

Ultracapacitors + DC-DC Converters in Regenerative Braking System

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ABSTRACT

An ultracapacitor system for an electric vehicle has been implemented. The purpose of this device is to allow higher accelerations and decelerations of the vehicle with minimal loss of energy and minimal degradation of the main battery pack. The system uses a dc-dc power converter, which is connected between the ultracapacitor and the main battery pack. The design has been optimized in weight and size, by using water-cooled heat sinks for the power converter, and an aluminum coil with air core for the smoothing inductance. The ratings of the ultracapacitor are: nominal voltage: 300 Vdc; nominal current: 200 Adc; capacitance: 20 Farads. The amount of energy stored allows us to have 40 kW of power during 20 seconds, which is enough to accelerate the vehicle without the help of the traction batteries. The vehicle uses a brushless dc motor with a nominal power of 32 kW and a peak power of 53 kW. A control system based on a Digital Signal Processor (DSP) manipulates all the aforementioned variables and controls the Pulse Width Modulation (PWM) switching pattern of the converter transistors. The car used for the implementation of this system is a Chevrolet LUV truck, similar in shape and size to a Chevrolet S-10 which was converted to an electric vehicle at the Catholic University of Chile.

INTRODUCTION

Ultracapacitors are a new technology that allows us to store 20 times more energy than conventional electrolytic capacitors [1, 2]. Despite this important advance in energy storage, they are far from being compared with electrochemical batteries. Even lead-acid batteries can store at least ten times more energy than ultracapacitors. However, they present better

performance in specific power than any battery and can be charged and discharged thousands of times without performance deterioration. These characteristics can be used in combination with normal electrochemical batteries to improve the transient performance of an electric vehicle, and to increase the useful life of the batteries [3-6]. Fast and sudden battery discharge during acceleration, or fast charge during regenerative braking can be avoided with the help of ultracapacitors. Besides, ultracapacitors allow regenerative braking even when the batteries are fully charged.

In this paper, an auxiliary ultracapacitor bank using a bi-directional DC-DC converter has been implemented. The ultracapacitor has a capacity of 20 farads, a nominal voltage of 300 Vdc, and a maximum voltage of 330 Vdc. It comprises 132 units in series, each one with 2,700 farads and 2.3 volts dc nominal (2.5 volts maximum). The nominal current is 200 amp and the maximum current is 400 amp. The weight of the capacitor bank is 95 kg and the total weight of the equipment (including the smoothing inductor and the DC-DC converter) is estimated at 130 kg.

THE SYSTEM IMPLEMENTED

Figure 1 shows a diagram of the system implemented into the vehicle. It has three main components: the bidirectional DC-DC converter based on Insulated Gate Bipolar Transistors (IGBTs), the smoothing inductor LS, and the ultracapacitor bank. The equipment is connected in parallel to the main battery which has 26 batteries in series (312 Vdc nominal), with a total weight of 520 kg. Five of the 26 batteries are located in the front. During acceleration, the capacitor voltage is allowed to discharge from full charge (300 Vdc) to one-third of its nominal voltage (100 Vdc), allowing it to deliver 220 Wh of useful energy. This apparently poor amount of energy allows us to take 40 kW of power during 20 seconds which is more than enough time for a good acceleration without detriment to the battery life. During deceleration (regenerative braking), energy is recovered in a similar way, charging back the ultracapacitors.

The DC-DC converter works in two ways: Boost operation, used for acceleration which discharges the ultracapacitor; and Buck operation used for deceleration (regenerative braking), which charges the ultracapacitor. During Boost operation

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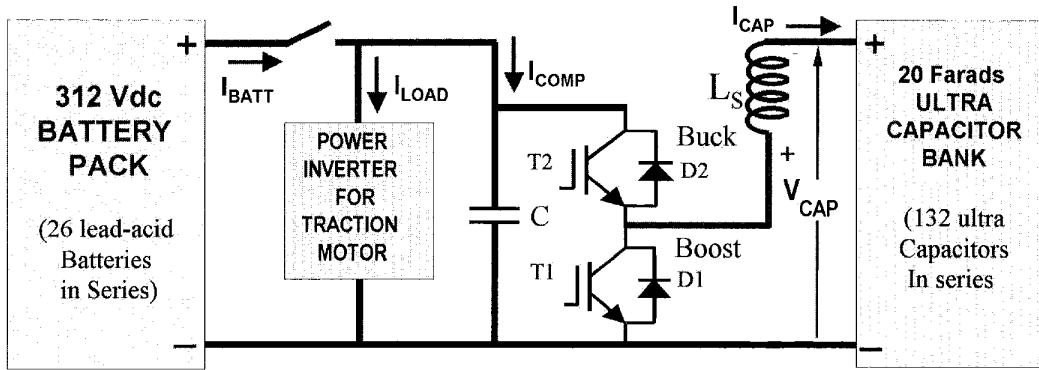


Fig. 1. Ultracapacitor system

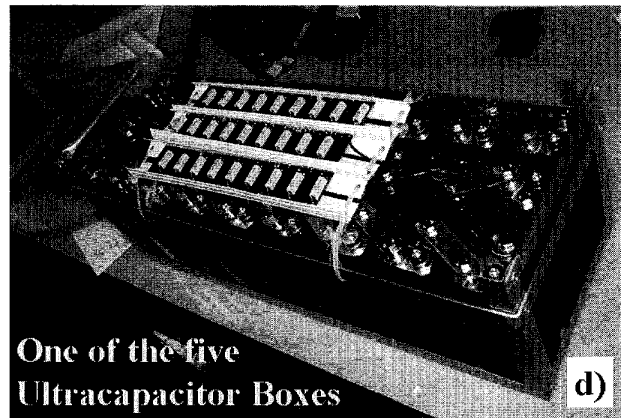
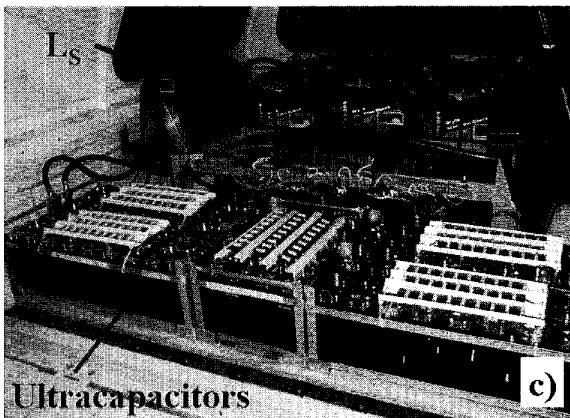
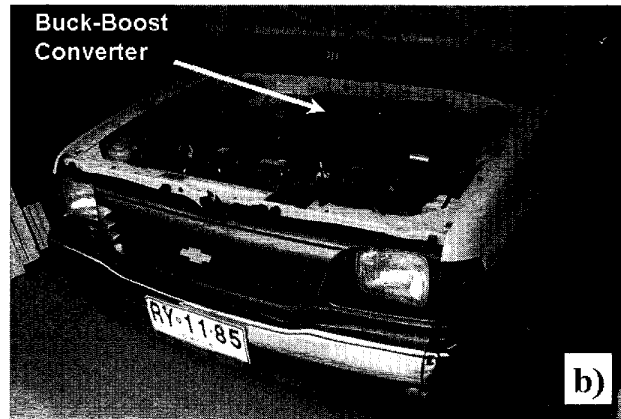


Fig. 2. Installation of the ultracapacitor system: A) the EV; B) the DC-DC converter; C) inductance L_S and ultracapacitors installed at the pick-up of the EV; D) one ultracapacitor box

(acceleration), the IGBT T1 is switched on and off at a controlled duty cycle, to transfer the required amount of energy from the capacitor to the battery pack. When T1 is ON, energy is taken from the capacitor and stored in the inductor L_S . When T1 is switched OFF, the energy stored in L_S is transferred into C, through D2, and then into the battery pack. During Buck operation, the converter introduces energy from the battery to the ultracapacitor. That operation is accomplished with a controlled operation on T2. When T2 is switched ON, the energy goes from the battery pack to the ultracapacitor, and L_S

stores part of this energy. When T2 is switched OFF, the remaining energy stored in L_S is transferred inside the ultracapacitor through D1.

IMPLEMENTATION AND MAIN COMPONENTS OF THE SYSTEM

The ultracapacitor system was installed in an electric vehicle implemented at the Department of Electrical Engineering of the Catholic University of Chile. The vehicle

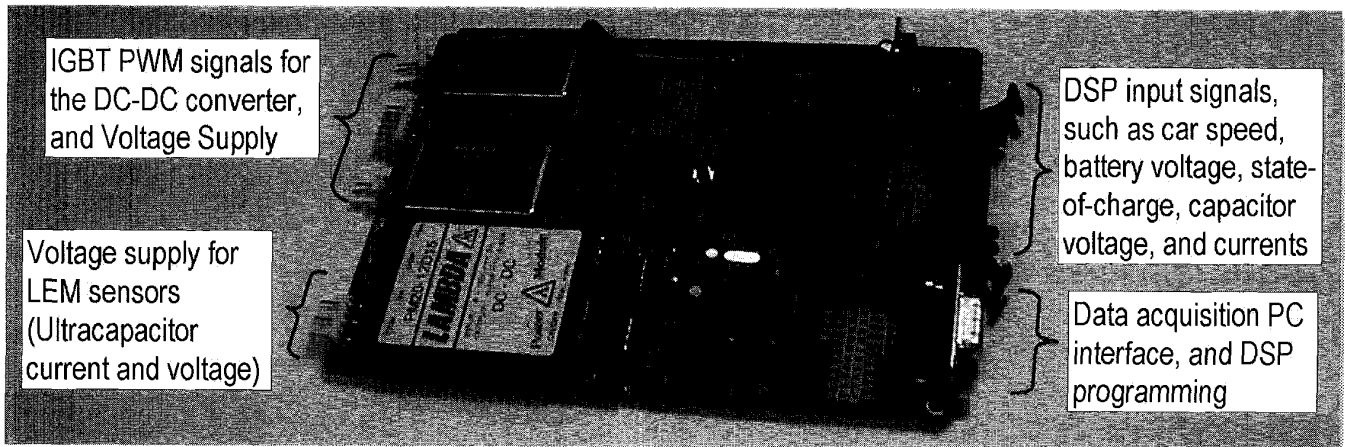


Fig. 3. DSP control

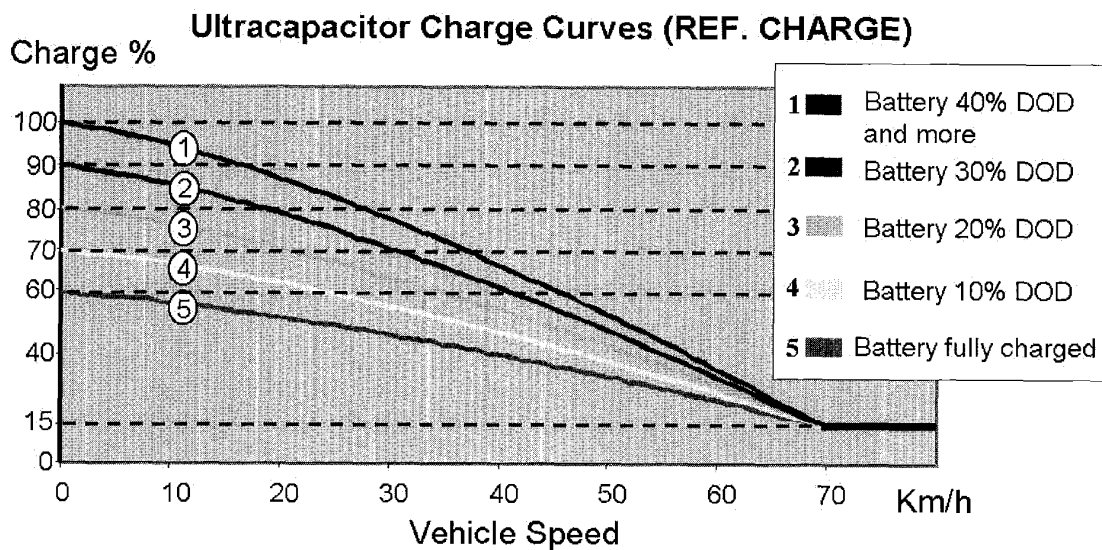


Fig. 4. Family plots of the Reference Table, to evaluate the Reference Charge

uses a high specific power brushless dc motor with a nominal power of 32 kW and a peak power of 53 kW. The car transformed to an EV is a double cabin Chevrolet LUV truck, with an actual gross weight of 1,920 kg (720 kg in the front and 1,200 kg in the rear). Some of the performance characteristics of this EV are: maximum speed, 120 km/h; acceleration, 0-60 km/h in nine seconds; efficiency, 4 km/kWh (0.25 kWh/km). Five passengers can be accommodated inside the double cabin.

The photographs of Figure 2 show: A) the vehicle used for installation of the ultracapacitor system; B) the location of the DC-DC converter in the front; C) the location of the main inductance LS and ultracapacitors in the rear; and D) a detail of one of the five ultracapacitor boxes used for the system implementation.

The DC-DC converter was designed using IGBTs (Intellimod type PM400DSA060) and a water cooling system

to reduce weight and size. It was built in a very compact shape to allow its installation inside the normal engine compartment. The photograph of Figure 2B shows the final installation of the DC-DC converter into the engine compartment of the Chevrolet LUV truck.

The inductor LS of Figure 2C was designed using aluminum coils. The coils were made with flat plates, 0.5 mm thick and 120 mm width. In this way the skin effect was minimized and the losses and weight were optimized. It can sustain 100 amps under steady-state and 200 amps for two minutes. Other parameters of this inductance are: $L = 1.6 \text{ mH}$, $R = .03 \text{ Ohms}$, and $m = 20 \text{ kg}$. It uses air core and, hence, iron losses or saturation problems are eliminated.

The 132 ultracapacitors were grouped in five independent boxes made of aluminum. Four contain 27 units in series of 2,700 farads of capacity each. The fifth box contains 24 units.

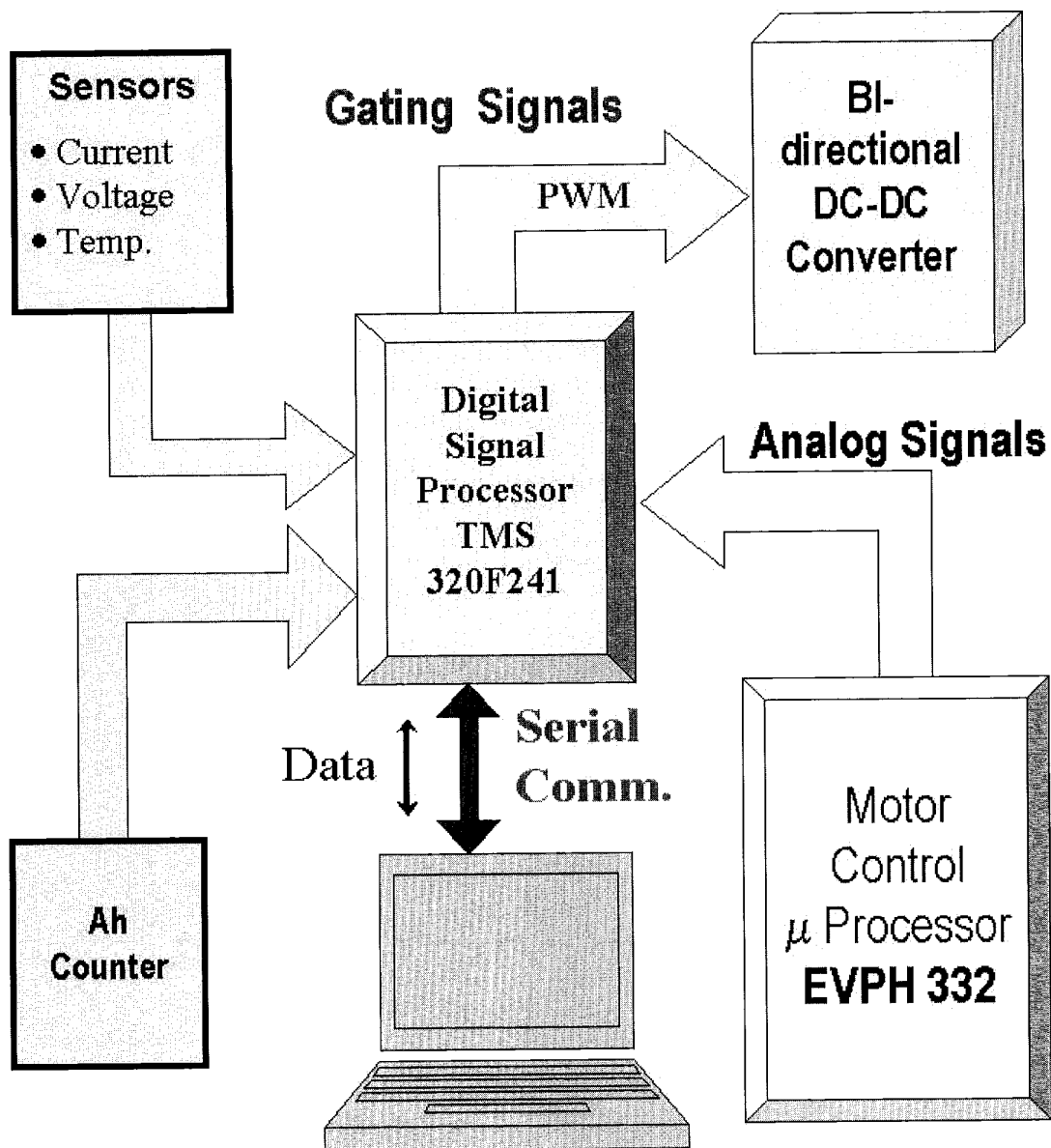


Fig. 5. DSP main functions

When connected in series, ultracapacitors have the tendency to charge unevenly, due to slight differences in the actual capacitance C of each unit. This may cause a dangerous overvoltage condition in a single capacitor when the whole package is near its maximum voltage. To avoid this, and to ensure a good voltage equalization, Voltage Cell Balancing (VCB) units were added to the boxes. These units work discharging the ultracapacitors when they reach the threshold voltage of the VCBs (2.47 V). The VCB units are mounted on top of the ultracapacitors, and they can be seen in Figure 2D.

CONTROL STRATEGY

Considering the high cost of the ultracapacitors, the total capacity in farads has to be minimized, and then, a special

control strategy is required. Every variable, such as instantaneous battery voltage, battery state of charge, instantaneous battery current, ultracapacitor initial conditions, capacitor current, and vehicle speed need to be sensed.

As the energy stored in the ultracapacitor is proportional to V_{CAP}^2 , this voltage gives a good indication of its remaining charge. The capacitor voltage is controlled through the interaction of the aforementioned variables, such as vehicle speed and the state-of-charge of the battery.

When the vehicle accelerates, the battery delivers the amount of current the motor needs. If this current exceeds a previously established current limit for the battery, then the ultracapacitor gives the difference. The regenerative braking operation is similar. In this case, the motor works as a generator delivering the recovered energy into the battery, but if the

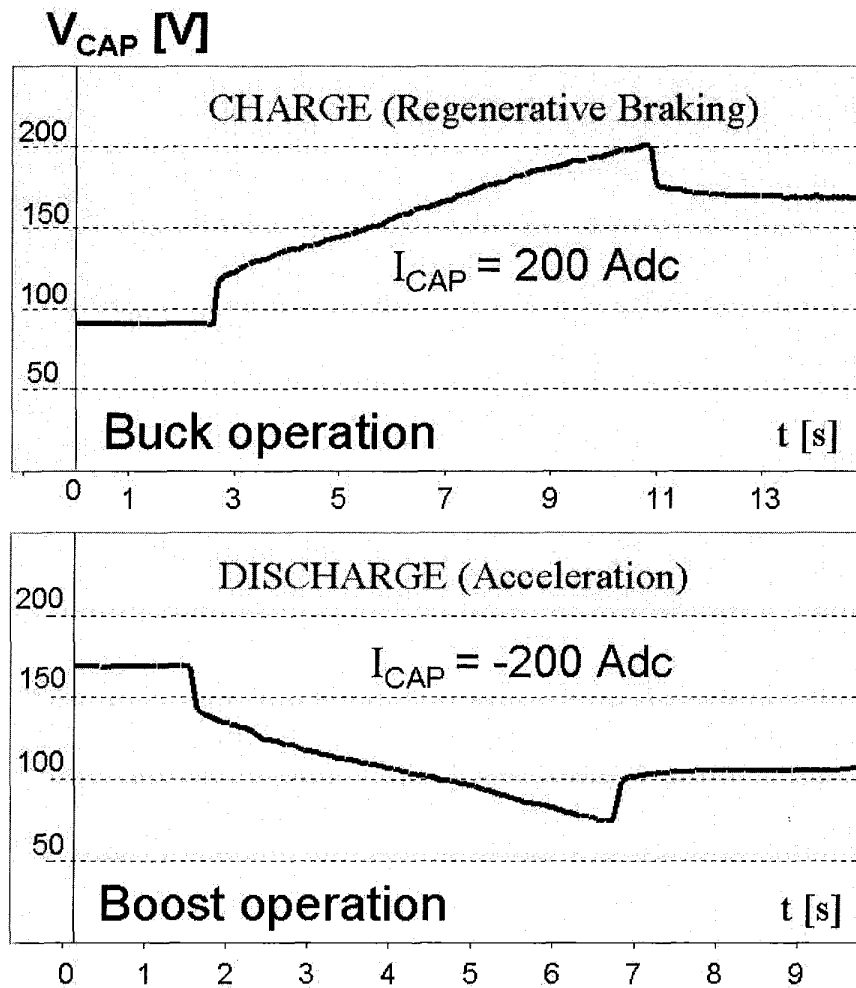


Fig. 6. ESR effect during charge and discharge of ultracapacitors

current injected exceeds the previously established limit, then the DC-DC converter injects the excess into the ultracapacitor.

All of the operations described above, must be controlled by a microprocessor which discriminates and makes the appropriate decisions for each particular situation. The microprocessor is a Digital Signal Processor (DSP) based system which uses a programmed control. This programmed control has two levels: a Primary Control and a Secondary Control. The Primary Control establishes the Current Reference (I_{REF}) to be given to the ultracapacitor for each operation condition, and the Secondary Control generates the PWM signals for the power Converter. Figure 3 shows the printed board of the DSP control.

The first duty of the Primary Control is to keep an adequate level of energy in the ultracapacitor (Charge Control). This level of energy, or charge, is calculated through the EV speed (Car Speed), and the battery state of charge (Battery % DoD). The higher the speed, the lower the charge, and the higher the battery state-of-charge, the lower the charge, too. The shape of these curves was estimated taking into account the fact that the

kinetic energy is proportional to the square of the speed, and the time the control takes to reach the desired ultracapacitor charge. This operation is shown graphically in Figure 4.

The Buck and Boost control of the DC-DC converter is based on a TMS320F241 Digital Signal Processor (DSP) from Texas Instruments, which executes a program based on the algorithm presented. In order to execute this program, the DSP needs to have available certain data and deliver the output to the IGBT gating ports. Also, a personal computer interface is desirable for debugging and testing purposes. The interaction between the DSP, data sources, IGBT and personal computer is described below.

The vehicle has a main microcomputer that controls the inverter and the operation of the traction motor (EVPH 332 from Unique Mobility). It delivers several parameters data in a 0-10 VDC analog format. From them, three are relevant to the system algorithm: vehicle speed, system current, and bus voltage. Information about other parameters such as converter temperature, ultracapacitor current, and voltage, are obtained using specially installed sensors. All of these parameters are

acquired by the A/D converter module contained in the TMS320F241. Information about the battery state-of-charge is obtained from the Ah meter of the vehicle.

The program outputs are two PWM signals delivered to the IGBT's gating ports through optocouplers. To generate these signals, a PWM module included in the TMS320F241 is used. Figure 5 shows the links of the DSP with their electronic environment.

TEST RESULTS

In order to corroborate the correct functioning of the program, and to acquire valuable data for analysis and evaluation, a personal computer interface, linked to the DSPs serial port was designed using Visual Basic language. A simple protocol was developed so the DSP program understands commands coming from the computer, and the interface program can store data in a consistent way.

Figure 6 shows the Equivalent Series Resistance (ESR) effect of the ultracapacitor during charge and discharge under the worst conditions. That is, maximum current during regenerative braking, and also during acceleration (± 200 Adc). The experiment shows the drop of the capacitor voltage which is around 25 Vdc. That means, around 5 kW power losses inside the ultracapacitor bank during these transient periods. This result also means that the total ESR of the 132 ultracapacitors in series is around 0,125 ohms, which is in agreement with the data sheet of these devices [1]. During charge (eight seconds of regenerative braking) 248.000 Joules were generated from the converter, from which only 208.000 Joules were stored in the ultracapacitor. That means an efficiency of around 84%. During discharge (acceleration during five and one-half seconds) 219.000 Joules were taken from the ultracapacitor, and only 191.500 reached the DC-DC converter which means an efficiency of around 87%. These two results are not bad because they represent the worst condition, given by the minimum capacitor voltage (around 100 Vdc) and the maximum current.

CONCLUSION

An ultracapacitor system for an electric vehicle has been implemented. The purpose of this device was to allow higher accelerations and decelerations of the vehicle with minimal loss of energy and minimal degradation of the main battery pack. The system uses a bidirectional IGBT DC-DC converter,

and the control of the system measures the battery voltage, the battery state-of-charge, the car speed, the instantaneous currents in both terminals (load and ultracapacitor), and the actual voltage of the ultracapacitor. The design was optimized in weight and size by using a water-cooling system for the power converter, and an aluminum coil with air core for the main inductance. The control system based on a DSP, interfaces with the user through a Visual Basic program to acquire valuable data for analysis and evaluation. Final tests are still underway and the results are being analyzed to evaluate overall system efficiency.

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REFERENCES

- [1] Epcos,
Ultracapacitors Data sheets and technical information for 2,700 Farads/2,3 Vdc,
Part number B49300-H1276-S.
- [2] Jun Takehara and Kuniaki Miyaoka, 1996,
EV Mini-Van Featuring Series Conjunction of Ultracapacitors and Batteries for Load Leveling of its Batteries,
Technical Research Center, The Chugoku Electric Power Co., Inc., 3-9-1 Kagamiyama, Higashihiroshima-City, Hiroshima 739, Japan,
14th Electric Vehicle Symposium, 1996 [on CD ROM].
- [3] F. Caricchi, F. Crescimbeni, F. Giulii Capponi and L. Solero, 1996,
Ultracapacitors Employment in Supply Systems for EV Motor Drives: Theoretical Study and Experimental Results,
University of Rome,
14th Electric Vehicle Symposium, 1996 [on CD ROM].
- [4] A.F. Burke, 1996,
Electrochemical Capacitors for Electric Vehicles, Technology Update and Implementation Considerations,
University of California at Davis, EVS-12 Symposium Proceedings, pp.27-36.
- [5] Hans Kahlen, October 1999,
Energy and Power from Supercapacitors and Electrochemical Sources,
16th International Electric Vehicle Symposium, Beijing, China, paper PA 95 on CD-ROM.
- [6] B.J. Arnet and L.P. Haines, October 2000,
Combining Ultracapacitors with Lead-Acid Batteries,
17th International Electric Vehicle Symposium, Montreal, Canada, paper 2B-2 on CD-ROM.