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Voltage balancing: Long-term experience with the 250 V supercapacitor module of the hybrid fuel cell vehicle HY-LIGHT

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Abstract

On the occasion of the “Challenge Bibendum” 2004 in Shanghai, the hybrid fuel cell—supercapacitor vehicle HY-LIGHT, a joint project of Conception et Développement Michelin and the Paul Scherrer Institut, was presented to the public. The drive train of this vehicle comprises a 30 kW polymer electrolyte fuel cell (PEFC) and a 250 V supercapacitor (SC) module for energy recuperation and boost power during short acceleration and start-up processes. The supercapacitor module was deliberately constructed without continuous voltage balancing units. The performance of the supercapacitor module was monitored over the 2 years of operation particularly with respect to voltage balancing of the large number of SC cells connected in series. During the investigated period of 19 months and about 7000 km driving, the voltage imbalance within the supercapacitor module proved negligible. The maximum deviation between best and worst SC was always below 120 mV and the capacitor with the highest voltage never exceeded the nominal voltage by more than 40 mV.

Keywords: Ultracapacitor; Series connection; Initialization; Leakage current

1. Introduction

Fuel cell cars, utilizing a polymer electrolyte fuel cell (PEFC) as the prime mover, are being discussed as an important contribution for future reduction of greenhouse gas emissions originating from road traffic. For this the hydrogen should be obtained from renewable primary energy sources. An experimental vehicle “HY-LIGHT” equipped with a power train based on a hydrogen/oxygen fueled PEFC has been developed in collaboration between Conception et Développement Michelin (CDM) and the Paul Scherrer Institut (PSI). With this vehicle it was demonstrated that a fuel consumption of 2.5 l/100 km gasoline equivalent can be achieved for a full four-seated lightweight fuel cell car [1]. The excellent fuel efficiency could be realized based on three main factors: low curb weight of the vehicle (800 kg), a highly efficient fuel cell system ($\eta_{LHV} > 56\%$ [2]) and by hybridization of the power train with an electrochemical energy storage device, in this case a supercapacitor bank. The hybridization allows for recuperation of braking energy, reducing fuel consumption by about 11–13%, depending on the drive cycle. A detailed analysis of the energy flow from tank to wheel for the HY-LIGHT vehicle has been presented by Büchi et al. [2].

In the present communication we address explicitly the reliability of the supercapacitor bank in the HY-LIGHT vehicle, which consists of 95 capacitors in series. Each capacitor has a nominal capacitance of 2600 F. The issue of voltage balancing for supercapacitors connected in series has been described in many patents but only rarely in scientific papers [3,4]. Supercapacitor (SC) manufacturers provide various electronic circuits for voltage balancing of their own devices [4]. The different approaches vary from simple parallel resistors for passive balancing to sophisticated electronic devices for active balancing. In any case voltage-balancing measures need additional weight, cost and energy and contribute to the reliability issues of the complete module.

We report about our experience with a cost efficient alternative using the supercapacitor bank without any on-line

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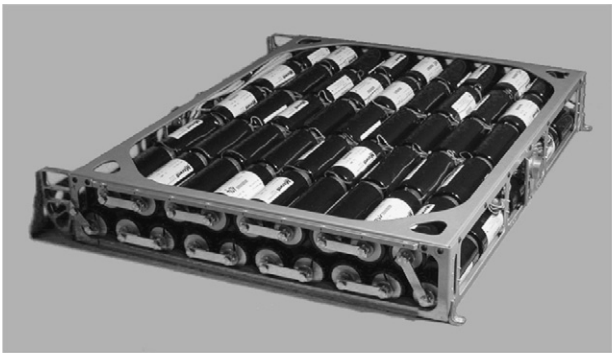

Fig. 1. Picture of the 250 V supercapacitor module for the HY-LIGHT hybrid vehicle.

voltage-balancing device at all and utilizing a remote balancing unit.

2. Technology background

2.1. Capacitor module

The SC module was designed for a maximum voltage of 250 V and low internal resistance. In order to achieve the desired energy content for delivering 40 kW during 15 s Maxwell Technology BCAPA010 with 2600 F nominal capacitance were chosen. The nominal voltage of the capacitor is 2.5 V. In order to cut down space and weight the capacitor stack consists of 95 individual capacitors connected in series, the average maximum voltage of each capacitor thus being 2.63 V for a stack voltage of 250 V.

The capacitors were connected in series by threaded bolts utilizing the internal thread on the capacitor terminals enabling direct connections between the capacitors. Five capacitors were thus connected in a string. Each string was connected to the next string by an aluminum bar. As can be seen in Fig. 1 the SC strings were stacked in two layers with 10 strings in the first layer and 9 strings in the second layer. A lightweight frame held the arrangement.

As is also evident from Fig. 1 no electronic or other balancing devices were used for continuous voltage control of the stack. The positive and negative terminals of each capacitor were connected to a 97 pin plug (Amphenol® Tri-Start™) on the side of the rack with light cables. The performance data of the SC module are summarized in Table 1.

Quarter sections of the capacitor module were tested on a 10 kW test bench utilizing a 10 kW programmable DC power

Table 1
Key data of the supercapacitor module

Number of capacitors	95
Type of capacitor, Maxwell Technologies SA	BCAP010A 2600 F
Max Power (@ matched impedance)	625 kW
Power (@ 15 s)	40 kW
Max energy/usable energy	250 Wh/187 Wh
ESR (@1 kHz)	25 mΩ
Capacitance	29 F
Weight	53 kg

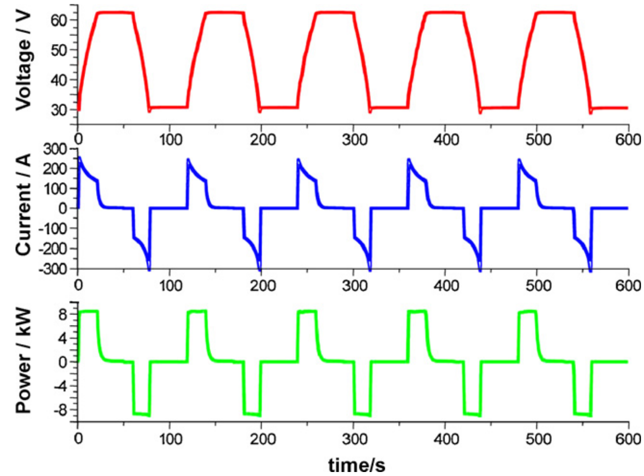

Fig. 2. Constant power test of 25 BCAP010 in series (one quarter of the final module) at 8 kW between 30 V and 62.5 V.

supply (TopCon) and a 10 kW electronic DC load (Höcherl & Hackl GmbH, Germany). A constant power test of such a stack section is shown in Fig. 2 for (25 capacitors in series). The capacitors deliver 8 kW for 20 s in the voltage window of 62.5–30 V.

The voltage balancing strategy – as will be discussed below – consists of occasional initialization of all capacitors. For this procedure the respective voltage-balancing unit [5] utilizing a programmable 2-quadrant power supply (LAB/SLR, ET System electronic GmbH, Germany) and a multiplexing unit was connected to the 97-pin-connector. The voltages of all capacitors were measured at a stack voltage close to 250 V. Subsequently those capacitors, which fell out of a pre-defined band around the average voltage, were charged or discharged one by one until all capacitor voltages fell within the preset voltage window. This procedure was repeated occasionally when the vehicle was stopped for general services. A detailed description of the remote voltage balancing can be found in the respective patent application [5].

2.2. Vehicle performance

The drive train of the HY-LIGHT is sketched in Fig. 3 and comprises a PEFC stack, a supercapacitor bank, the electric motors on the two front wheels and the necessary power electron-

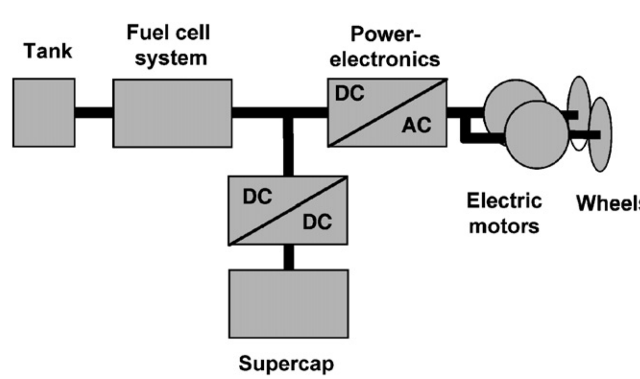

Fig. 3. Sketch of the HY-LIGHT drive train.