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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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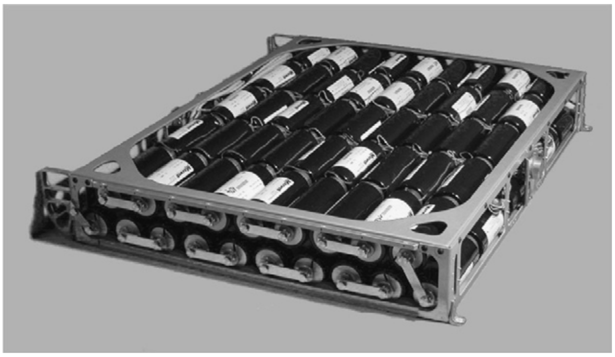

Fig. 1. Picture of the 250 V supercapacitor module for the HY-LIGHT hybrid vehicle.

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 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.

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

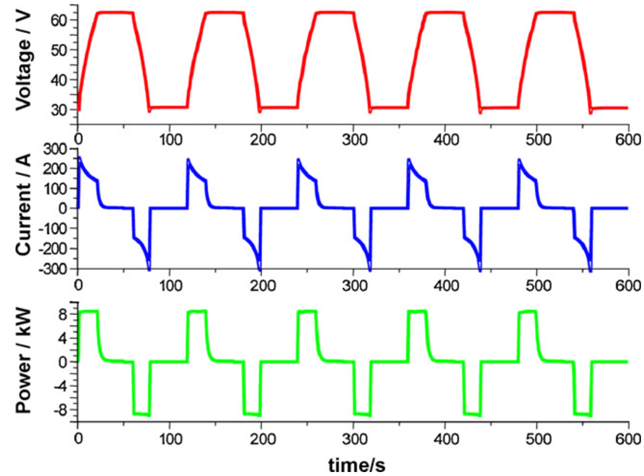

Fig. 2. Constant power test of 25 BCAP010 in series (one quarter of the final module) at 8 kW between 30 V and 62.5 V.

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-

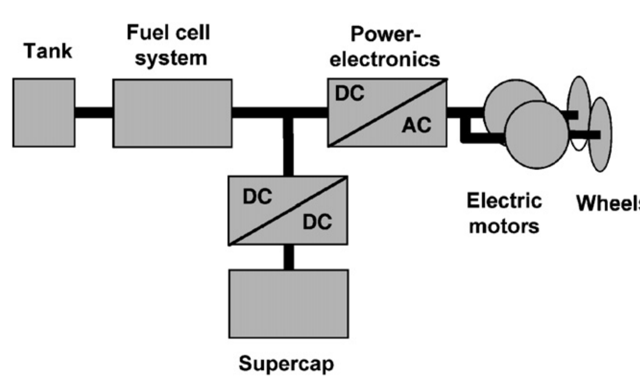

Fig. 3. Sketch of the HY-LIGHT drive train.

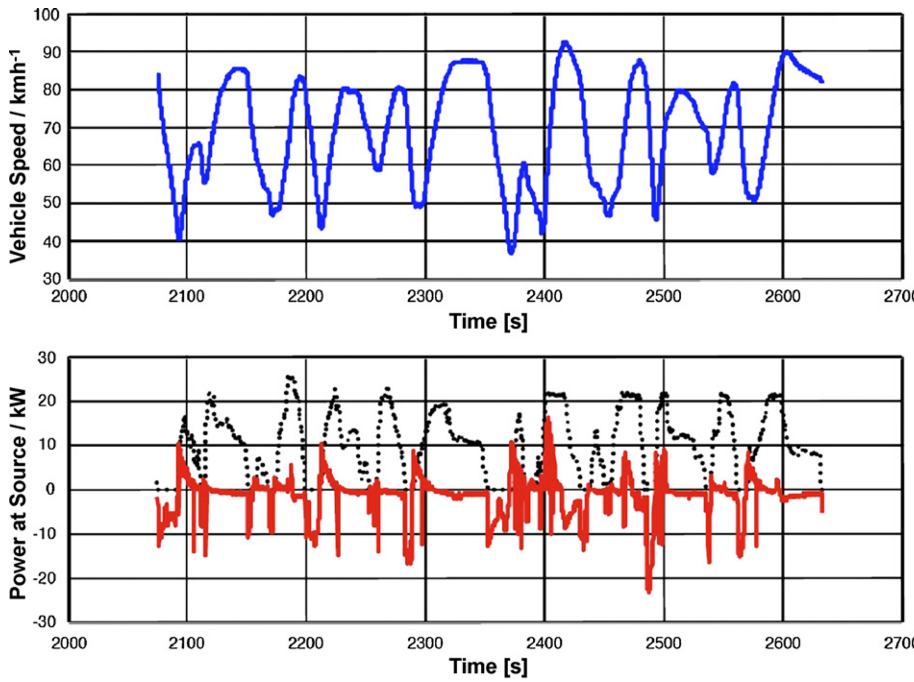

Fig. 4. Vehicle speed (top) and respective fuel cell (dashed line) and supercapacitor (full line) power during the test on the F-1 track in Shanghai (average speed of 70 km/h, two laps shown).

ics for a smooth connection of the different voltage levels. The PEFC was designed for a maximum power of 30 kW while the additional SC could deliver extra 30 kW for 20 s during start-up or acceleration processes. The energy management system and the fuel cell were described previously in various papers [2,6].

The interplay between PEFC and SC during a constant speed test on the Formula1-track in Shanghai is reflected in Fig. 4. The track was driven at an average speed of 70 km h^{-1}. Whenever the car decelerates approaching a bend the SC is recharged, while for acceleration processes the SC supports the fuel cell and is discharged. This helps the fuel cell to work as long as possible at an optimized power.

As can be seen from the graph in Fig. 4 the SCs are charged and discharged with up to 20 kW. The maximum voltage of the capacitor bank was limited to 250 V, which corresponds to a maximum voltage for each capacitor of 2.63 V, whereas the nominal voltage of the capacitor was 2.5 V in the data sheet.

3. Results and discussion

3.1. Balancing strategy

When running many passive electronic elements in series one of the main concerns is voltage balancing. For a long life time and optimal performance the voltage of each element in series should be close to the manufacturer determined nominal voltage. Due to the fact that only the voltage of the module is controlled equal voltages at each element in the series can only be guaranteed by absolutely identical element characteristics. This, however, is usually not the case. For capacitors there are two main parameters affecting the voltage distribution along the module during static and dynamic performance.

First, the capacitance of each element determines the voltage after charge. While the charge ΔQ accumulated in the various capacitors is equal the resulting voltage change ΔU is in general different because of capacitance variation. The element with a somewhat lower capacitance will have a slightly higher voltage after charging according to $\Delta U = \Delta Q/C$, where C is the capacitance of the element.

Secondly, most important during voltage hold periods, the capacitors' leakage resistances, which determine the self-discharge rate, are different for each capacitor. A reasonable quality control of the manufacturer will guarantee that the two quantities fall within a certain quality band, but differences will always remain.

Okamura et al. [7] have suggested a so-called "initialization" of capacitors within a module, which will overcome the voltage imbalance originating from the capacitance spread.

The idea is to balance all capacitors at – or close to – the upper module voltage. By this means the different capacitance of each element will result in a voltage imbalance only at lower working voltages, which does not affect the lifetime of the capacitor. At the high stack voltages, however, the all-individual voltages will show only a minor spread (see Fig. 5).

This kind of initialization has to be repeated after certain time intervals because the individual capacitance of the elements will change slowly with time and because a second process causing voltage imbalance is superposed.

The second cause of voltage imbalance with time cannot be compensated similarly. It is known that each SC has a certain rate of self-discharge, which can in the simplest approximation be described by a leakage resistor parallel to the capacitance. For the complete stack in constant voltage mode the loss of charge is compensated from the external source. The contribution of each

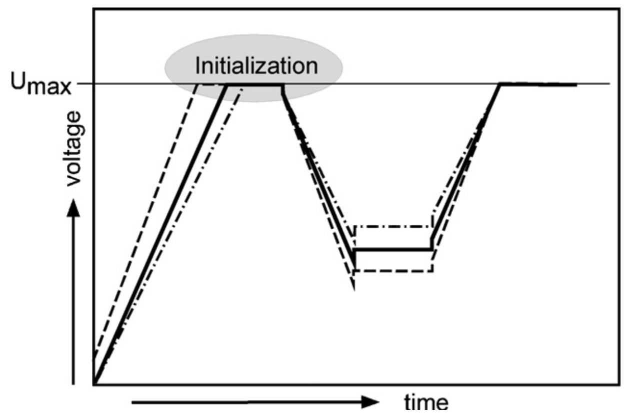

Fig. 5. Sketch of capacitor initialization after Okamura [7]. The charged capacitors with different capacitance are equilibrated at U_{max}. As a consequence the discharged capacitors have different voltage levels according to the spread in capacitance (full line: nominal capacitance, dashed line: capacitance smaller than nominal, dash-dotted line: capacitance larger than nominal).

capacitor in the module to the overall leakage current is identical, because the same current flows through each capacitor. The differences in leakage resistance are reflected in different contributions of each capacitor to the overall voltage of the module.

As a consequence, those capacitors with a fast self-discharge (low leakage resistance) will diminish in voltage with time, while those capacitors with low self-discharge (high leakage resistance) will slowly increase the voltage with the overall module voltage remaining constant.

3.2. 250 V capacitor module

The voltage distribution of the 95 capacitors in the module is shown in Fig. 6 immediately after an initialization of the SC module and 18 months later. It can be seen that after initialization at 250 V all of the 95 capacitors are within a voltage band between 2.63 ± 0.01 V. After 18 months the deviation from the nominal voltage value is never larger than +40 mV.

At certain intervals after the balancing/initialization procedure the voltages of the capacitors were measured but not balanced. The evolution of the highest and the lowest voltage in the stack is reproduced in Fig. 7 for a time interval of about 18 months. This time interval corresponds to about 7000 km driven with the HY-LIGHT fuel cell car.

It is evident that during this long operation plus standby time the largest voltage deviation above the average value of the stack never exceeded 40 mV. The total difference between highest and lowest potential is always smaller than 120 mV. The evolution of the curve demonstrates that initially after a balancing procedure the voltages of the individual capacitors run apart rather fast while the voltages seem to level off after 200 days and remain constant or even decrease again. The leakage current rate of the BCAP010 at room temperature is in the order of 1 mA at 2.5 V and room temperature.

This result nicely demonstrates that it is possible to run a large capacitor stack without continuous voltage balancing. This is particularly important if energy efficiency is a main boundary condition for a supercapacitor application. Any voltage-balancing unit – be it active or passive – consumes extra

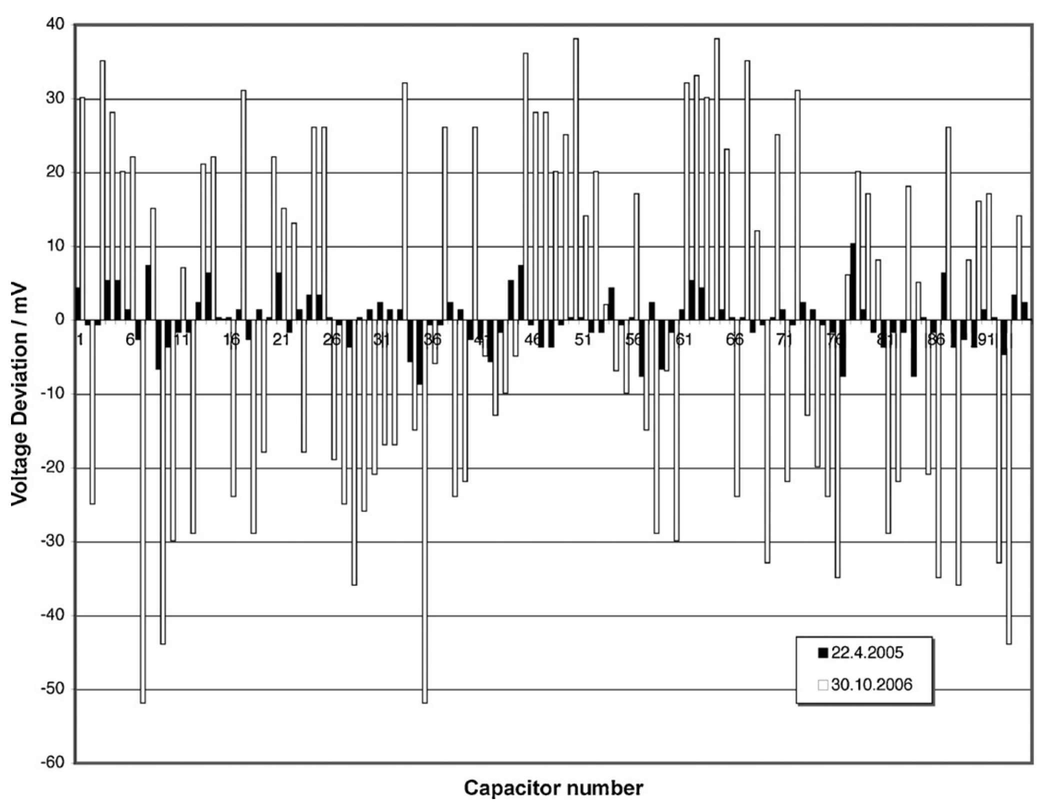

Fig. 6. Voltages of all 95 capacitors directly after initialization (full bars) and after 18 months – equivalent to 7000 km – of vehicle operation (open bars).

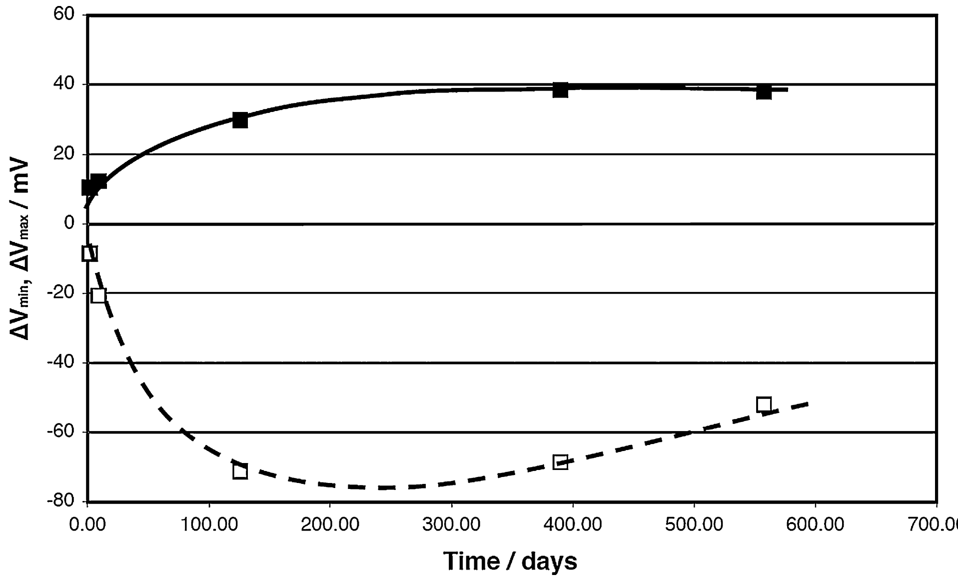

Fig. 7. Voltage evolution of the capacitor with the highest (full line) and the lowest (dashed line) voltage in the capacitor module of the HY-LIGHT.

charge from the capacitors themselves or an external source. If a certain imbalance of the capacitor module is acceptable, permanent balancing and energy loss can be avoided. It can be expected that those capacitors being exposed to a higher voltage age faster. However, with a max. voltage of 50 mV above the nominal voltage the aging rate is increased by less than a factor of two [4,8].

3.3. 10 V capacitor module

In order to learn more about voltage balance and to confirm the above behavior we monitored the voltage in a small module consisting of two capacitor strings in parallel using four BCAP350 in series in each string. The module voltage was 10 V and the different capacitors were initialized at 10 V resulting in a good voltage distribution of 2.496 ± 0.003 V for each capacitor.

Fig. 8 shows the evolution of the voltage spread ($U_{max} - U_{min}$) of the four capacitors in each string with time. It is evident that the voltages of the capacitors run apart after initialization but level off at a constant value. Due to the fact that the quality of the capacitors is different in each string the equilibrium values reached after 6 months are different. With only four capacitors in one string the distribution of leakage resistances is far from the statistical value in each string. The maximum deviations of the capacitors with the highest voltage for the two strings are 11 mV and 39 mV above the average value of 2.5 V.

Even if one capacitor would run into a short circuit (zero leakage resistance) this failure can be compensated by the remaining three capacitors, which for this 10 V module would shift to an average voltage of 3.3 V per capacitor. This is a dramatic change but does not lead to an immediate failure of the four-capacitor string. In addition, due to the slow time constant of the

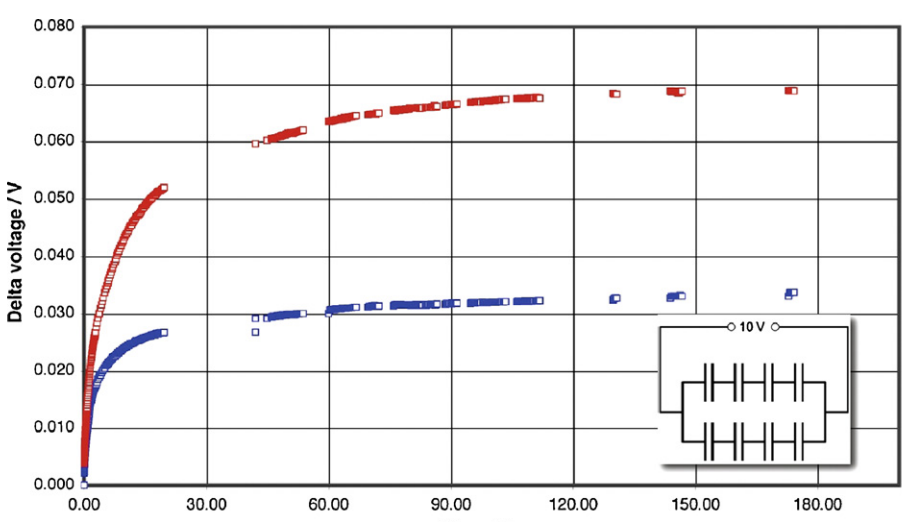

Fig. 8. Evolution of the voltage difference between the capacitors with the highest and the lowest voltage in a 10 V module with two parallel capacitor strings with 4 capacitors each. The two curves represent the voltage difference in each string measured at room temperature. The insert shows the circuit.

capacitor—leakage resistance circuit with a capacitance C of 350 F and leakage resistance R_{leakage} in the order of $10^3\ \Omega$ individual capacitor voltages reach their voltage equilibrium after a couple of days.

Can the observation made for the SC module of the HY-LIGHT with 95 capacitors in series and the behavior of the small 10 V module with four capacitors in series be generalized to an arbitrary number of capacitors in series? This question arises also in view of the calculation presented in the paper by Linzen et al. [4] where a significantly larger voltage imbalance was predicted. In order to estimate the evolution of the individual voltages of a capacitor module it is of utmost importance to know the voltage dependence of the leakage current which determines the rate of self-discharge. Therefore we measured the leakage voltages of a commercial 350 F capacitor BCAP350 (Maxwell Technologies) as a function of capacitor voltage at various temperatures. The data obtained for 20 °C, 40 °C and 60 °C and the measurement procedure were described before [8]. The data were obtained on one single capacitor after an initial holding time of 60 h and additional holding times of 10 h for each new temperature or voltage change. Therefore the total hold time accumulated to about 400 h. The data for a temperature of 65 °C were taken separately on additional capacitors from a new production series. As can be seen from Fig. 9, an exponential correlation exists between the leakage current and the capacitor voltage.

The observation of an exponential correlation is not too surprising, because the leakage current represents the currents of both the anodic and cathodic reactions at both electrodes of the capacitor. In a first approximation both reactions will follow the Butler–Volmer behavior and therefore the slope of the lines in Fig. 9 can be called an effective Tafel slope. The effective Tafel slope for the leakage current is about 0.4 V at 20 °C. At 60 °C the Tafel slope increases to 0.6 V. The corresponding effective exchange current is defined as the current i_0 measured at the nominal voltage (in this case 2.5 V) of the capacitor at the respective temperature.

A minor change in cell voltage causes a significant change in leakage current. For example at 60 °C a 100% deviation (doubling) of the leakage current of one of the capacitors could be compensated by a voltage reduction of 0.2 V. The dashed line in Fig. 9 shows the calculated dependence of the leakage current for a constant leakage resistance, which is much weaker than the experimentally observed behavior of a supercapacitor.

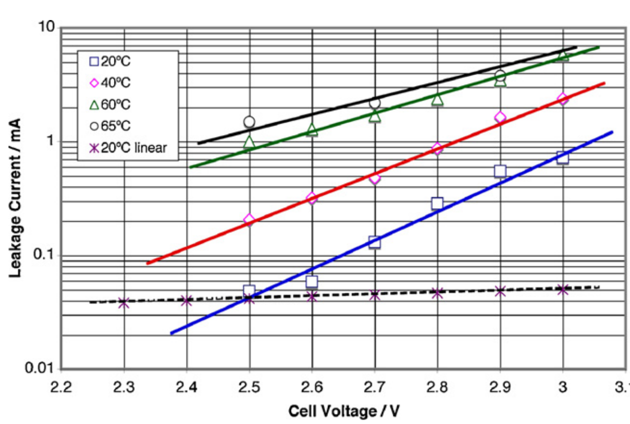

Fig. 9. Leakage current of BCAP350 capacitors as a function of capacitor voltage and temperature. The leakage current for 65 °C was measured after 100 h at the respective constant voltage. The other data [8] were taken after 100 h to 400 h.

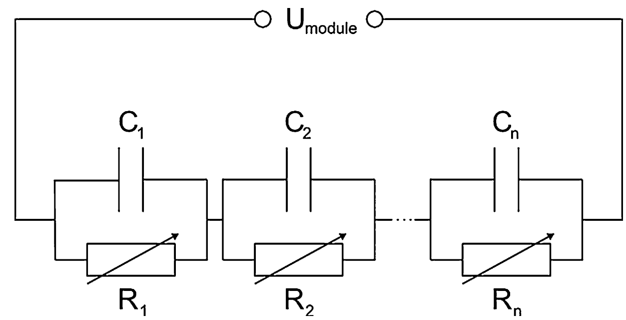

Fig. 10. Equivalent circuit for a capacitor module with n capacitors in series.

3.4. Model calculation

A simple model calculation was performed based on an iterative two-step approach with small time intervals Δt for the discharge of each capacitor k with capacitance C_k through a voltage-dependent leakage resistor R_k and a subsequent recharge step to reestablish the overall voltage of the module (Fig. 10).

The discharge process results in a voltage decrease according to the voltage dependent leakage current i_k.

$$\Delta U_{\mathrm{discharge},k} = \frac{i_k \Delta t}{C_k} = \frac{i_0 \Delta t}{C_k} 10^{(U_k - U_0)/b} \quad (1)$$

U_0 in equation (1) denotes the nominal voltage of the capacitors, b the effective Tafel slope and i_0 the leakage current at U_0 (exchange current). According to Fig. 9 the leakage current i_k is a function of the capacitor voltage U_k. The second step in the calculation is the simultaneous recharging of all individual capacitors with a charge ΔQ from the external source until the overall voltage equals the initial module voltage of 250 V again.

$$\Delta U_{\mathrm{charge},k} = \frac{\Delta Q}{C_k} \quad (2)$$

A model calculation of a series connection of 100 capacitors was performed for a nominal leakage current i_0 of 1 mA (typical for 2.5 V and a temperature of 65 °C (BCAP350)) and a nominal capacitance of 350 F with a normal distrubution of 10% (350 ± 35 F). The initial voltages of all capacitors were set to $U_0 = 2.5$ V. The Tafel slope of the leakage current was assumed to be 0.6 V. For the respective leakage resistors of the capacitors a normal distribution around 2500 Ω (2.5 V/1 mA) with a standard deviation of 500 Ω was assumed. The resulting evolution of the capacitor voltages in the string is shown in Fig. 11a.

From Fig. 11a it is evident that the 100 capacitor voltages will reach a steady state after about four days. The highest capacitor has a voltage of 2.585 V.

The reason for the stabilization of capacitor voltages within a certain voltage range is clearly visualized in Fig. 12, where

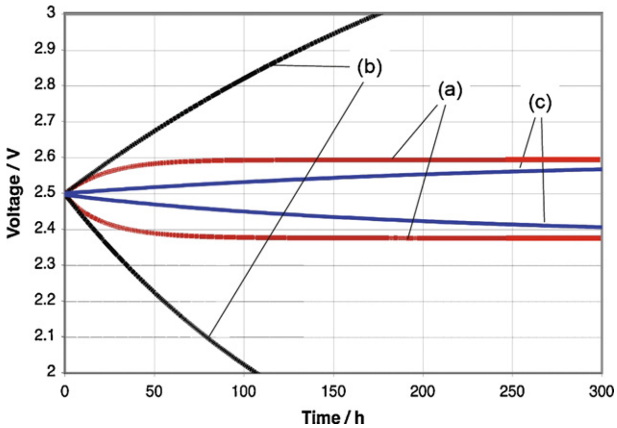

Fig. 11. Calculated voltage evolution of the capacitors with highest and lowest voltage of 100 capacitors ($C_k = 350 \pm 35$ F) in a series connection. (a) Tafel slope of the leakage current was set to 0.6 V. The leakage resistors had a normal distribution around 2500 Ω with 20% deviation. (b) Same parameters as above but with a leakage current proportional to U_k (constant leakage resistor 2.5 kΩ). (c) Same parameters as for (a) but with a larger nominal leakage resistor of 25 kΩ. For all curves a normal distribution of the capacitance C_k around 350 F with 10% deviation was assumed.

the distribution of leakage resistances is plotted directly after initialization and after 100 h of constant module voltage. After initialization, with all capacitors at 2.5 V the leakage resistances vary from 1500 Ω to 3500 Ω with most of the capacitors falling between 1750 Ω and 3250 Ω. Only 17 out of 100 capacitors fall outside this range. However, as a consequence of the voltage changes of individual capacitors after 100 h all resistances fall within a band of only 250 Ω width.

A similar calculation was performed by Linzen et al. [4] for a 42 V capacitor module. For a ±15% distribution of the leakage resistors (300 ± 45 Ω) these authors calculated a much larger voltage deviation for the capacitors in the module after 40 days. The highest capacitor voltage was 0.35 V above the average module voltage. The significantly different result is due to the assumption of constant leakage resistors [4].

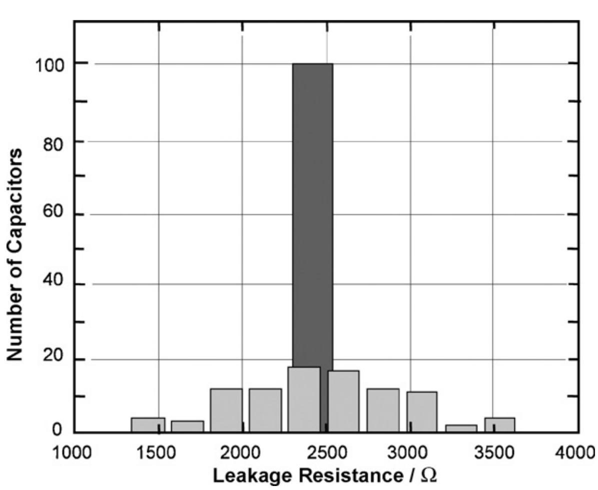

Fig. 12. Assumed statistical distribution (grey) of leakage resistors for capacitors at 2.5 V and (black) after 100 h of the module at constant voltage (250 V). Other parameters same as in Fig. 11a.

We could reproduce the findings of Linzen et al. [4] for 100 capacitors in series (see Fig. 11b) by assuming a constant leakage resistance – i.e. the leakage current depends only linearly on the capacitor voltage – with the same distribution as assumed for the curve in Fig. 11a. The voltage deviation determined in Fig. 11b is much larger and approaches a voltage of 3.55 V for the capacitor with the highest voltage after 50 days.

This large voltage spread is not in accord with the experimental experience for supercapacitors where the leakage current increases exponentially with increasing voltage.

The effect of an increased leakage resistor of the capacitors at lower temperatures is demonstrated in Fig. 11c, where a leakage resistor of 25 kΩ was assumed. From the comparison between curves (a) and (c) in Fig. 11 it becomes clear that the higher resistance (lower temperature) increases the time needed for the capacitors to reach a steady state. The voltage deviation for both curves is unchanged and depends mainly on the Tafel slope of the leakage current and the distribution of leakage resistance. The smaller the Tafel slope, the smaller the voltage deviations within the capacitor string.

In the above calculations it was assumed that the capacitor strings were initialized (see Fig. 5) first, thus eliminating the effect of different capacitance on the capacitor voltage at the upper module voltage. Including a normal capacitance distribution of 10% did not affect the voltage balancing behavior significantly.

4. Conclusions

We have demonstrated in theory and praxis that voltage imbalance within a large SC module is not necessarily a severe problem. A fast run-away effect of the capacitor voltages is not expected because the leakage currents, determining the evolution of imbalance between individual capacitors over time are small and depend on the capacitor voltage in an exponential manner. The exponential increase of the leakage current (exponential decrease of the leakage resistance) with capacitor voltage is the fundamental reason for the development of a steady state within a relatively narrow voltage window around the initial capacitor voltages.

It is of course necessary to quality control capacitors entering a stack in terms of capacitance and leakage resistance. However, with typical leakage currents in the order of fractions of mA for a 350 F capacitor at room temperature the time constant of the equilibration of individual capacitors is in the order of months.

For a normal-distribution of leakage resistances within ±20% the capacitors' voltage deviations are limited below 0.1 V for the highest capacitor.

In case of a short circuit event all other capacitors have to compensate the defect capacitor. In case of a 5% failure rate the good capacitors will increase their voltage by 140 mV only. This is a considerable voltage increase, but will not lead to an immediate catastrophic failure of the stack.

In case of an open circuit event – which is rather unlikely – the series string of capacitors will fail. The only counter measure against such open circuit events is running capacitor cells in parallel.

The experience with the SC module of the HY-LIGHT showed that continuous on-board voltage balancing of the module is not necessary. Without any balancing measure at all the voltage deviations are acceptable. However, monitoring of the individual capacitor voltages is recommended at certain time intervals. Those capacitors developing a bad performance could be exchanged during the next service stop, prior to a remote voltage balancing service of the SC module.

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