristics by adjusting the compressor speed.

A majority of the heat, produced in the stacks, is dissipated by the DI-water, whereby the heat is transferred by a heat exchanger to a glycol/water mixture. The heat exchanger is shown in Figure 4 directly under the schematized fuel cell stacks. Finally, the glycol/water mixture delivers the heat via air cooler to ambient air. This circuit is not included in figure 4.

The DI-water mass flow, which is fed to the stacks, is controlled by an electric-driven 3/2-way valve. At the inlet of the pressure control valve an air cooled condenser is installed to recover a part of the product water in order to be fed back into the separator.

The operating range of the fuel cell stacks is limited by a set of conditions:

- An excessive hot medium, which is supplied to the stack, can damage the cell membranes. The maximum operating temperature of the NUVERA stacks is limited to 80°C. Nevertheless, it is recommended to operate not above 75°C. The operating temperature of the air/demineralised water mixture is measured on air side in the discharge lines [3].
- An excessively high differential pressure between anodic and cathodic side may cause the mechanical membrane destruction. NUVERA specifies a max. pressure difference of 0.4 bar [3].
- The single cell voltages may differ significantly from the average cell voltage whilst increasing the current especially at high current density levels or dynamic load changes. Also any of the single cell voltages of a stack shall not fall below a certain level due to heavy operating conditions or even can be inverted. All effects may cause severe membrane damage. NUVERA specifies a minimum allowed single cell voltage of 0.4 V.

Several reasons could be responsible for significant deviations of cell voltages. The cells in the stack, electrically switched in series, are hydraulically connected in parallel. Therefore under-stoichiometric supply of individual cells with reaction media can cause a lack of reaction partners at the active surfaces. Consequently, the cell voltage decreases. The uneven distribution can e.g. be caused by differences in the geometry of the internal media supply structures. Other reasons for strong deviations in single cell voltages are different ageing of cells and flooding of cells by liquid water, which could be caused if stacks are operated at a significantly low temperature level. The description above shows that a substantial control effort was required to assure the continuously stable operation of the fuel cell system, whereby detailed system modelling is an important tool developing the control strategy [4].

4 Control system of the fuel cell powered vehicle

4.1 Overview of the control system

As above mentioned an electronic control unit was required for the fuel cell vehicle. Having in mind the function of the vehicle as technology carrier a controller solution was needed to handle significant changes of hardware components and adaptation of software. Important criteria selecting the hardware target were: available I/O modules, available number of I/O channels, required space, signal conditioning. Finally, a target based on PC104 structure has been chosen, for which a large number of PC data acquisition cards are applicable. The realized PC104-target offers 32 analogue input, 24 analogue output, 72 digital I/Os and 2 two CAN-busses. Its dimensions are: 270 x 170 x 120 mm (Length x Width x Height). However, because CAN signals were mainly used for communication between sensors, actuators and the electronic control unit, the number of analogue/digital inputs and outputs is oversized. The control algorithm is developed with Matlab/Simulink™ and the Matlab Toolbox Stateflow™. By means of the xPc target
compiler, executable code is generated on the target. The prerequisite to be able to use Matlab/Simulink as a development tool, also, was an important argument to select the PC 104 –target. Figure 5 shows the structure of the vehicle control. It consists of three main units - vehicle management unit (VMU), energy management unit (EMU) and electric drive train. A driver gives a power request to the VMU. Depending on the status of the vehicle and of the energy supply system, which is provided by the EMU, the VMU controls the motor inverter. The control systems were jointly developed by DLR and partner AVL. DLR design job was the EMU with I/O Display as indicated with the dashed line in Figure 5. AVL designed the driving strategy unit (i.e. VMU).

Figure 5: Structure of vehicle control

4.2 The vehicle management unit (VMU)

The main functions of the VMU are the driving mode detection, pedal to torque mapping, load change characteristics, conditioning of driver information and (sub-)controller initialisation with sensor signal verification. Further routines for limp home operation i.e. reduced power mode in case that just one of the two power sources is available, road incline calculation as well as limitation of maximum current for the motor inverter are tasks of the VMU. The unit has I/O interfaces to the driver information panel, EMU and to the drive power inverter. The following subchapter describes the VMU-functions more in detail.

4.2.1 Detection of driving modes

Regenerative braking energy charges the batteries and allows modifiable vehicle deceleration rates. As long as the batteries are in lower state of charge (SOC) ranges, the driver receives reliable and particularly reproducible vehicle deceleration rates. Anyhow high energy efficiency is the aim for this hybrid car. Combining this goal with the diversity of different driving conditions, the SOC target is continuously adapted depending on the actual driving mode or traffic conditions.

Five different driving modes are defined: Drive Away, Stop & Go, City, Extra-Urban and Highway. An extra trigger named “Kick-Down” indicates the driver’s wish for full acceleration power. If the battery SOC and the fuel cell unit allow, full power will be driven from both energy sources - the batteries and the fuel cell i.e. 24 kWel. In case that the SOC decreases below a specific minimum value, power reduction to fuel cell power only is enforced.
The trigger mechanism for the driving mode detection was designed with a state flow machine. The input parameters contain statistical parameters over a certain time window and instantaneous events. “Stop & Go” is e.g. triggered if during a specified observation time interval several “Drive Away” events occur but the vehicle speed still remains below 15 km/h [5]. A special anti-oscillation logic avoids that the driving mode is toggling between different conditions, even if e.g. during a “Stop & Go” overriding occurs. Figure 6 shows the driving mode detection during a NEDC cycle. Since the first 900 s are not comparable with the typical “Stop & Go” behaviour of realistic cycles the driving mode „City“ remains stable during this time period even if several drive away events occur. The typical average speed levels move around 9 km/h, 20 km/h, 60 km/h and 80 km/h during Stop & Go, City Traffic, Extra Urban and Highway.

Figure 6: Detection of driving modes in the NEDC FIG. NEDC

4.2.2 Pedal to torque mapping

In the HyLite vehicle the relief of the accelerator pedal means that the electric machine comes in to the generator mode. The zero torque position is somewhere at the first third of the pedal travel, but this is anyway a fictive value without practical meaning for the driver. A driver can therefore modulate both, the acceleration and deceleration rate as well. In a conventional ICE, the pedal to torque map is designed for a particular driveability constellation and specific vehicle characteristic, respectively [6]. Based on the pedal to torque mapping of a small class ICE-car, the mapping of the HyLite vehicle is a function of speed (higher gradient at higher speeds) and pedal position for both acceleration and deceleration. The highest possible regenerative braking power is limited by the batteries and comes to about one third of the highest acceleration power.

4.2.3 Load change behaviour

Transient load changes and smooth reduction of driving power during full load in case of low battery SOC (i.e. usage of fuel cell power only) are controlled by this module. During transient load changes, the driver’s input via the pedal is transformed into smoother torque shapes especially in the upper range of these torque shapes. It is crucial for the driveability assessment that this smoothing does not cause any delays in the load change response i.e. at the beginning of each torque change [7]. Since power train oscillations are not expected to be relevant in this FCV, oscillation damping routines are not envisaged.
4.2.4 Information Setup and Initialisation

This sub module generates driver information which is transferred to the dashboard. Basic data are speed, maximum available power (<130 % i.e. fuel cell power only represents the status 100 %), readiness for regenerative braking, indication of current and a near-term power reduction, on-going initialisation routine, indication of reverse driving direction, active electronic accelerator pedal and malfunctions of components or sensors of the systems. The majority of data is not to be displayed permanently but are only presented in case that pre-defined events occur.

Beneath the driver information level, the module contains initialisation routines controlling reliable EMU and power inverter module start-up and shut down. Also, a so-called “limb-home” function is implemented in order to enable reduced driving power in case of e.g. severe fuel cell system mal-function.

4.3 The Energy Management Unit (EMU)

The energy management unit contains the following sub modules, wherein all functions for control and monitoring of the energy generation system, i.e. battery and fuel cell system, of the vehicle are realized.

- IO Control Unit (IOCU)
- Energy Allocation Unit (EAU)
- Fuel Cell Control Unit (FCCU)
- DC-Control Unit (DCCU)
- Battery Control unit (BCCU)
- Battery Management Unit (BMU)

4.3.1 IO Control Unit (IOCU)

Within the IOCU module all input and output signals to the electronic control unit are processed. This includes e.g. encoding of CAN messages, scaling of signals and plausibility check of signals.

4.3.2 Energy Allocation Unit (EAU)

The main functions of the EAU are

- Provision of the requested power by splitting power demand between fuel cell system and battery.
- Limitation of the available electric power according to the actual states of battery and fuel cell system
- Initialization of the start-up and shut-down of the fuel cell and the complete energy system, i.e. the combination of battery and fuel cell system.
- Control of the start-up and shut-down procedure of the complete energy system.

The energy system has 6 states: (1) energy system is off, (2) energy system initialising, limited power available, (3) energy system in normal use, (4) energy system in normal use, recuperation allowed, (5) energy system going down, (6) emergency shutdown.

4.3.3 Fuel Cell Control Unit (FCCU)

The FCCU controls start-up and shut-down of the fuel cell system. There are 6 pre-defined states such as (1) standby, (2) shut down, (3) start up (4) automatic operation, (5) manual operation and (6) alarm. The FCCU calculates a number of properties, e.g. mean cell voltage, air ratio, and actual fuel cell power. Important tasks of the FCCU are:

- Controlling the operating pressure of the system as function of the current.
- Regulating the mass flow rate of air as function of the actual current.
- Controlling the outlet temperature of the fuel cell stacks.

It also provides the maximum available power of the fuel cell system and the maximum possible power gradient, which can be applied to the fuel cell system. These figures are based on an experimental characterization of the fuel cell system on a test bench [8].
4.3.4 DC-Control Unit (DCU)
There are several electric switches in the system, e.g. a power switch, which connects the fuel cell stacks to the DC main bus. The DCU monitors the position of the switches, controls the switching sequences according to the status of subsystems, and is responsible for emergency shut-down actions.

4.3.5 Battery Control Unit (BCCU)
The battery control unit sets the limits and parameters of the DC/DC-converter.

4.3.6 Battery Management Unit (BMU)
Within the battery control unit the state of battery charge is estimated and the temperature limits of the battery are monitored. Depending on state of charge and temperature, the maximum allowed power for charging and discharging of the battery is determined.

5 Package and Safety Concept of the fuel cell powered vehicle
The chassis of the HyLite vehicle is an outgrowth of the basic Hotzenblitz design and was assembled from three chassis parts. A steel profile construction welded together from round and rectangle steel profiles forms the basic outer form and size of passenger compartment. The car bottom is a welded aluminium double bottom in octagonal form made from plain and honey comb plates. The front compartment in the form of a cubical is a separate steel weld construction made of rectangle profiles. Car bottom and front compartment are fixed with screws to the steel profile frame. The carriage of the vehicle consisting of few glass-fibre enforced plastic parts is only fixed with screws on to the vehicle steel frame.

Figure 7: 3D- picture of HyLite package (left) and (right) comparison of Hotzenblitz and HyLite carriage

Figure 7 now gives in the left part a detailed 3D-overview about the modular package of the fuel cell energy supply system in its newly formed compartments. The vehicle has a total number of 14 separate equipment compartments for both, the fuel cell system and the drive train. Starting from left to right in the figure, the front compartment houses the main coolers, the drive train, the high power DC/DC-converter and the basic 12 V DC-supply. The double bottom of the passenger area includes the control and measurement units in the two foot room areas followed by the electric inter-connectors, low power relays and hybrid battery system in four compartments underneath the front seats. In the middle tunnel from front to rear the high power DC connectors and fuses, 24 V DC supply system and the FC air supply system are located. Left and right of the air supply in the rear part the main components of the FC DI-water circuit and of the water-glycol cooling circuit are mounted. In the space about 10 cm behind the door thresholds along the seats two hydrogen storages are fixed in separate compartments. Above the rear wheels on the driver side the hydrogen supply system and on the co-driver side the air intake circuit is integrated in newly formed compartments. A gas-tight case located in the rear space between air and hydrogen
compartment contains the FC core system with the two PEFC stacks. Stack case and core system installation are shown in the right part of Figure 8. The enforced rear drawer below the stack case contains essential components of the air supply circuit, air-water separation, DI water recirculation and air compressor control. The formation of FC system compartments and specific gas-tight separation of the hydrogen compartments from the others is an essential part of the vehicle safety concept. Figure 7 presents these compartments with a simplified view on the hydrogen system inside. The compartments are numbered consecutively from R 1 to R 5. For the realisation of the package concept and with respect to the operation of a fuel cell system certain carriage parts and cases have been newly designed and realized. Specifically these are - front hood with cooler openings, swing doors with safety glass screens, electric equipment drawers below the seats, hydrogen storage compartments, hydrogen compartment case, stack case, rear drawer and rear end drawer panel. The right part of Figure 7 gives a comparative view on the original Hotzenblitz carriage (right vehicle) and the improved HyLite carriage (left vehicle).

Figure 8: Simplified scheme of the hydrogen supply system of the HyLite vehicle

The vehicle safety concept consists of several complementary active and passive safety measures. The basic passive measure is the physical separation of the hydrogen supply and PEFC-core system from the other circuits by integration into 5 separate compartments which are gas-tight to the vehicle interior and all other system circuits. Theses spaces named with R1 to R5 in Figure 8 have permanent exhaust openings EP1 to EP4 to ambient air outside the vehicle. The second passive measure is the combination of all circuit expansions lines EL1 to EL4 to a main pipe which releases the hydrogen through a flame arrestor directly to ambient air. Due to the separate location of storage room R1 its single exhaust pipe has been equipped with a separate flame arrestor.

The basic active measure is the permanent measurement of the hydrogen in air-content in the exhaust pipes of the compartments and the vehicle interior and the immediate hard-wired release of an emergency system shut down in case of exceed of 40 Vol.-% of the lower explosion limit at one of the measurement locations. The realisation of these basic safety measures in the vehicle is presented in the left part of Figure 9 in form of a 3D-sketch.
The active safety measure “hard-wired emergency shut down chain” includes various signals from limit switches distributed all over vehicle, drive train and fuel cell system. Specifically these are: (1) 3 \( \text{H}_2 \)-in-air measurements, (2) 4 acceleration limit switches, (3) manual switch, (4) 10 process limit switches. The emergency shut down reacts equally to every signal - decouple the fuel cell system from the drive train, cut off the hydrogen supply, depressurise all fuel cell circuits, shut down air supply, cut off all electric circuits to the system components.

Specific effort was undertaken to make the hydrogen supply system as simple and safe as possible (see Figure 7). Two storages at start up 10 l pressure bottles, later improved hydride storages vessels deliver hydrogen to a common 2-stage pressure reducer with attached filter, flame arrestor and over pressure safety valve. Through a consecutive line of electromagnetic valve (NC) for main supply shut off, flow measurement, electromagnetic pressure controller and heat exchanger (optionally) the hydrogen is delivered to two PEFC stacks in parallel. The stacks have outlets which can deliver excess hydrogen into a common expansion pipe EL4 which is closed by a second electromagnetic valve (NO). The piping between main shutoff valve and stacks is equipped with a certified over pressure safety valve and will be depressurised automatically and flow-controlled through the expansion pipe EL 2 which includes a NO electromagnetic valve. All system components are certified for the use with hydrogen and the system is designed to follow the guidelines for the classification Ex-zone 2.

## 5 Summary and outlook

The paper explains the conversion of a battery-operated vehicle to a hybrid fuel cell power “technology carrier”. The characterization of the battery vehicle showed high potential of regenerative braking as it turned out that 94.8 % of all braking events in the city cycle are covered by the regenerative braking mode. Corresponding figures for the extra urban and highway cycle are 77 and 81 %, respectively. Consequently, a hybrid fuel cell system was designed. However, the description of the control strategy and the control system shows the increasing system complexity. Installing the system in to the vehicle, the limited space was a challenge. Since the vehicle serves as “technology carrier” extra space is needed for data acquisition. Additionally, the components had to be installed in a way to allow future modification of the system. The packaging concept is presented in the paper and closely linked to the hydrogen safety concept, which is also explained.

Recently the integration of the system in the vehicle has been completed. Following that, successfully vehicle operation could be demonstrated. The validation of the different controller systems was done on hardware in the loop (HIL) test bench by using the components asynchronous motor, power inverter and DC/DC converter in real hardware. The behaviour of the power sources i.e. batteries and fuel cell system was simulated by two power supply units in two quadrant operation. The electrical engine was mechanically loaded by the test bench simulating dynamical positive and negative power flows during different test cycles.

Now follows the investigation of components and the complete system, whereby comparative assessments are foreseen on stationary test benches on component and module level.
References


[3] NUVERA: Personal communication


Authors

Peter Treffinger, Dr., German Aerospace Centre, Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, phone: +49 711 685 7468, fax: +49 711 685 7465, email: peter.treffinger@dlr.de.

Master degree (Dipl.-Ing.) in chemical engineering from University of Karlsruhe, 1988, Ph.D. (Dr.-Ing.) from University Karlsruhe, 1994. In DLR since 1994. Dr. Peter Treffinger has been responsible in several projects in the field of fuel cell systems and alternative power trains. He is project leader of the HyLite project and heads the simulation and modelling group of the DLR Institute of Vehicle Concepts.

Andreas Brinner, DI, German Aerospace Centre, Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, phone: +49 711 685 7464, fax: +49 711 685 7465, email: andreas.brinner@dlr.de.

Andreas Brinner joined DLR in 1984 and has been responsible in numerous projects in the field of solar thermal energy, hydrogen technology, fuel cell systems and alternative power trains. Presently he is heading the hardware and prototype group at the DLR Institute of Vehicle Concepts.

Markus Gräf, Dr., German Aerospace Centre, Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, phone: +49 711 6862 457, fax: +49 711 6862-570, email: markus.graef@dlr.de.

Dr. Gräf studied electrical engineering. Following his PhD work in the field of transversal flux machines, he was working in a number of industrial hybrid vehicles and electromagnetic design of electric machines, sensors and actuators. He is head of the electric machines and electrical storage group of the DLR Institute of Vehicle Concepts.
Franz Philipps, DP, German Aerospace Centre, Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, phone: +49 711 685 7464, fax: +49 711 685 7465, email: franz.philipps@dlr.de.

Franz Philipps studied physics. He was responsible in several projects in the field of hydrogen technics and fuel cell systems. As managing director he led the “Special Research Centre 270 – Hydrogen as Energy Carrier”. Franz Philipps joined DLR in 1998. He is head of the Group “Test Facilities and Measurement Technology” of DLR Institute of Vehicle Concepts.

Erich Ramschak, DI, AVL List GmbH, Engineering and Technology, Dep. R&D, Hans-List-Platz 1, 8020 Graz, Austria phone: +43 316 787 3784, fax: ext. 3799, email: erich.ramschak@avl.com

Senior project manager for engineering & testing of fuel cell (sub-) systems and customised FC development at the AVL-headquarter Graz. At AVL since 1997. Four years experience in the real-time measurement and assessment of driveability ratings and vehicle character of passenger cars. Before two years electronic development of a two-wheel (ISG-) hybrid vehicle at the Tech. Univ. Graz. Graduated engineer, has studied Electronics at the Technical University of Graz.

Peter Prenninger, Dr., AVL List GmbH, Hans-List-Platz 1, A-8020 Graz, phone: +43 316 787 1484, fax: 570, email: peter.prenninger@avl.com

Master degree (Dipl.-Ing.) in engine engineering from University of Technology Graz in 1984, 1984-87 Institute of Mechanics at University Innsbruck, PhD (Dr. techn.) from University Innsbruck in 1987; 1988-89 Research at Kyoto University; Since 1989 at AVL Graz – currently responsible for AVL’s research on future technologies including AVL’s fuel cell department.