HY.POWER - A Fuel Cell Car Boosted with Supercapacitors

R. Kötz, M. Bärtschi, F. Büchi, R. Gallay[1], Ph. Dietrich

Paul Scherrer Institut, CH-5232 Villigen, Switzerland

[1] montena components SA, CH-1728 Rossens, Switzerland

Introduction

Fuel cell cars are generally accepted as very promising approach to the solution of future environmental and energy issues. In order to reduce emissions, improve urban air quality and in view of the declining oil reserves hydrogen/methanol made from renewable sources such as biomass or solar must be the future fuel. Without fuels made from renewable sources the contribution of EV and HEV to the solution of environmental problems is of second order.

Fuel cells (FC) can exhibit the highest energy density of all electrochemical energy storage and conversion devices; therefore the FC is well suited to provide sufficient energy for vehicles with a high range. However FCs are limited in power density and are not capable of energy recuperation. Therefore it appears to be straightforward to combine the FC with a second, high power, intermediate storage device such as supercapacitors (SC, electrochemical Double-Layer Capacitors will be called supercapacitors throughout this paper) or a high power battery.

The implementation of a second storage device allows reducing the size and cost of the FC and provides extra power during acceleration, improving driving comfort. With a booster device the FC can operate most of the time at moderate power, which increases its efficiency and thus results in fuel savings. Finally, depending on the actual driving mode, recuperation of braking energy will also contribute to fuel savings.

The question as to whether a short term storage device is needed and whether a capacitor or a battery is the optimum choice for the intermediate storage device will be answered in the future most probably on a cost basis /1, 2/. For HY.POWER technology platform presented in this paper, capacitors were considered to be the better choice.

Recuperation of braking energy is a main argument for using a second storage device combined with a fuel cell. Fuel consumption of a HEV varies depending on the driving cycle and the weight of the vehicle. Figure 1 shows the fuel consumption for several American, European and Japanese driving cycles. It is evident that during urban cycles more fuel is consumed than on the high way. The fuel consumption was calculated for a small (750 kg) and a large (1500 kg) car and does not vary significantly with the weight of the car.

The corresponding theoretical fuel savings potential with energy recuperation are also shown in Figure 1. Recuperation energy of up to 20 % can be used for an urban driving cycle with many stop-and-goes.

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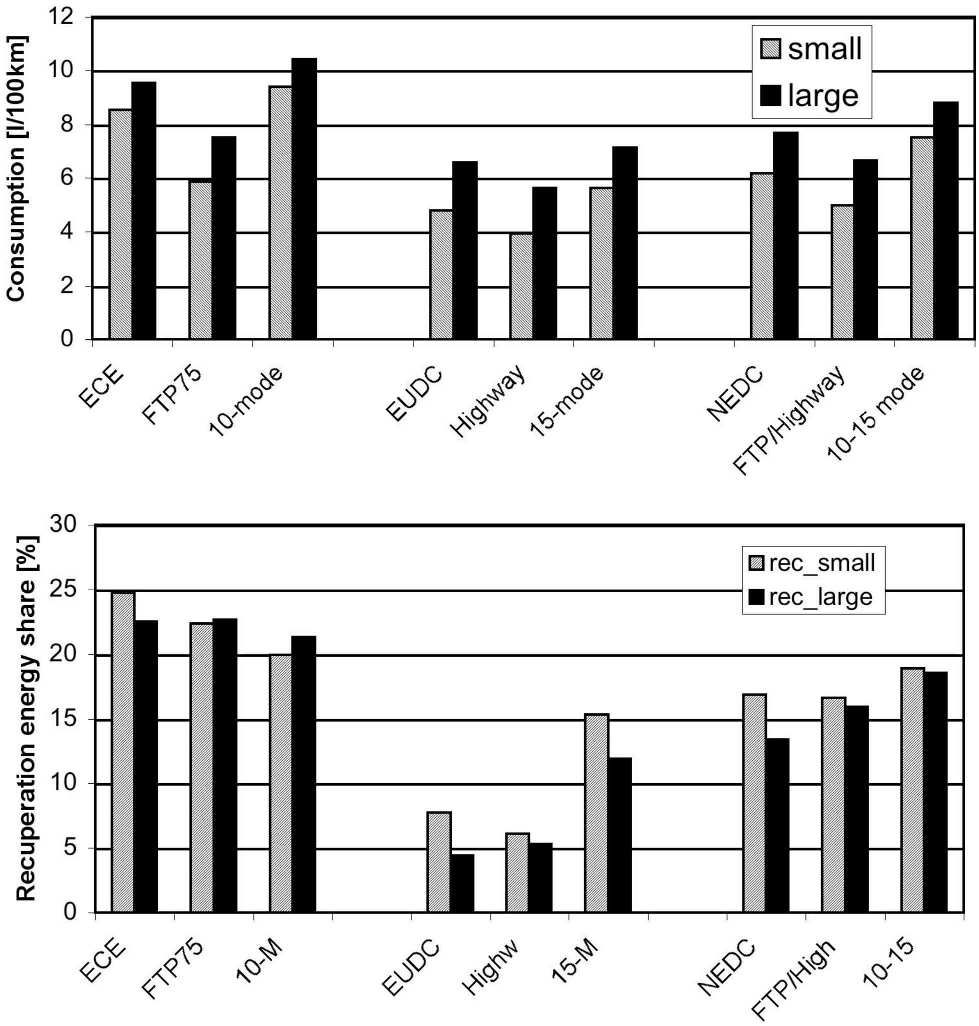

Figure 1: Fuel consumption (top) for various urban, highway and mixed driving cycles for a small and a large car. The respective fuel saving potential due to recuperation of braking energy is also shown (bottom). Small car: 750 kg plus 140 kg load; Large car: 1500 kg plus 140 kg load

HY.POWER concept

The concept of a hybrid-electric powertrain opens up the possibility to custom design the performance level of the storage and the fuel conversion device.

The research power train presented in this paper, which has been realized as a technology platform is used to explore the performance of new materials and system architectures to give insights for further development. The performance of the storage device and the fuel cell system were chosen in an extreme way to demonstrate the possibilities of this architecture.

The Volkswagen Bora HY.POWER (see figure 12) is an electric car with an electric machine propelling the front wheels, the fuel cell system in the trunk and a supercapacitor module as short-term energy storage device (see also [3, 4]). One part of that module is located below the rear seat; the other part is integrated in the engine compartment.

The aims of the design of the vehicle consist in achieving a moderate but acceptable driving performance, which means a top speed of 136 km/h and an acceleration from

0 – 100 km/h in 12.5 seconds. The realization of functional modules with a minimal number of interfaces, being strictly defined, is another design criteria. The modules are realized as closed boxes.
The vehicle mass of 1922 kg is the sum of the subsystems: vehicle body 957 kg, components of the electric drive system 301 kg, the fuel cell system 496 kg and the supercapacitor system 168 kg.

The power train of the HY.POWER is shown in Figure 2 and consists of a fuel cell, capacitors, power electronics and electric motor. Compressed hydrogen was stored in two 26 l tanks at a pressure of 350.bar.
Use of the various components with high efficiency requires an intelligent energy management controlling the energy fluxes from the fuel cell and from and to the capacitors in order to respond to the power demands of driver in an optimal way. The respective driving strategy is described in /5/ and allows a good optimization without knowing the driving profile in advance.

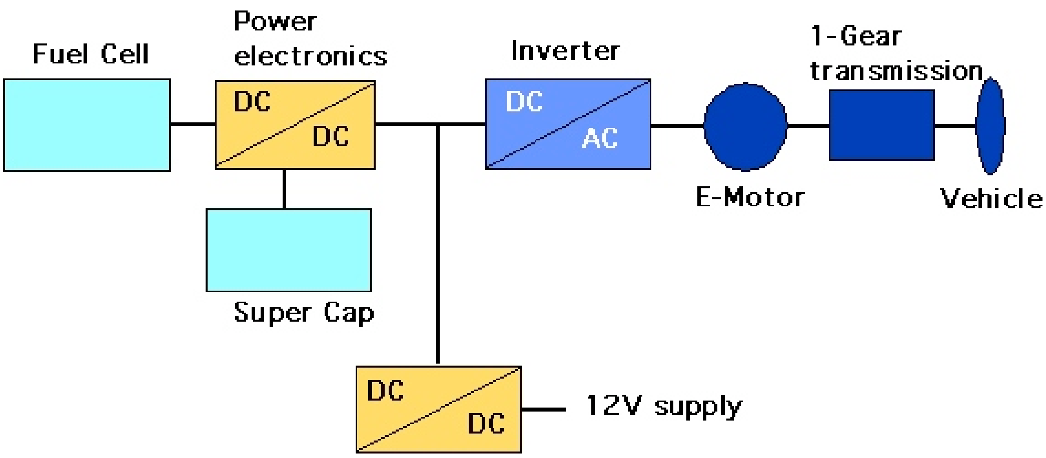

Figure 2: Scheme of the fuel cell- Supercapacitor hybrid powertrain

Components
Fuel Cell The fuel cell consists of six stacks with 125 single cells in series each. The six stacks were assembled to an array. In this array the stacks were connected gas wise in parallel and electrically as two parallel strings of 3 stacks in series in order to match the voltage requirements of the power train. For efficient manifolding of the process gases and the cooling liquid, requiring 6 connections to each stack, these media were connected to all stacks through a manifolding plate of a thickness of less than 10 cm. Figure 3 shows the set-up of the 6-stack array including manifolding plate. The weight of the complete array is 185 kg (stacks 140 kg and manifolding plate and structure 45 kg). The total power of the array is 48 kW (8 kW for each stack). During operation part of the power is consumed by the peripherical fuel cell system, i.e. at 35 kW FC gross power the FC net power is reduced to 28 kW.

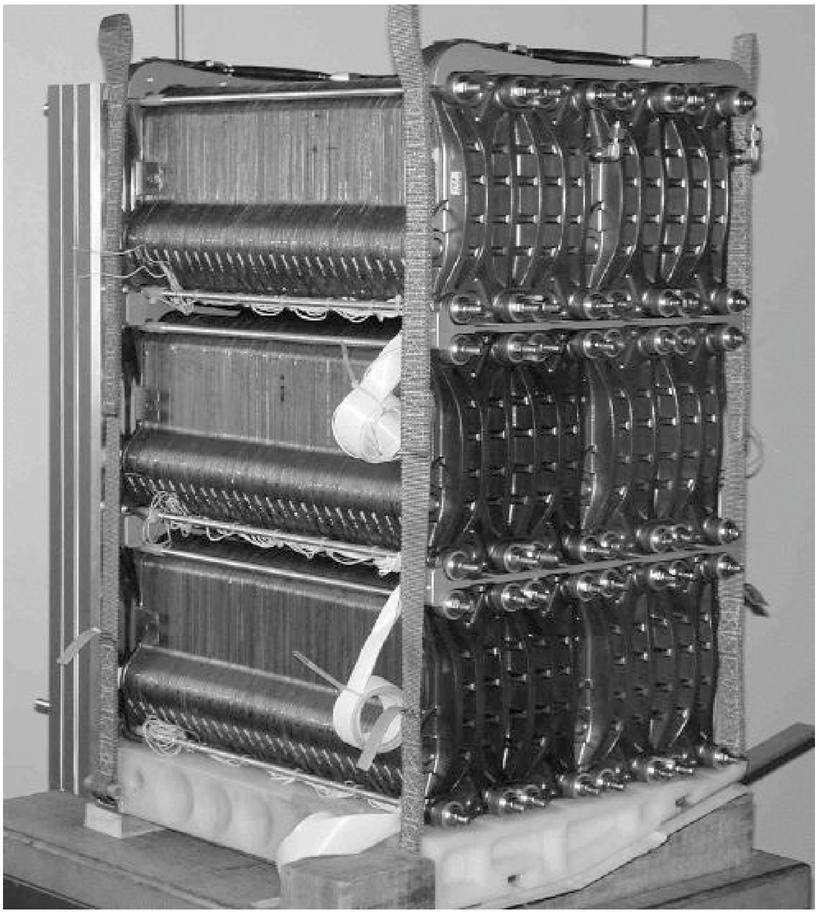

Figure 3: Array of six stacks of 125 cells with manifolding plate (below and left side). Total weight 185 kg.

Adequate performance under the conditions of the mobile fuel cell system, low degradation potential over time and the possibility for optimized preparation procedures have guided the selection process of the electrochemical components. Commercially available membranes (Nafion® 112, DuPont) and electrodes (ELAT, E-Tek) were evaluated and the respective preparation and assembly procedures developed. At the conditions of the mobile fuel cell system a specific power density of 320 mW/cm^2 (64 W/cell) was obtained.

The scale-up from a single cell (64 W) to a 125 cells stack (8 kW) was realized with small deviations between the stacks. The current/voltage characteristics of the 6 stacks integrated in the stack array (Fig. 3) and the comparison to a single cell under standard test conditions (stack temperature 70 °C, gas pressures 2 bar_{abs} (exit), stoichiometrics of 2 for both process gases, and dew points of 55° and 50° C for hydrogen and air respectively) are shown in Figure 4. The variation between the different stacks is fairly low. The results from Figure 4 show that the design of bipolar plates and stacks as well as preparation procedures are well scalable.

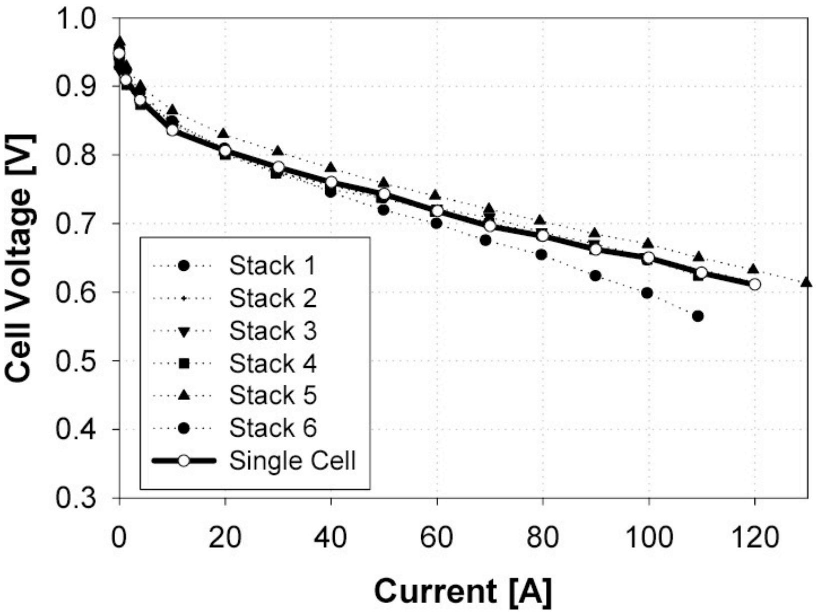

Figure 4: Current/voltage characteristics of single cell and of the six stacks (averaged of the 125 cells of a stack).

Power Electronics The simultaneous use of two different DC electrical power sources in the powertrain requires the application of DC-DC converters to properly control the electrical power flows /6/. The DC-DC converters are the interface between the drive inverter, the fuel cell system and the super capacitor-modules. Initiated by the drivers demand, the drive inverter transmits the required power to speed the vehicle. This power can be delivered from the fuel cell or from the super capacitor or from both systems together. The DC-DC converters allow sharing the power flow of the drive inverter between the super capacitor and the fuel cell in accordance to a reference value calculated from the strategy-controller.
For the hardware realisation triple interleaved DC-DC converters were chosen for the fuel cells and the super capacitors. A brake chopper was also installed in the DC-link to reduce its voltage in case of severe failure. The semiconductors are 600V-IGBTs with anti-parallel diodes. The chosen topology is shown in Figure 5.

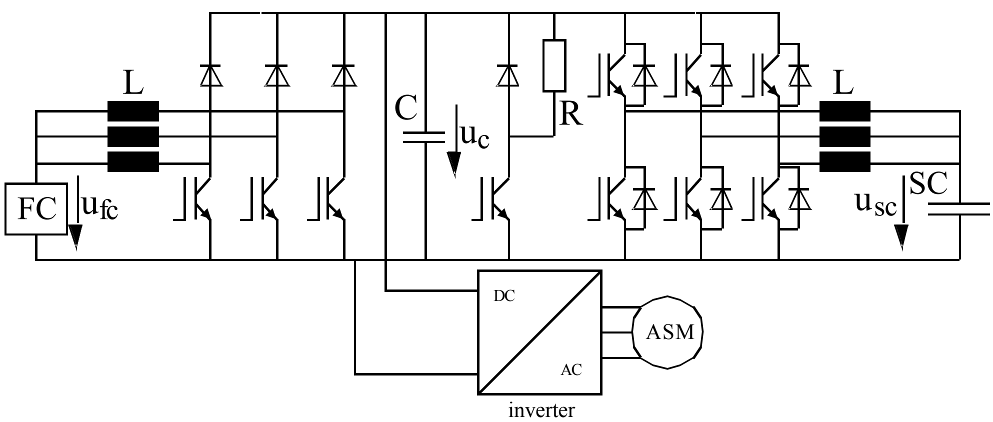

Figure 5: Topology of the DC-DC converters.

Supercapacitors

Single cell Supercapacitors with an organic electrolyte and activated carbon as electrode material were especially developed for the present application in a collaboration with montena components SA. Size and capacitance of the devices had to be adapted to the predetermined space available for the capacitors in the car. The single supercapacitor cell had a minimal capacitance of 1500 F and a nominal voltage of 2.5 V. The cells have a maximum specific energy of 5.3 Wh/kg and a maximum specific power of 4.8 kW/kg. Figure 6 shows the supercapacitor, which has a diameter of 50 mm and a length of 150 mm.

Figure 6: Supercapacitor cells used in the HY.POWER technology platform

The performance plot (Ragone Plot) of the capacitor is plotted in Figure 7. The Data were calculated from electrochemical impedance spectroscopy measurements according to a linear approximation developed by Christen et al. /7, 8/. The characteristics of the capacitor depend on the state of charge, which is a result of the voltage dependent capacitance. At full charge the capacitance achieves the maximum value.

12.5 V module Scale-up from the single cells to the complete modules for the vehicle was performed with intermediate steps. A small capacitor module of 10 capacitors (5 times 2) in series with a total voltage of 12.5 V was assembled including the voltage balancing electronics. The Ragone plot of this 12.5 V module, measured in terms of several constant power discharge cycles on the 10 kW test bench is also plotted in Figure 7.
On a 10 kW test bench, this module was exposed to a down scaled driving profile determined from a test drive across the Simplon pass with a real car equivalent to the HY.POWER fuel cell car. The results showed that the capacitors were capable of

providing the needed power and energy for such a profile. During this cycle of about 40 minutes the temperature of the module was measured in a thermically insolated box (no heat dissipation by cooling). During the cycle the temperature increase was only about 3.5 °C without any cooling.

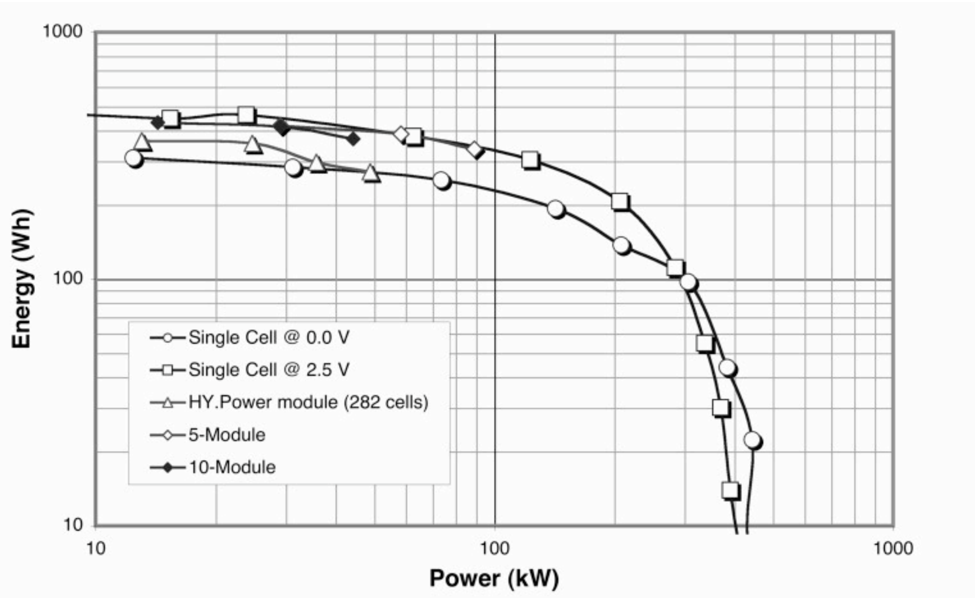

Figure 7: Ragone plots of the single cell (at 0.0V and 2.5 V), two 12.5 V modules (5 and 10 capacitors) including voltage balancing electronics and of the HY.POWER 360 V module.

Although, inclusion of the active electronic voltage balancing unit increases cost and weight of the capacitor unit, it turned out to be necessary in order to reduce overcharging of individual capacitors. However, the type of voltage balancing unit necessary is debatable. The active electronic unit used in the HY.POWER vehicle does not waste excess charge but detours it to capacitors with lower voltage /9/. Further studies are needed to decide which voltage balancing unit is optimal for a fuel cell car application.

In addition, a 10 kW supercapacitor module (48 capacitors, 60 V) was tested in combination with a respectively down scaled fuel cell on a test bench and showed good performance. These tests and the module were described previously /10/. This 10 kW unit, however, was built with a previous generation of the voltage balancing electronics and with smaller (800 F) capacitors.

SC Module for HY.POWER

In order to meet the maximal voltage demand (360 V) of the HY.POWER application, as many as 141 pairs of 2 supercapacitors had to be connected in series, corresponding to an average voltage across each capacitor unit of 2.55 V. One module includes 2 times 70 capacitors while the other module is build with 2 times 71 cells. The two modules shown in Figure 8 are connected in series and had a total weight of 168 kg made up of 90 kg capacitor cells, 20 kg balancing electronic and electrical contacts and 58 kg for the metal housing, contactors, fuses and supplementary electronic components e.g. power electronic- and CAN-buscomponents. The total volume of the capacitor modules was 160 liters. The total ESR of both modules was 0.11 Ohm.

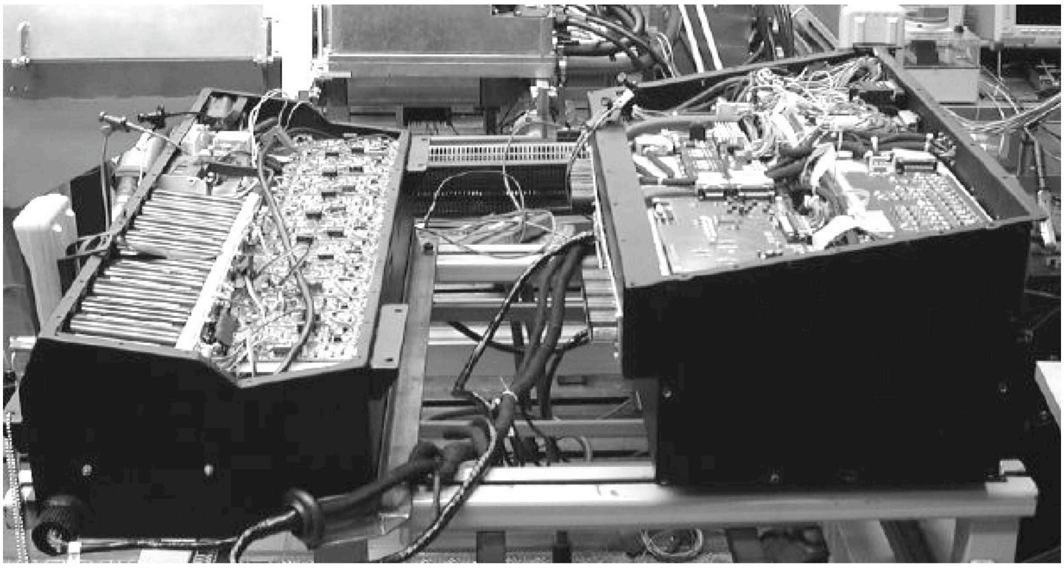

Figure 8: The fully assembled two supercapacitor modules integrated in the powertrain

The energy content and the power of the module was measured on a dynamic test bench with an electric motor to charge or discharge the capacitors at constant power between half (180 V) and full (360 V) rated voltage. The module was capable of providing a constant power of 50 kW during 15 seconds of discharge from full to half rated voltage, as shown in fig. 9. This is equivalent to an energy content of 210 Wh @ 50 kW. The theoretical efficiency of this discharge process with the above-mentioned ESR is 92 %. The maximum energy content of the module is 360 Wh.

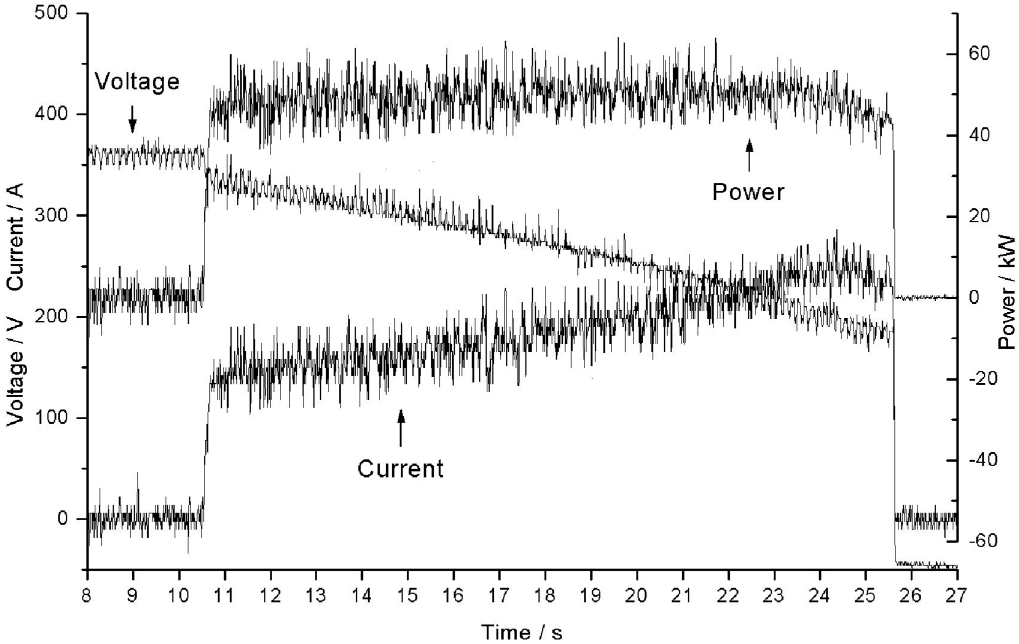

Figure 9: Measured current, voltage and calculated terminal power during a constant 50 kW discharge of the capacitor modules.

We also measured the Ragone Plot of the two capacitor modules by application of constant power charge and discharge runs on the test bench. The resulting data are also plotted in Figure 7. The plots of Figure 7 clearly demonstrate that it is well possible to estimate the performance of larger SC modules from single cell measurements. The measurement for the 360 V module also shows, that power to be delivered by the capacitors is not an issue. The capacitor bank works well below the optimum working point, which falls between 100 kW and 200 kW.

Despite the great number of series connections, it was possible to keep the series resistance ESR of the module low, which contributes to the high power capability and to a good efficiency, both essential for the use in a drive train system. The chosen cooling system seems to be sufficient to keep the module temperature at a tolerable level during cycling and helps to cool the capacitors to a lower temperature during breaks, which leads to a lower self discharge and a longer lifetime of the capacitors.

In order to verify the thermal performance of the modules and its cooling system, the modules were charged and discharged with 30 kW load (corresponds with a charge-/discharge-time of 30 seconds) generated from the test bed and the electric motor. In a duty-cycle of 50 % the capacitor modules showed a maximum temperature increase of 15 °C after 2700 s of cycling with 30 kW. During the following 1800 s break the temperature dropped about 10 °C. During the test the modules were closed and only small air ventilation was forced with small fans.

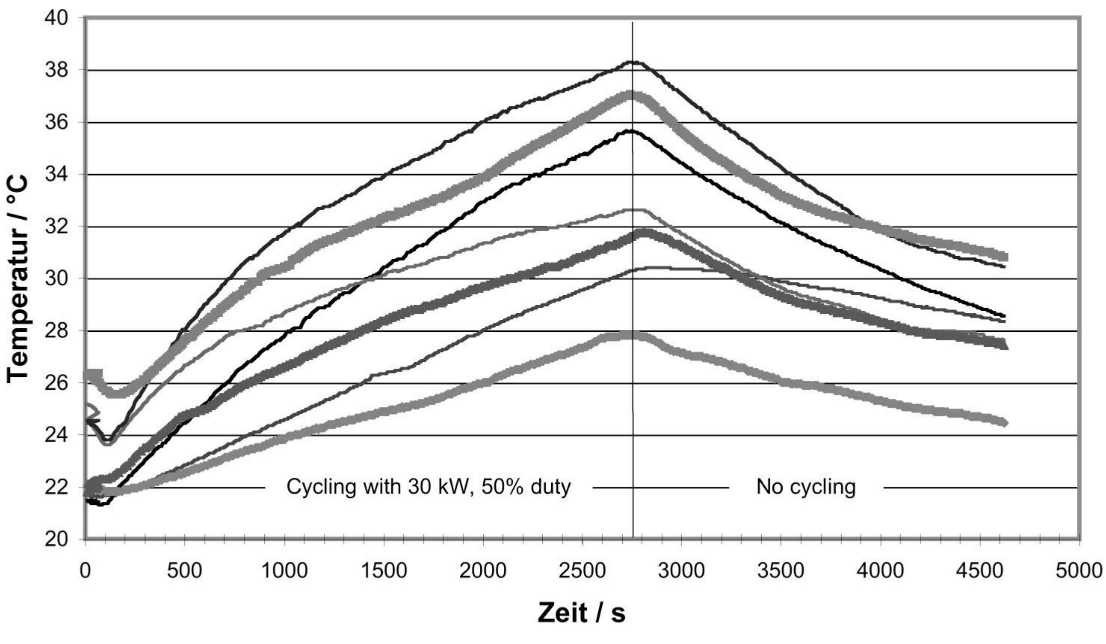

Figure 10: Temperature evolution at various test points in the two SC modules placed in the front (thick lines) and under the rear seat (thin lines) of the car during constant power charge and discharge with 30 kW and a duty cycle of 50%.

The interplay between fuel cell and supercapacitor during part of an NEDC is visualized in Figure 11. Between 1000 and 1450 sec the power profile of the fuel cell is relatively smooth compared to the total power of the inverter. Positive as well as negative peak power is consumed / provided by the supercapacitors.

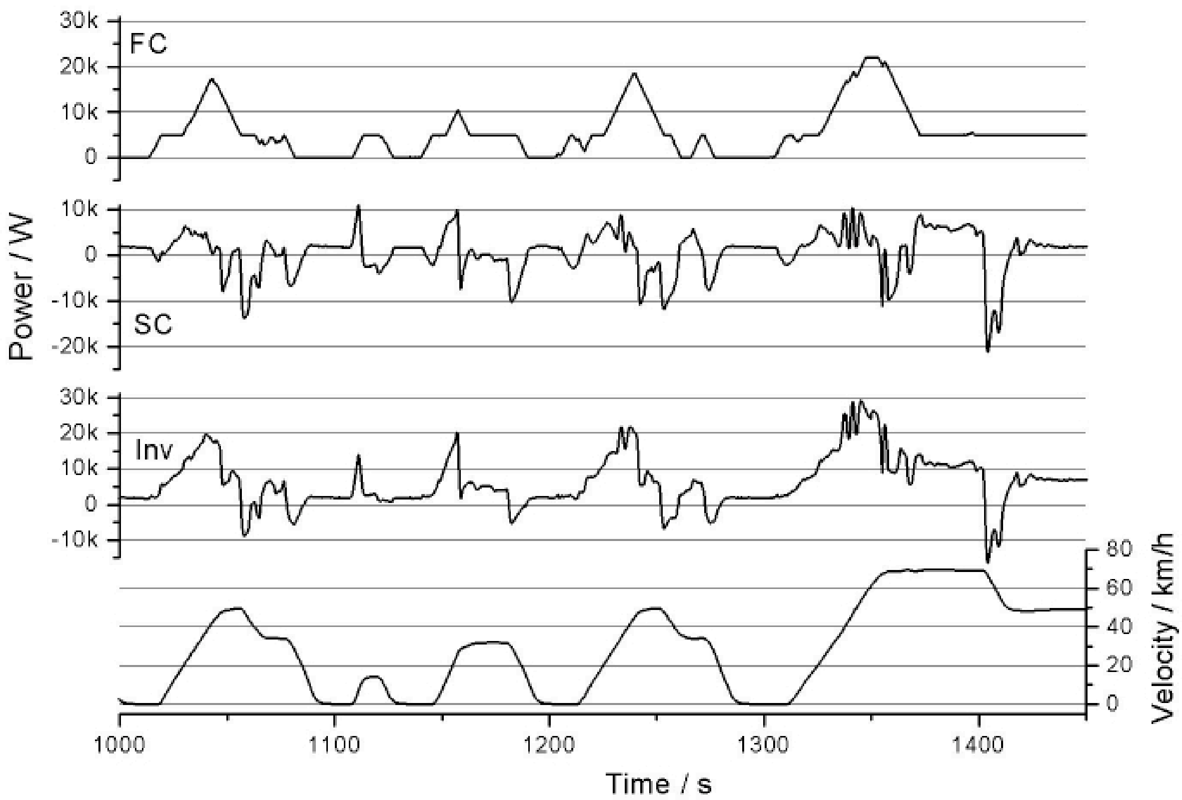

Figure 11: Vehicle speed and power of FC, SC and Inverter during a section of the NEDC.

The main argument for the intermediate short term storage device is recuperation of braking energy. Therefore the fuel consumption of the vehicle was measured for the NEDC with the recuperation mode switched off and on. The fuel consumption, based on the H_2 transformed into electricity, without recuperation was equivalent 6.1 l/100 km and with recuperation only 5.3 l/100km, which corresponds to a saving of 15%. This is close to the theoretical savings shown in Figure 1 and is only possible if all components of the electrical recuperation chain work at average efficiencies of 95% or above.

The high power and energy requirements, the high demand for regenerative braking and the extreme climate conditions (-10 °C) made the drive from Brig over the Simplon pass an ideal test drive for the demonstration of the maturity of the developed fuel cell, energy storage and drive train technology.

In Figure 12 the HY.POWER is shown arriving at the top of the Simplon pass in the Swiss Alpes.

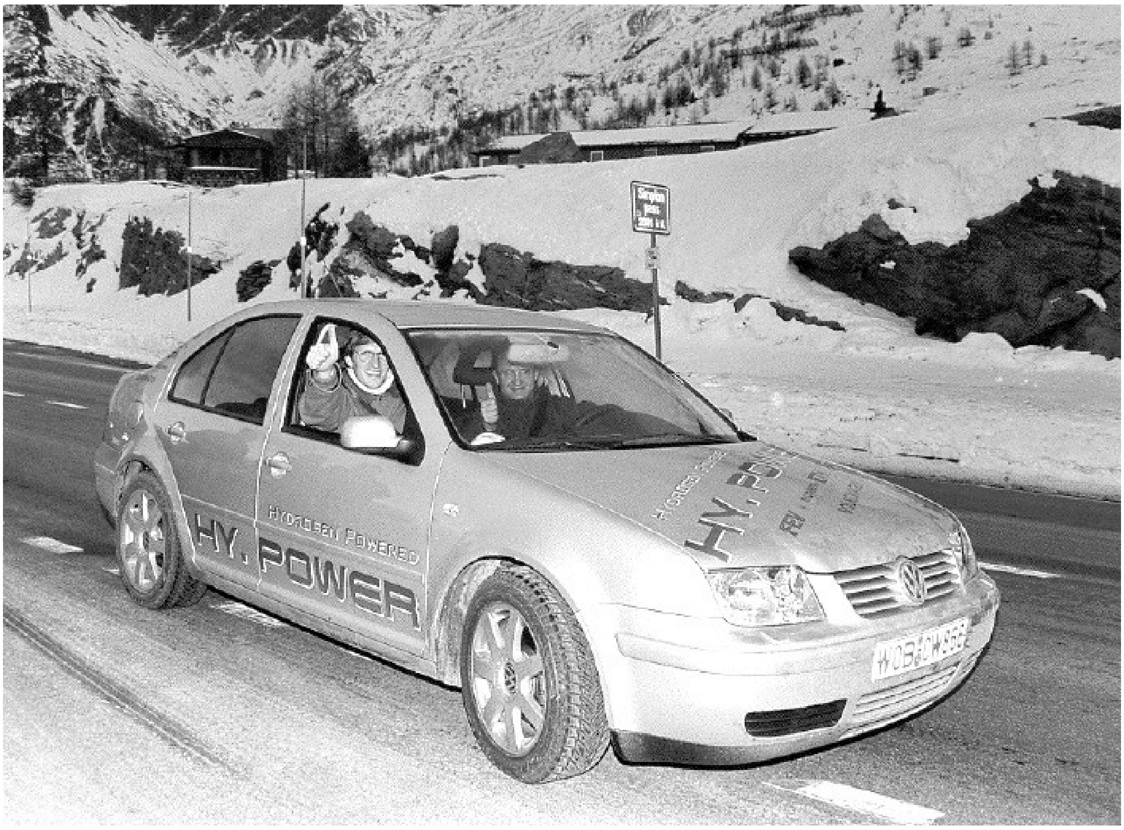

Figure 12: On January 16, 2002 the Bora HY.POWER crossed the Simplon pass in Switzerland

Summary

In the presented paper the power train of the HY.POWER vehicle, a technology platform, is presented with emphasize on the supercapacitor which was used as the short term electrical storage device. The combination of the supercapacitors and the fuel cell system enables the use of an advanced asynchronous electro-motor as passenger car propulsion unit. Recuperation of braking energy resulted in an equivalent fuel saving of 15%. On January 16, 2002 the HY.POWER vehicle crossed the Simplon Pass in Switzerland (elevation 2002 m over sea level).

Acknowledgements

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