SUPERCAPACITORS FOR PEAK-POWER DEMAND IN FUEL-CELL-DRIVEN CARS

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ABSTRACT

A downscaled drive train with a 6.5 kW fuel cell and a 10 kW supercapacitor module was realized and tested. The voltage levels and the energy flow between fuel cell and supercapacitor were controlled by an electronic unit. The combined fuel-cell/super-capacitor drive train was tested with a modified New European Driving Cycle (NEDC).

The 60 V, 60 F supercapacitor module consisted of 2 x 24 capacitors in series having a capacitance of 800 F each. The capacitors had a max. specific energy of 2.75 Wh/kg and a max. specific power of 6.5 kW/kg. An active electronic unit managed voltage balancing among the 24 capacitors in series. The capacitor module had a max. total energy of 30 Wh and a total max. power of 45 kW and could deliver 10 kW over a period of 6 seconds.

It was demonstrated that a supercapacitor is an energy storage device that can be used efficiently in vehicle applications for recuperating braking energy and boosting peak power.

INTRODUCTION

Reduction of local emissions and improved fuel efficiency of passenger cars has for many years been the driving force for new power train technologies. In this context fuel-cell-powered cars turned out to be those most likely to meet future environmental demands. In addition to a highly efficient electric-to-mechanical energy conversion, recuperation of braking energy is a potential further step toward higher mileage of passenger cars. The fuel cell itself is not capable of energy recuperation.

For such recuperation a storage device is needed. If an electric motor propels the vehicle, the braking energy can be transferred in the generator mode to an electrical energy storage device, which can be a supercapacitor.

In a fuel-cell/supercapacitor power train an electronic power unit is needed to match the voltage levels of the fuel cells and supercapacitors. The electrical energy flow is controlled by an electronic unit (1) and can be split between the sources fuel cell and supercapacitor. For recuperation the total flow has to be transferred to the supercapacitors.

Supercapacitors are known for their enormous cycle stability and for their relatively high specific power (2). A Department of Energy (DOE) ultracapacitor development program was initiated in 1989, and near-term (spec. energy: > 5 Wh/kg, spec. power: > 0.5 kW/kg) as well as advanced goals (spec. energy: > 15 Wh/kg, spec. power: > 2.0 kW/kg) were defined for 1998-2003 and after 2003, respectively (3). This supercapacitor was supposed to boost the battery or the fuel cell in hybrid electric vehicles to provide the necessary power for acceleration, and additionally allow braking energy to be recuperated. However, the specific energy of capacitors available today still is typically below 10 Wh/kg. Another drawback of electrochemical capacitors is the low single-cell voltage of about 2.5 V. The voltage requirements in an electric vehicle are about 300 V, therefore, many capacitors have to be connected in series. In order to prevent significant voltage imbalance between the capacitors, measures have to be taken for voltage equilibration. Various methods for voltage balancing exist, ranging from parallel resistors to active electronic devices. In any case, such measures create additional cost and weight.

In the present paper we demonstrate that the combination of a fuel cell with a supercapacitor is a feasible way to boost a fuel cell and to enable energy recuperation in an electric vehicle. We will not discuss alternative systems such as a fuel cell/battery or a battery/supercapacitor combination.

EXPERIMENTAL

10-kW test stand for SC

The 10-kW dynamic test stand consists of a polymer electrolyte membrane (PEM) fuel cell, a supercapacitor module, an electronic load (DS5010 Höcherl&Hackl GmbH, Prackenbach, Germany), power electronics and a control system.

The fuel cell with a nominal power of 6.5 kW was developed at PSI and is described in more detail elsewhere (4). The nominal power of the fuel cell is defined at an efficiency of 0.5, which corresponds to a single-cell voltage of 0.62 V. The fuel cell system includes all auxiliaries such as compressor, cooling and humidification.

The power electronics was developed at the Chair of Power Electronics and Electrometrology at the Swiss Federal Institute of Technology (ETH). Dc-dc converters control the power flow between the various elements.

The controller unit consists of a dSpace MircoAutoBox 1401/1504 and WAGO CANopen CAN-Bus system. Matlab/Simulink software was used for programming.

Capacitor

Electrode preparation. Activated Carbon, Norit A supra eur. (Norit, 2000 $m^2 g^{-1}$ BET), sieve fraction < 60 µm was used as the active material. Carboxymethyl cellulose (CMC, as sodium salt, low viscosity, Fluka) to be used as the binder was dissolved to a 5-% solution in water/methanol (1:1) solvent. The current collector was a specially treated aluminium foil 35 µm thick (the treatment leads to a better adhesion and better electrical contact).

Twenty grams of the sieved Norit A supra eur were stirred into the appropriate amount of CMC binder solution. The mixture was diluted with a certain volume of solvent (water/methanol) and then homogenized for 1 minute in order to obtain a readily flowing slurry. The mixture was cast onto the metal foil with a doctor-blade coating assembly using a blade-to-foil distance of 300 µm. The coated electrode was first dried with a hot air stream, then in an oven at 100 °C for at least 1 h.

Using the above formulation, electrode bands were produced on a commercial coating machine. With these electrodes capacitors were built at montena SA. The electrodes were spiral-wound on commercial winding machines with separators between the electrode layers. Before soaking with electrolyte the electrodes were dried in a vacuum oven. The electrolyte was tetraethylammonium tetrafluoroborate (TEATFB) in acetonitrile.

Impedance. All impedance measurements were carried out with a Zahner EIS IM6 module. The spectra were recorded from 10 kHz to 10 mHz with an amplitude of 10 mV. For complete electrolyte impregnation, all cells were left in the electrolyte for at least 15 min prior to the measurements.

Module. 48 capacitors were connected in a module with 2 x 24 capacitors in series. Connections were made by copper plates 2 mm thick. For better contact the surfaces of the capacitor terminals and the copper connectors were cleaned with an abrasive. A resistance of about 30 µOhm was achieved in the individual contacts. Six electronic units were mounted on top of the capacitors (see Figure 5) for voltage equilibration. Each unit consisted of a power board and a control board. Details of these units are described in (5).

DISCUSSION AND RESULTS

Today, fuel-cell cars are considered as the most promising solution for sustainability in transportation because they are efficient, may run on renewable fuel, and have near-zero emissions when H_2 is used as the fuel. Recuperation of braking energy, however, is not possible with a fuel cell alone. Supercapacitors (electrochemical double-layer capacitors) when combined with the fuel cell allow energy to be recuperated and are able to assist in brief power-demanding acceleration periods.

Within an ongoing project at the PSI a 10-kW dynamic test stand was developed in order to test the interplay between a PEM fuel cell (6.5 kW), a supercapacitor module (10 kW), and the power electronics controlling the flow of energies.

Energy Recuperation

Braking energy recuperation will increase the efficiency of fuel consumption in any vehicle. Estimates of the percentage of energy which can be recuperated as a function of different driving cycles in a small (750 kg) and a large (1500 kg) car are shown in Fig. 1 (6). Up to 25 % of energy may be recuperated in an ECE cycle. The difference between the two cars is not significant. However, the details of the driving cycle have a significant impact on recuperable energy. In a highway cycle the percentage is only about 5 %.

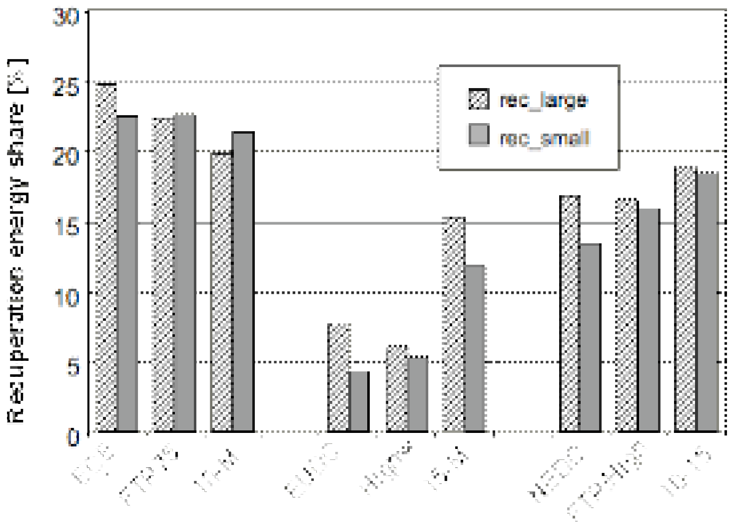

Figure 1: Potential energy savings by recuperation in a small vehicle (mass 750 kg, rolling resistance 0.01, air drag 0.6 m^2) and in a large vehicle (mass 1500 kg, rolling resistance 0.013, air drag 0.7 m^2) in different driving cycles.

For electrical energy recuperation the efficiency chain of all components involved must be optimized. During recuperation and reuse the energy flows from the wheels through the transmission (trans), the generator (Gen), and the power electronics (PE) to the supercapacitor (SC) and later back to the wheels. Thus, the recuperation efficiency defined as

$$\eta_{rec} = \frac{\textit{delivered energy at the wheels}}{\textit{restored energy from the wheels}}$$

is given by:

$$\eta_{rec} = \eta_{trans} * \eta_{Gen} * \eta_{PE} * \eta_{SC} * \eta_{PE} * \eta_{EM} * \eta_{trans}$$

For advanced components the efficiencies at medium load are given by η_{trans} = 98, η_{Gen} = 0.9, η_{PE} = 0.97, and η_{EM} = 0.9. Therefore, supercapacitor efficiency translates with a factor of 0.73: η_{rec} = 0.73 * η_{SC}.

Overall efficiency is a function of power transferred. As a rule, the efficiencies of all components other than the supercapacitor increase with increased power, but that of the supercapacitor decreases. At a power output of 8 kW the supercapacitor module used in the present work had a calculated charge/discharge efficiency of 0.88, whereas at a power of 2 kW its cycle efficiency increased to 0.95.

System Characteristics

The present power train consists of a fuel cell system based on a stack with a nominal electrical power output of 6.5 kW and a supercapacitor module able to deliver a peak power of more than 10 kW for several seconds. The configuration of the power train can be seen from Fig. 2. An electronic power unit is needed to match the voltage levels of the fuel cell and supercapacitors (1). The electrical energy flow can be split between the sources fuel cell and supercapacitor. In the recuperation mode the total flow is transferred to the supercapacitors.

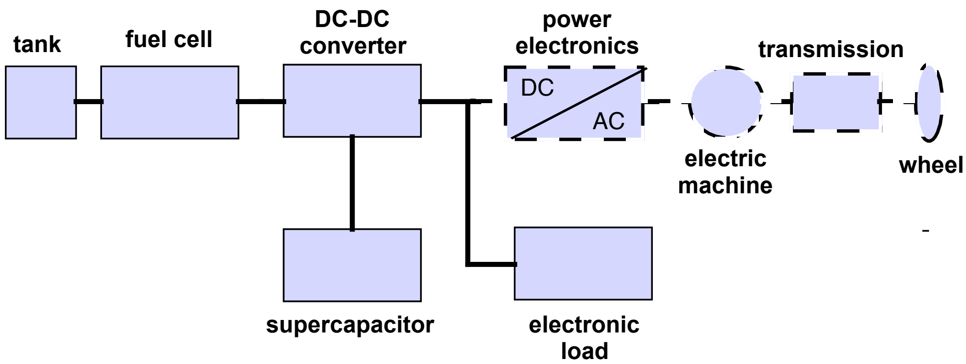

Figure 2: Schematic view of the power train system combining a fuel cell and supercapacitors. For the tests presented in this paper an electronic load replaced the motor.

The power electronics (PE) which controls the power flow between the sources and sinks was assembled from IGBT elements. It was not optimized for the voltage level of 60 V, but the voltage levels of the different sources and sinks could in fact be adapted to the driving-cycle requirements with the needed speed and accuracy. The PE switching frequency is in the range of 10 kHz.

The design of the power train is based on a vehicle with the following parameters:

Vehicle mass:	1100 kg
Rolling resistance:	0.01
Air drag (c_w*A):	0.6 m^2

For a top speed of 150 km/h the power train must deliver 30 kW at the wheels. Combined with another maximum power of 30 kW drawn from the supercapacitors, the vehicle can accelerate to 100 km/h within less than 12 seconds. For full-power acceleration to 100 km/h, the mechanical energy derived from the supercapacitor is about 100 Wh.

During braking, the supercapacitor must be able to absorb energy at a rate proportional to deceleration, which implies values of power equivalent to those of maximum acceleration. The kinetic energy content of the vehicle at 80 km/h is 85 Wh.

In practice, it will be desirable in order to conserve PE efficiency and power capability to not operate at less than one-half of the nominal voltage in any part of the cycle.

Considering the power values discussed in preceding paragraphs, the following specifications were developed:

Power demand out of the supercapacitor	P_{SC}	37 kW
Energy demand for acceleration	E_{SC_acc}	164 Wh
Energy demand for recuperation	E_{SC_rec}	92 Wh

Such demands can be satisfied by a supercapacitor module of 66 kg having an energy density of 2.5 Wh/kg and a specific power of 1000 W/kg.

The pilot power train was tested as a mobile unit where an electronic load replaced the electric motor of a car. This load is a mere power sink, it cannot be used to simulate the power output due to braking. Recuperation was simulated, therefore, by charging the supercapacitor from the fuel cell at an appropriate level of power. With respect to all other operating conditions the setup can be regarded as a realistic demonstration.

Supercapacitors

The supercapacitors were carbon-based double-layer cells with organic electrolyte. In a research collaboration between the Paul Scherrer Institute and montena SA, a super-capacitor (Figure 3) with the following characteristics has been developed:

U_{nom}:	2.5 V
Capacitance:	800 F/cell
Max. spec. power:	6500 W/kg
Max. spec. energy:	2.75 Wh/kg
ESR (@ 1kHz):	1.0 mOhm

Electrodes have been developed at the Paul Scherrer Institute (PSI) specifically for these capacitors, and are produced on a commercial coating machine. For improved electronic conductance, different binder concentrations and the effects of special additives were tested. The specific capacitance of the active carbon decreased with increasing binder content, as expected. On the other hand, no positive effect could be detected with graphite additives (7). Capacitors were produced with these electrodes at montena SA on commercial winding machines. For further details see the Experimental section above.

Figure 3. Supercapacitor cells with a capacitance of 800 F developed in a collaboration between PSI and montena SA.

The Ragone plot of the supercapacitor cell is shown in Fig. 4. It was calculated from the electrochemical impedance data using the equation given by Christen et al. (8).

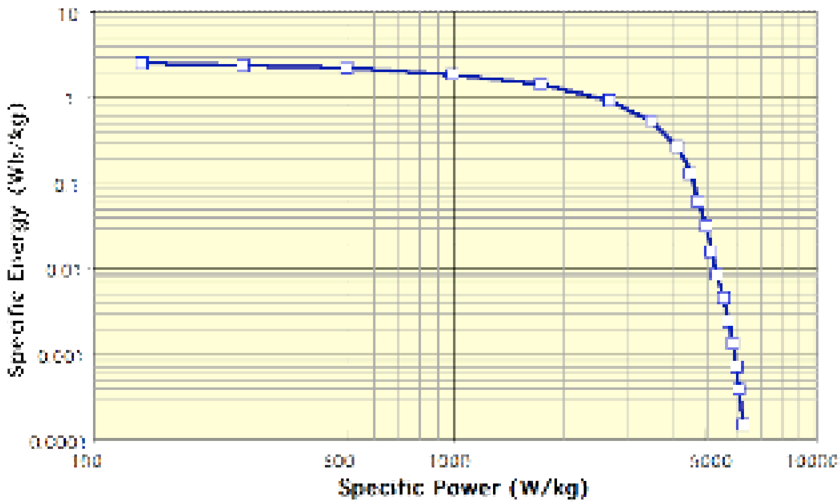

Figure 4: Ragone Plot of the 800-F capacitor with PSI electrodes.

Capacitor Module

For tests of dynamic behavior, 48 cells of this type were combined to a module (two trains of 24 series-connected cells put in parallel) in order to achieve a maximum voltage of the module of 60 V, a capacitance of 60 F, and an ESR of 20 mOhm (@ 1 kHz). This module is shown in Fig. 5. Note that about 30 % of the ESR originates from contact resistance, which is an important factor when connecting many single devices in series. This resistance must be minimized (see Experimental), and in addition it must remain constant over the lifetime of the capacitors.

Cycle tests performed with the capacitor module clearly revealed the need for voltage balancing preventing single cells from being overcharged. An active electronic voltage-balancing unit developed at the Swiss Federal Institute of Technology (EPFL) is able to equilibrate voltage differences existing within a capacitor unit of five cells in series (5). Cycle tests between 11 V and 12 V at a constant current of 20 A which were performed with five of our capacitors in series (12.5 V) showed that there was a spread of 300 mV between cell voltages when the electronic unit was switched off. With it switched on the spread decreased to 20 mV after 100 cycles.

Six of these voltage-balancing units were used for the 60-Volt supercapacitor module with its 24 cells in series. Here the voltage spread was never larger than 150 mV.

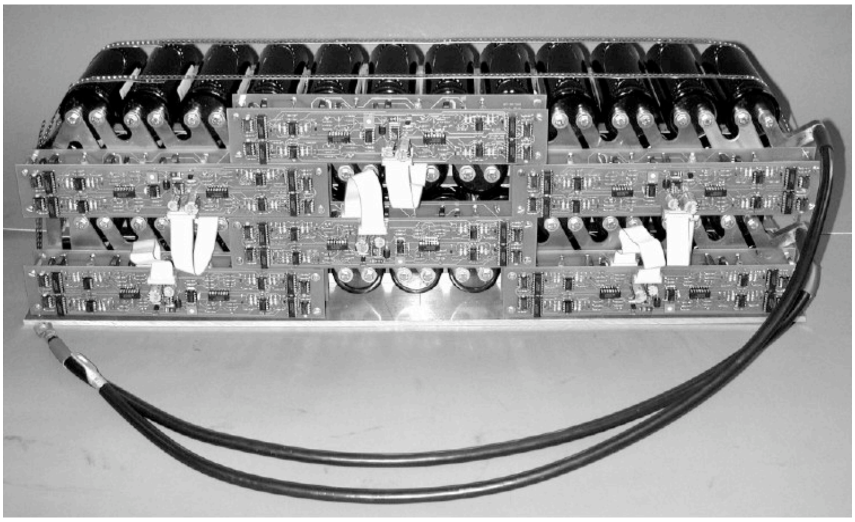

Figure 5: The supercapacitor module developed jointly by PSI and montena, combined with a voltage-balancing (charge-exchange) unit developed at EPFL. Its key data: 48 cells, 60 V, 60 F, ESR=20 m□., max. energy 30 Wh, max. power 45 kW.

The power train built from this supercapacitor module and a 6.5-kW fuel cell is designed to drive a reduced virtual vehicle.

Driving Cycle and Strategy

The power train was operated under the conditions of a New-European-Driving-Cycle (NEDC) with the power appropriately reduced to that of the virtual vehicle. The split of the power flow can be defined in different ways. One solution may be formulated as follows. Whenever the vehicle demands power for a given driving mode, this demand is covered by some power split between the fuel cell and the capacitor. When no power is demanded (idling) or during braking, power is delivered to the capacitors from the fuel cell or the electric machine (provided the capacitor is not completely charged). The system works most efficiently when satisfying average driving demand by the fuel cell and peak power demand (or rather the differential between average and peak demand) by the supercapacitor. In a defined driving test cycle, the average and instantaneous power demand can be calculated in advance. Under real-world driving conditions one can only rely on past and current performance. Therefore a more sophisticated driving strategy is needed, optimizing the energy exchange between fuel cells, supercapacitors and electric motor, while taking into account the limited power dynamics of the fuel cell system. Details of such driving strategy can be found in (9).

The combined system is greatly improved in its dynamics. A system with a similar configuration consisting of fuel cell, supercapacitor, and electric motor (or load) has been designed for a virtual vehicle, which can be propulsed with our test components. The power flow within a New European Driving Cycle (NEDC) for that virtual vehicle is shown in Fig. 6.

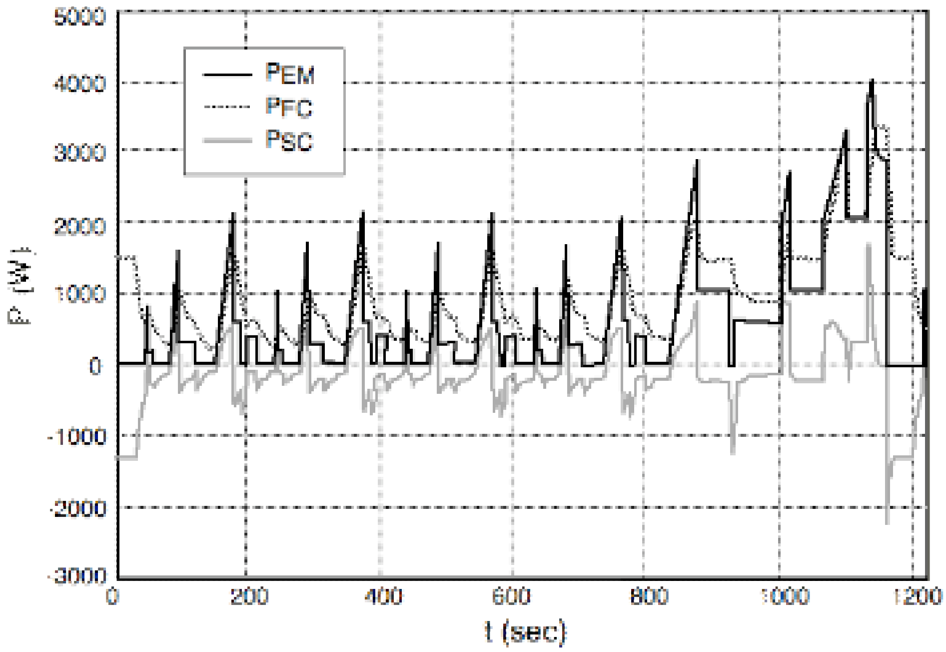

Figure 6: Power demand and measured power of the electric motor, the supercapacitor, and the fuel cell system during a NEDC.

The power flow from and to the supercapacitor module can be seen for the same reduced driving cycle in Fig. 7 in terms of the supercapacitor's voltage and current. For this particular experiment an additional 1000 W was demanded by the load in order to simulate the energy consumption of various auxiliaries and to maintain a power output of the fuel cell > 1.5 kW.

The advantages arising with the use of supercapacitors are obvious in high-speed acceleration and braking phases such as occurring toward the end of the test cycle. Rapid changes in power demanded by the electric motor (P_{EM}) are immediately satisfied by power from or to the supercapacitor (P_{SC}). The power demanded from the fuel cell (P_{FC}) follows a much smoother function. It is distinctly seen in these measurements that toward the end of the cycle where a high-speed acceleration step occurs, the dynamic power demand of the vehicle is furnished by the supercapacitor.

In the power range involved in the downscaled NEDC (<2 kW), the cycle efficiency of the supercapacitor cells was found as $\eta_{SC} > 0.94$, which implies an efficiency of reuse of the braking energy of almost 70%.

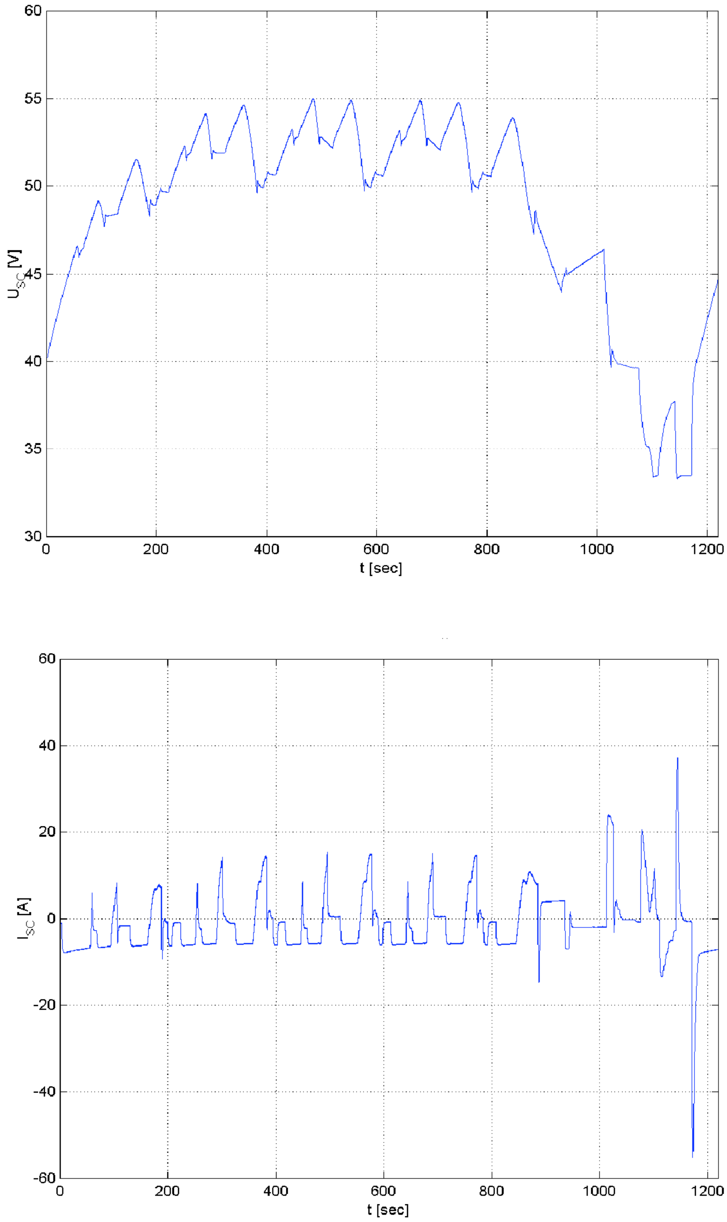

Figure 7: Voltage of the supercapacitor module (top) and the current flowing into and out of the module (bottom) in a reduced NEDC (P_{EM} + 1000). At the end of the cycle the charge level of the module is higher than at the start.

In the arrangement shown in Fig. 5 the voltage-leveling device consumes part of the energy stored in the supercapacitor. This constitutes a parasitic current outwardly equivalent to self-discharge of the supercapacitor which reduces the charge/discharge efficiency. However, these losses are small and will be further reduced in the future by an enhanced operating strategy according to which the voltage-balancing units will be off during less demanding driving periods, idling, and when the vehicle is parked.

The dynamics of the pilot power train are readily transferred to a virtual full-scale system. However, the efficiencies will be better in a full-scale system, since the power electronics had not been optimized for the reduced voltage level causing certain losses. Certain auxiliaries designed for bigger nominal power levels also operate less efficiently in a lower-power system such as our pilot.

CONCLUSIONS

From our experiments we can safely conclude that supercapacitors have the potential for brief-period peak-leveling applications especially in hybrid electric vehicles. The recuperation of braking energy is an ideal application for supercapacitors. An overall recuperation efficiency of close to 70 % can be expected when including all components of the drive train. The energy density of the supercapacitors needs to be further increased in order to meet the requirements of driving cycles more demanding than the NEDC. For higher efficiency the equivalent series resistance of the capacitor module should be further reduced. The dynamics of the pilot power train is representative of the potential of the full-scale setup. Its efficiency is not readily scaled up to the full-scale system; it should turn out to be higher.

ACKNOWLEDGEMENT

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