Ultracaps in power-assist applications in Battery Powered Electric Vehicles - Implications on Energy Management Systems

Dipl.-Ing. Detlef Heinemann
Siemens AG
SPE Technik Akademie Berlin
Nonnendammallee 104
D-13595 Berlin

Detlef.heinemann@bln.siemens.de

Prof. Dr.-Ing. Dietrich Naunin
Gregor Petsch
Technische Universität Berlin
Institut für Elektronik und Lichttechnik
Einsteinufer 17
D-10587 Berlin

naunin@tubife1.ee.tu-berlin.de

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Abstract

In this paper a research project at the 'Siemens AG Technical Academy of Berlin', started in January 2001 will be described. The project focuses on the development of an energy management system for light electric vehicles (LEV), introducing latest technology.

A power-assist system (Ultracaps) has to be added to a battery powered LEV. An energy management system to control both sources has to be developed. The Ultracaps used in this project have a capacity of 1200F per cell and are manufactured by EPCOS AG, Munich. 18 cells are connected in series and mounted in a case, resulting in a module capacity of 67F/42V. In that project, as an option, two of these modules can be used. In this case they are connected in parallel due to the voltage requirements of the vehicle. These modules have been designed especially for applications in the new 42V powernet being introduced to internal combustion engine vehicles (ICE) in the near future. The energy management system (EMS) described in this paper controls the flow of energy through the Ultracaps.

The behavior of the ultracaps has been measured under different testing conditions on a test bench. Therefore a test bench has been developed allowing discharge currents up to 4kW continuous power, 600A maximum discharge current, 200A constant charging current. The source as well as the sink are parametrized either by a PC or a special microcontroller/DSP. The microcontroller controlling the energy management system is the new 32-Bit TriCore TC1775-B (Audo) Controller from Infineon Technologies AG. It has been designed especially for automotive applications, such as engine management. The bench is controlled by a 80C164 Microcontroller.

Introduction

The 'Siemens AG Technical Academy of Berlin' started a research project in January 2001. The goal of that project is the development of a microcontroller-based energy management system introducing latest technology and demonstrating system capabilities in a light electric vehicle equipped with a battery as energy source and Ultracap moduls for power-assist applications.

The project has been split in several tasks

- X designing the hardware structure of the energy management system
- X evaluation of Ultracap behavior
- X evaluation of behavior of the batteries used in the demonstrator vehicle
- X development of a bench capable to handle necessary peak powers in order to run tests independently from road tests
- X development of an ac-inverter 6 kW
- X development of management system hardware and software for complete control of drive-train and energy storage systems
- X defining a control strategy for the energy management system
- X realization of the whole system
- X testing the system

Till the end of June 2001 the first seven steps have been realized. The developed energy management system will be presented on the conference and can be seen on the exhibition in the frame of EVS 18 in Berlin.

Laboratory Tests

In a first step bench tests have been performed in order to identify the behavior of the energy storage systems used. The Ultracaps have been cycled using constant current discharging and charging pulses between 100% and 60% SOC. Single cell voltages of all cells have been measured over time

a) without charge balancing unit

b) by use of a charge balancing unit principle: bypassing

The charge balancing unit equipped with the Ultracaps allows only small balancing currents (figure 1a). It has been designed for 42V powernet applications having a smoother load profile for the Ultracaps than that in traction applications. Measurements have shown, that deviations in cell voltages are in a range of U_{Diff}=150mV, calculating U_{Diff} by

$$U_{Diff} = \max(\mathit{Cell\ voltages}) - \min(\mathit{Cell\ voltages})$$

Due to the limitation of the maximum voltage to a value of 42V, an average voltage of 2.33V per ultracap cell can be reached. No critical voltages rising to more than 2.5 Volts can occur.

Figure 1b shows the results of a one hour lasting bench test, having connected 9 Ultracaps in series, representing half a 42V/67F module. The case-temperature of the modules increased from 30°C to 40°C during the test run, indicating no thermal problems when handling currents below 150A.

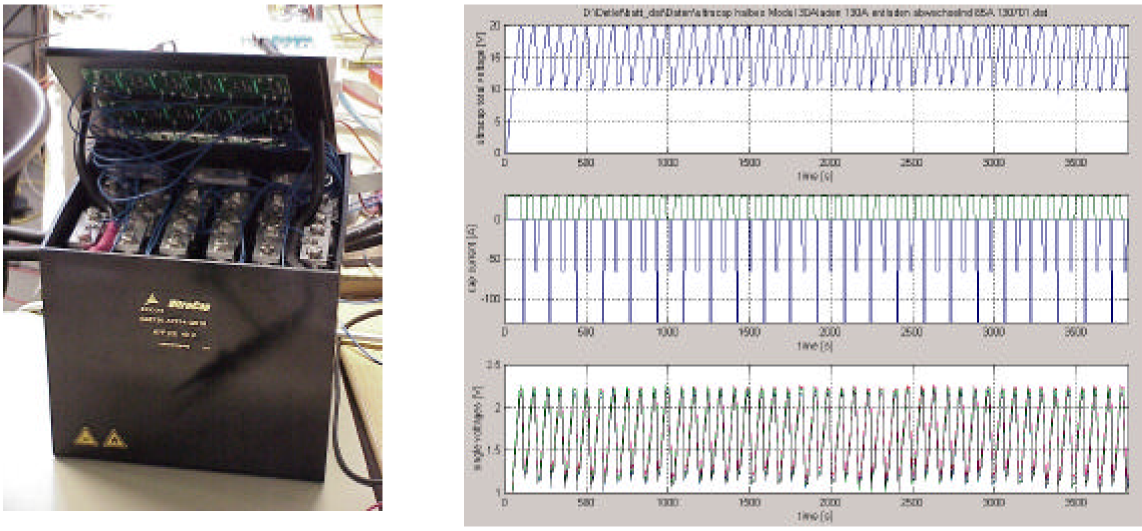

Fig 1: Ultracap module with charge balancing unit – Bench test indicating all cell voltages within their limits

An electric equivalent circuit has been simulated by use of PSPICE. The comparison of measured and simulated data will be shown. Cycling the caps by use of dynamic constant current load profiles causes non-linear voltage slopes. Therefore a complex electrical equivalent circuit has been used for simulations [EPC01]. In figure 2 the simulation model is shown, figure 3 compares the results between measurement on a bench and simulation results.

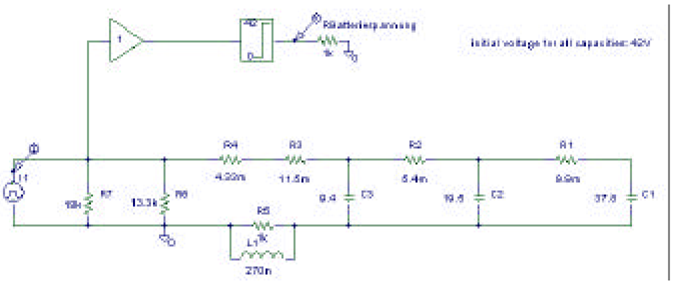

Fig. 2: Simulation model for 67F/42V Ultracap module

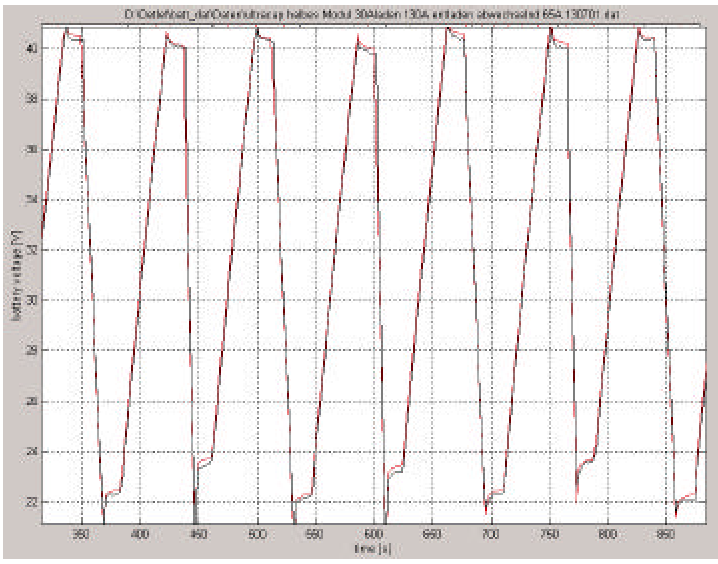

Fig. 3: Simulation results versus bench data

Temperature measurements inside the ultracap module have been performed in order to decide the technical solution of a thermal management system (TMS), a function controlled by the powerful Audo-Controller driven energy management system (EMS). In order to achieve a critical heat generation more powerful test cycles have been performed. The caps have been discharged using 4kW constant power phases down to 10V. Due to the disabled bypasses the Ultracap module has been charged only up to 75% of its nominal voltage. The temperature rises approximatly linear by 0.6K/cyc (figure 4). The cycle has been terminated reaching a case temperature of 45°C. Latest information from the manufacturer announcing 60°C to be the critical value for the caps. As a result one can consider, that a temperature management of ultracap modules becomes necessary when using dynamic high power cycling.

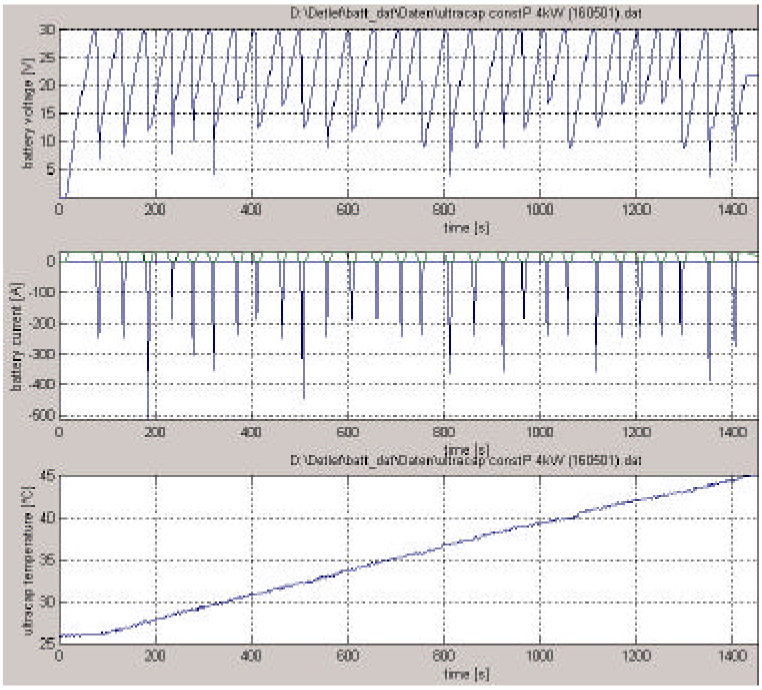

Fig. 4: Heat generation during 4 kW cycling of Ultracap module

Structures of energy management systems

The energy management system of the vehicle has to determine the available power from each energy source. In this application a fuzzy-controller has been designed, calculating the avaible power from several input values, represented by module temperature of the caps, SOC of Caps, SOC of the battery, velocity of the vehicle, dynamics of discharge current. The structure of the fuzzy controller is shown in figure 5.

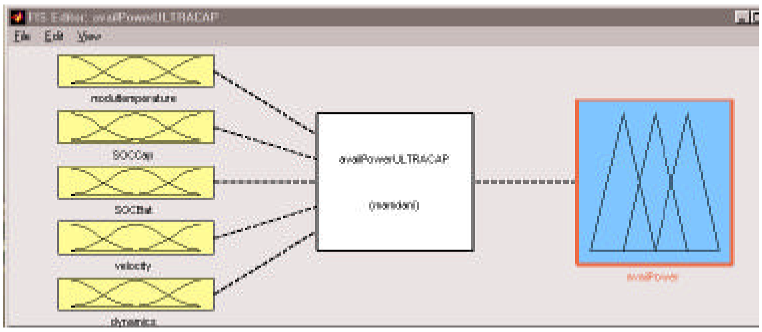

Fig. 5: Fuzzy system calculating available power

The Energy Management System has to optimize energy flow by the results of the fuzzy-calculations. Therefore a strategy related for managing the two sources depending to the application has to be defined. In principle, several different approaches can be found. [DIX00] announced a buck-boost converter to manage the transportation of energy (figure 6).

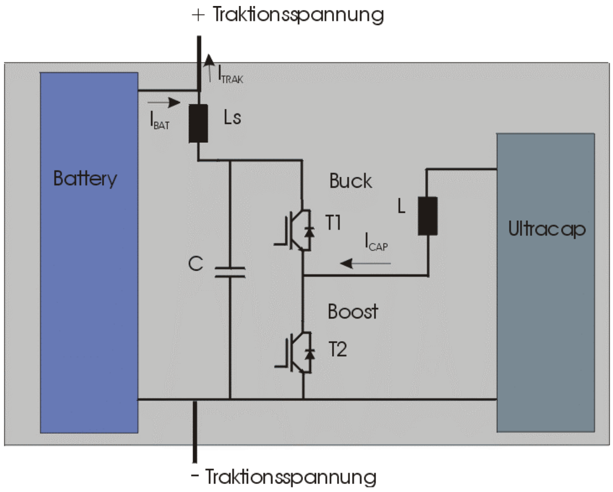

Fig. 6: Buck-Boost converter keeping Ucap < Ubat

The buck-side is used to charge the Ultracaps, while the boost-side is needed for discharging the caps. In our application, the LEV city-el hybrid, the battery has a nominal voltage of 36V. Keeping the caps always below the voltage of the battery results in only small amounts of energy stored inside the Ultracaps due to

$$W = \frac{1}{2} CU^2$$

The nominal voltage of the Ultracaps should be defined equal to the gassing-voltage of the battery, resulting 36% more energy stored inside the Ultracaps, so the principle shown in figure 6 is not applicable in our vehicle. If higher voltages than the battery voltage are needed, a step-up converter has to be used for recharging the Ultracaps. The EMS realizes the driving behavior by reading battery voltages. The decrease of the battery voltage is a result of an acceleration, so the Ultracaps will be discharged immediately. An increase of the battery voltage indicates a regenerative braking, resulting in charging the Ultracaps. The control algorithm of the EMS always wants to have a constant battery voltage. Low velocity assumes a coming acceleration, so energy has to be stored in the caps, while higher velocity shows the need of an immediate discharge of the Caps in order to be able to store regenerative power in the Caps. The DC-DC converter has to be designed for high power, resulting in higher system costs.

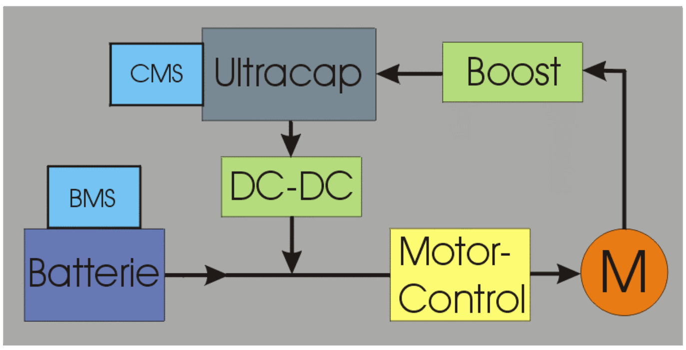

Fig.7: Additional current supplied by Ultracaps

A similar structure is shown in figure 7. The battery current is limited to 1.5*Iav of a normal drive cycle. Higher currents need the Ultracaps to be additionally connected to the traction chain by use of a DC-DC converter. Recharging the Caps is only possible during regenerative braking. The boost converter has to be designed in way, that high current charging of the caps becomes possible.
The maximum voltage of the caps can be higher than the battery voltage, now. The DC-DC converter can be unidirectional if the boost converter can drive high currents. The capacity of the Caps has to be so large, that not only acceleration from 0 km/h is possible, there has to be enough energy inside the Caps to allow accelerations within the cycle. It makes sense to have a bidirectional conververter in order to recharge the Ultracaps while the drive current remains relatively low. Both converters also have to be designed to deal with high powers.
A third principle is shown in figure 8. The difference to other structures bases on the switch. This way, only one of the energy sources can be connected to the drive-control. The switch is realized by semiconductors, it is controlled by the energy management system. Accelerations should be driven from the caps, while smaller currents are supplied by the battery. The EMS derives data from the CMS as well as from the BMS controlling on the basis of the data achieved the smitch, the boost-converter and the DC-DC-converter.

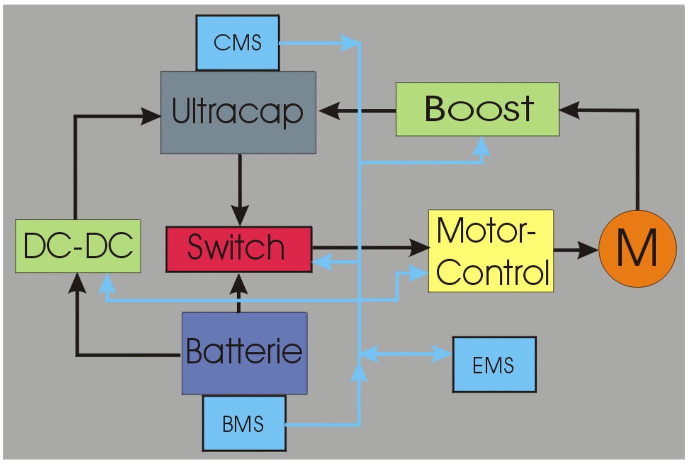

Fig. 8: Driving accelerations from Ultracap and normal loads from batteries

The DC-DC converter needs a nominal power of 700 W in order to fully recharge the Ultracaps from 30V to 42V in 40 seconds, a value which has been determined from different test runs in the city of Berlin. Maximum power demands having pulse width discharging the Ultracaps down to 30V normally occur every 30 to 50s. A standard city el load profile from a battery driven city cycle in Berlin is shown in following figure 9. A current limitation to 130A results in a discharge time of approximately 6 seconds for the Ultracaps.

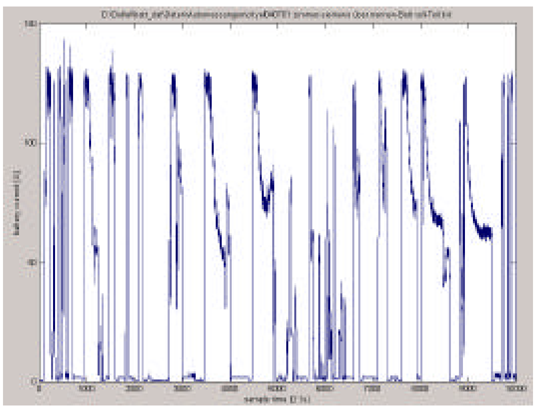

Fig. 9: Normal load profile for battery powered city-el in city-cycle

Realization of an EMS

The structure shown in figure 8 has been realized in this application. In order to minimize system costs all the functions of the BMS, the CMS and the EMS have been realized consisting of only one hardware device based on a TriCore AUDO 1775. All BMS and CMS functions are now logical subfunctions of the EMS, implemented as independent software tasks, the hardware structure is shown in figure 10.

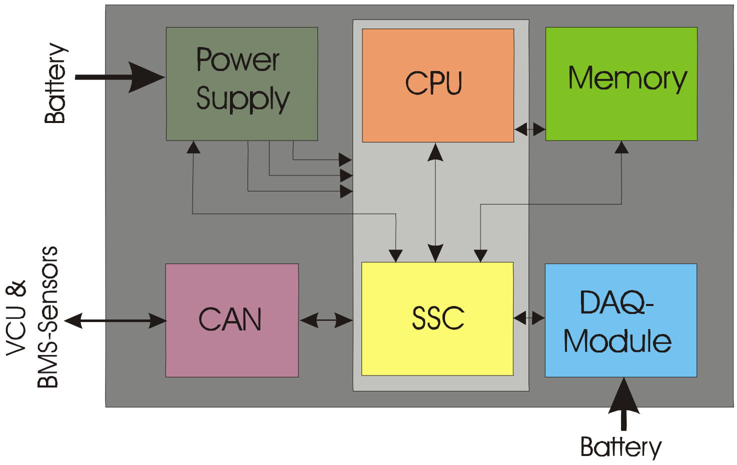

Fig. 10: Hardware structure of TriCore-based EMS

The EMS measures every single voltage of the ultracap module as well as the three battery module voltages. Using a data-preprocessing unit, all voltages are directly connected to the analog inputs of AUDO controller. Each value can be measured directly because of the elimination of voltage-offsets by the data-preprocessing unit. The principle of the voltage sensing is shown in figure 11. Five currents are measured in order to get every current value for each logical subsystem directly from measurements independently from calculations. The measured currents are the battery current, the cap discharge current, the charging current derived from the DC-DC-converter, the charging current derived from the boost converter and the motor current. Having separate measurements, the sampling rate for each logical block can be set independent from other tasks. An external ADC, having a 16-bit resolution, is connected via SPI-Interface to the microcontroller-unit (MCU). A demultiplexer controlled by the MCU switches the current to be measured to the ADC-input. The reference voltage of the ADC is measured by the 12-bit ADC of the MCU itself in order to fulfill software-recalibrations. The principle of the current sensor is shown in figure 11.

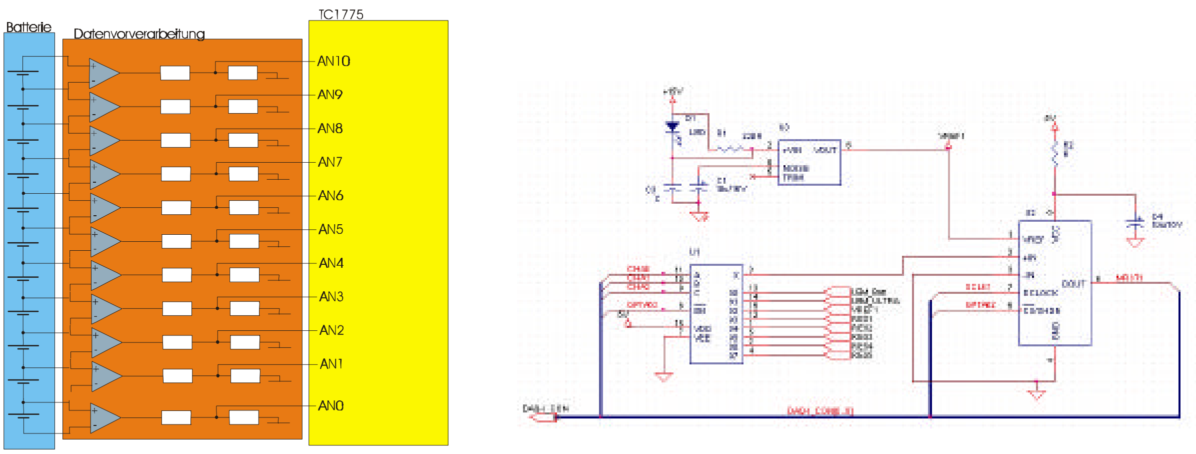

Fig. 11: Voltage sensing – current sensing

The EMS is supplied from the 36V traction battery by use of a step-down converter. The power consumption of the whole EMS is around 1W, but could be reduced by the implementation of the on-chip power-down capabilities. In different applications the supply should be realized in the same way due to the galvanic-coupling of EMS and data-preconditioning-unit. To install the EMS in the 12V net requires a galvanic decoupling. If a SPI-Interface gets used in combination with an external ADC and opto-couplers inside the SPI lines, such a demand can be satisfied.
A downsized hardware for a different data acquisition application, having only internal RAM (40k) and a size of 3.8 x 1.85 inches (9,5cm x 4,8cm) , has been tested successfully under motorsport conditions including real drive cycles, shock- (17g) and temperature-tests (125°C). The precision of all measured data fulfilled formula 1 demands. In order to minimize system costs, larger dimensions (resulting in less board-layers and more flexibility) have been chosen in this application. The EMS hardware BattMobil V is shown in figure 12

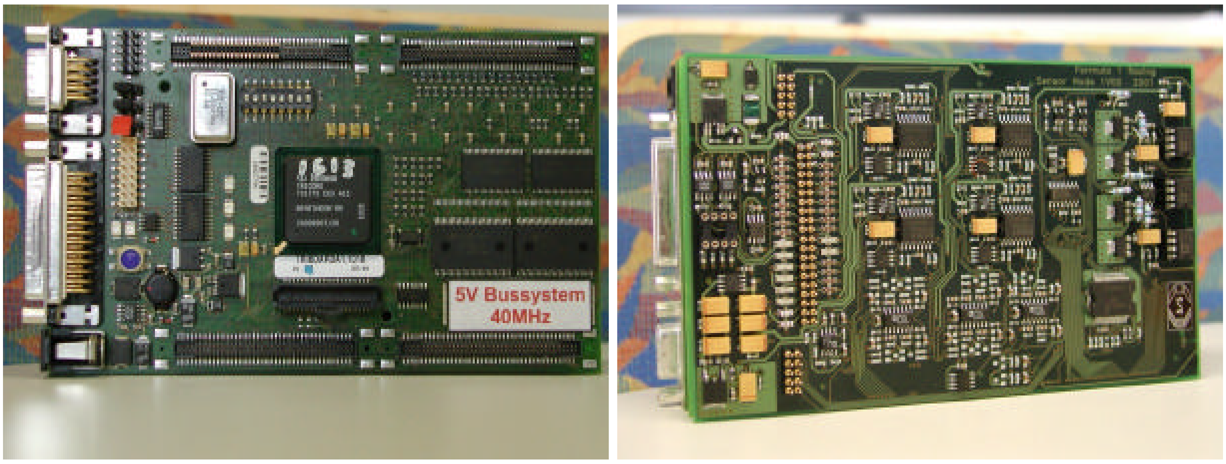

Fig. 12: TriCore- based MCU and data acquisition

DC-DC converter

The DC-DC converter recharges the ultracaps from the battery. The provided current is 10 A per module. This current is not enough to have the ultracaps always in a charged state. It takes too long to recharge the ultracaps from 30V to 42V. One solution to solve this problem is a parallel connection of several DC-DC modules. The microcontroller inside the DC-DC converter is able to control up to four power modules, which can be operated time-cascaded in order to minimize the ripple achieved. The principle of the DC-DC converter is shown in figure 13.

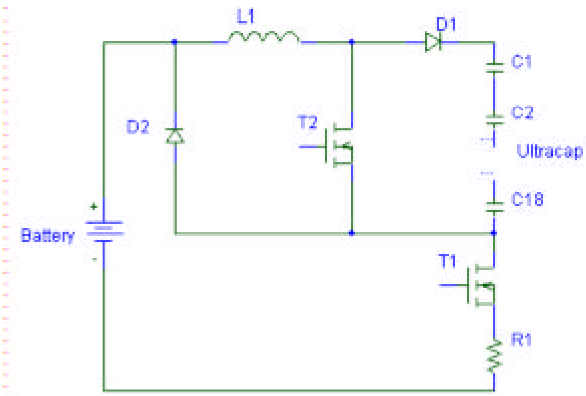

Fig. 13: Principle of DC-DC converter

T1 is operated always when Ucap < Ubat. T2 is off, then. The pulse width is controlled in a way that an allowed riple current is kept within its limits. When Ucap reaches Ubat, T1 is permanently on and T2 is chopped working as a step-up converter. Shunt resistor R1 measures currents when T1 is operated. The microcontroller gives the set values for the switching patterns. Although there is a demand of integrating regenerative braking for higher system efficiency, the DC-DC converter has to be designed for charging the Ultracap alone. The additional boost converter, needed for that purpose, helps to fulfil the power demands in a way, that the EMS initiates the stop of charging by use of the DC-DC converter, if the kinetic energy of the vehicle is high enough to get 100% SOC of the Ultracaps by use of regenerative braking. Different control strategies are shown in figure 14 to figure 16. Normally the city-el is a pure electric vehicle, having no additional power sources. Energy is taken from the battery during acceleration and constant velocity driving. There is no regenerative braking.

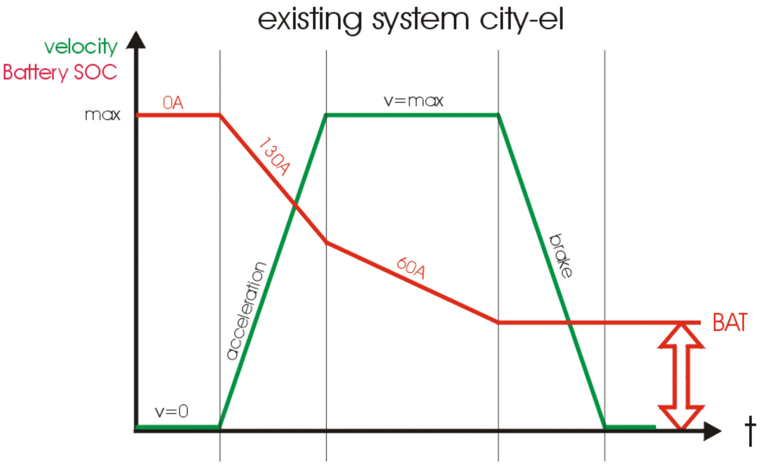

Fig. 14: Pure battery powered driving

In a first step the Ultracap module has been implemented to the traction powernet in a way that acceleration from zero speed are performed taking energy from the Ultracaps until a certain voltage level of the Ultracap module is reached or the current demand falls below a defined limit. Then, energy is taken from the battery for driving only. Recharging the Ultracaps is performed only by regenerative braking (figure 15). To get an Ultracap SOC of 100% requires braking from a speed of 50km/h, which is maximum speed. This way, it can't be guaranteed, that the Ultracap module reaches 100% of SOC. The energy management system is very simple, the benefits are limited, a DC-DC converter is not needed.

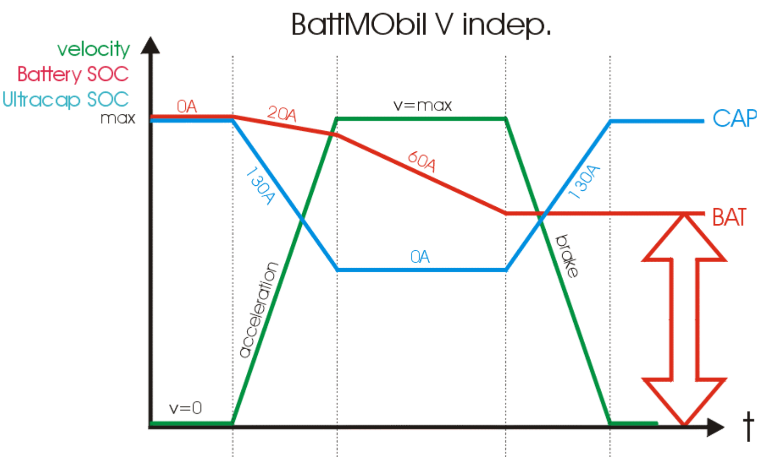

Fig. 15: Accelerations from Ultracap, recharging Ultracap by regenerative braking

The most intelligent control algorithm is needed, realizing a control structure based on figure 16. A DC-DC converter has been added to the system, resulting a structure discussed in figure 8. Accelerations should be driven by the Ultracaps in order to minimize the dynamics of the load profile for the batteries. Lab tests using our power bench have shown, that a significant increase in unlimited driving time can be achieved by the use of the control algorithm proposed in figure 8 and figure 16.

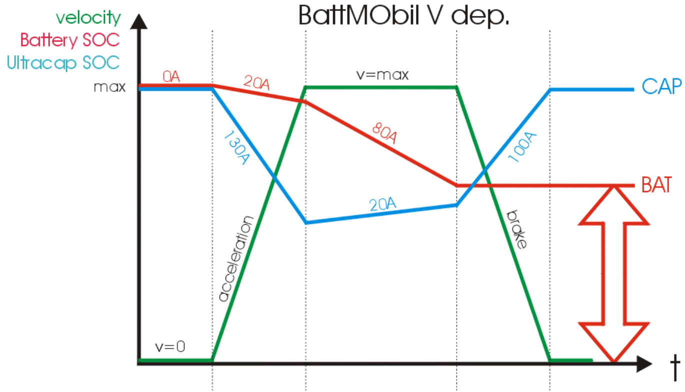

Fig. 16: Recharging of Ultracap controled by EMS

In figure 17 the results of three discharge-cycles for city-el batteries mentioned above are shown. All cycles show the same average discharge current, which is realistic for a normal driving cycle. The blue curve is representing a pure battery driven cycle having maximum acceleration currents supplied by the battery, while the red curve symbolizes the battery-load having an Ultracap permanently charged from the battery with 20A, if not used for accelerations. The magenta curve symbolizes a constant current discharge showing the battery can be operated the longer without limitations in discharge current, the less dynamic the load profile is, having the same average current in all cycles.

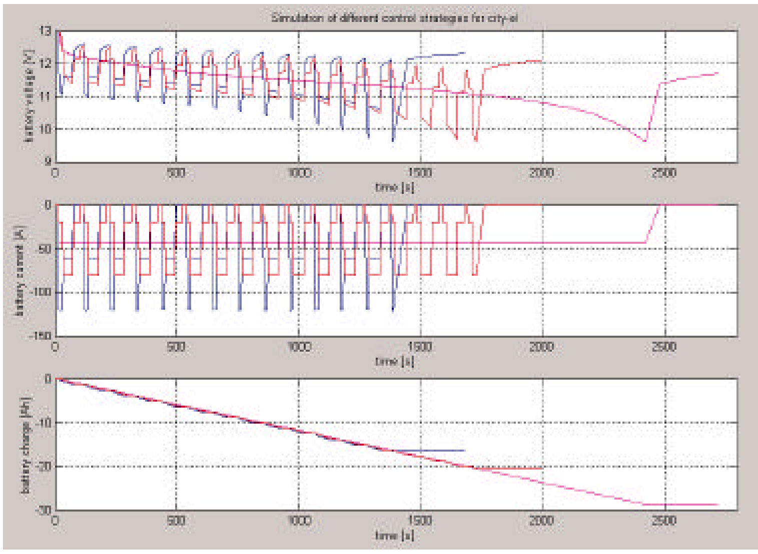

Fig. 17: Bench tests: Battery behavior having different control strategies

In order to discharge the battery always using the lowest possible current, the EMS calculates the available charging current for next regenerative braking of the Ultracaps from the velocity of the vehicle. This way the DC-DC converter as well as the power switch are controlled, which means that the SOC of the Ultracaps can be varied in order to optimize regenerative braking capabilities.

Conclusions

The main aim of the project described is the development of an energy management system for hybrid electric vehicles. The demonstrator vehicle is a LEV city-el powered by a battery as energy storage system. The introduction of a power-assist Ultracap module requires an energy management system running an optimized control strategy. The hardware and the software for this energy management system has been developed at the Technical Academy of Berlin. Only latest technology has been used in the hardware design, which is based on a TriCore Architecture from Infineon Technologies AG. Several approaches for the control strategy have been discussed and and the most promising has been realized. The project has shown the need of individual solutions depending on each application. A control strategy like that described in the project is not directly adaptable to other vehicles. For each vehicle, the strategy has to be optimized, resulting in software changes.
The developed hardware of the EMS is applicable to a wide range of EMS and BMS solutions for different types of vehicles and applications.
Also the developed sub-components like the DC-DC converter, the booster and the power-switch can be easily adapted to other automotive applications.

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