BOOSTCAP® Double-Layer Capacitors for Peak Power Automotive Applications

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Abstract

BOOSTCAPs®, the new energy storage devices for peak power applications from Montena components, store and release high electrical power bursts with high efficiency in the seconds range. BOOSTCAPs® are predestined for automotive applications, where they can save energy from braking and release it for acceleration, furnish the high power demands needed for the substitution of mechanical by electrical car systems.

The paper presents key characteristics of the BOOSTCAP® design as well as today's electrical and physical properties and future design and performance trends. In particular the aging behavior and cycle life are discussed. The trend of the performance dispersion of BOOSTCAPs®, due to production mass increase and production automation is touched on. Detailed system design of power modules, realized by series and parallel connection of capacitors, including voltage balancing and protection electronics are presented. To point out the potential of double-layer capacitors in the automotive domain actual applications and test data under realistic automotive profiles are shown. Finally realistic cost estimates for high production volumes in near future are given.

Keywords: Supercapacitor, Ultracapacitor, energy density, power density, cycle life

1. Introduction

Due to the increasing power demand in future vehicles for comfort improvement, as well as ongoing pressures for more environmentally friendly means of transportation, automotive manufacturers are developing alternatives to existing fossil fuel-driven vehicles. Perhaps the most promising near-term alternative to fuel-cell vehicles, which will not be ready for volume production for at least a decade, is the hybrid electric vehicle technology. While progresses have been made in control, engine and motor design, they have not been successful with regard to the electric power storage systems. This is due primarily to the fact that batteries are used to provide the power peaks in most of the currently developed hybrid electric vehicles. But the deficiencies of battery storage systems are multiple and they create many design challenges for automotive engineers. Batteries have a bad low temperature performance, a very limited lifetime under extreme conditions, which results in repeated replacement throughout the life of the vehicle, and they are not designed to satisfy the most important requirements of hybrid electric vehicles power source: to provide bursts of power in the seconds range for events such as acceleration, braking and cold starting.

Recently, a very promising technology has been introduced with the potential to improve energy storage in automotive applications: double-layer capacitors. These devices, also known as supercapacitors or ultracapacitors, represent a new generation of electrochemical components with very high capacitance for energy storage.

Montena components has recently started the production of very high capacitance double-layer capacitors under the trade name of BOOSTCAP®. These innovative storage devices possess capacitance values up to several thousand Farad, they are able to supply high power bursts in the seconds range and they can be cycled several hundred thousand times. BOOSTCAP® may not only be used to replace batteries, but instead complement them to overcome some of their disadvantages in power delivery and lifetime.

2. BOOSTCAP® technology

2.1. Energy storage technology comparison

In terms of energy density and access time to the stored energy, double-layer capacitors are placed between large aluminum electrolytic capacitors and smaller rechargeable batteries [1]. The Ragone diagram, presented in Figure 1, shows the domain occupied by double-layer capacitors in the power and energy densities space. It can be seen that the BOOSTCAPs® from Montena cover the highest part in power and energy density of double-layer capacitors.

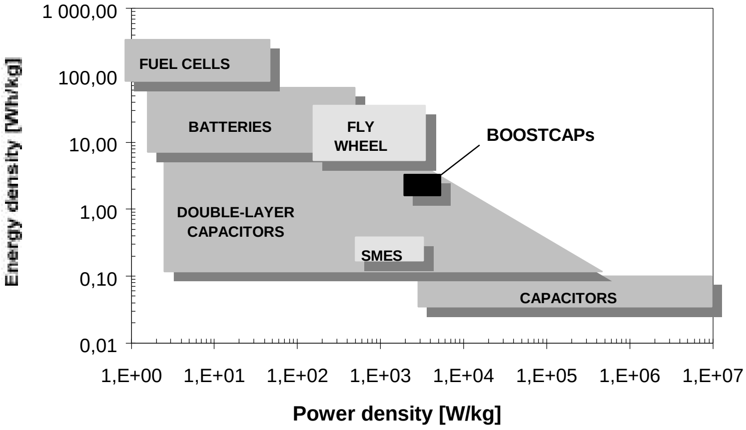


Figure 1: Ragone diagram, comparison of different energy storage and conversion devices

Peak power applications, as they occur in the transportation domain, need passive components to store the electrical energy in volume and weight as small as possible. The choice of the storage device type depends in particularly on the speed of the storage process, in some other words on the power required by the application. While the slower storage processes may be performed with batteries and the faster ones with capacitors, the ideal storage device to supply bursts of power in the seconds range are double-layer capacitors.

2.2. Double-layer technology

BOOSTCAPs® consist of two activated carbon electrodes, which are immersed into an electrolyte. The two electrodes are separated by a membrane which allows the mobility of the charged ions but forbids the electronic contact. The organic electrolyte supplies and conducts the ions from an electrode to the other if an electrical charge is applied to the electrodes. In the charged state, anions and cations are located close to the electrodes so that they balance the excess charge in the activated carbon. Thus across the boundary between carbon and electrolyte two charged layers of opposed polarity are formed. This layer, discovered in 1879 by Helmholtz, is called an electrochemical double-layer.

Thanks to the use of electrodes made of carbon powders with surfaces up to 3000 m^2/g, the extremely short distance between the opposite charges in the range of 10^{-9} m and electrolytes with a decomposition voltage of 3 V, Montena succeeded in developing double-layer capacitors with an energy density of up to 5 Wh/kg. Due to the impregnation with a high conductivity organic electrolyte and the excellent electrode electronic conductance as well as the high ionic separator porosity the series resistance of the BOOSTCAPs® is very low. Thus the capacitors show a very high matched power density of up to 10 kW/kg.

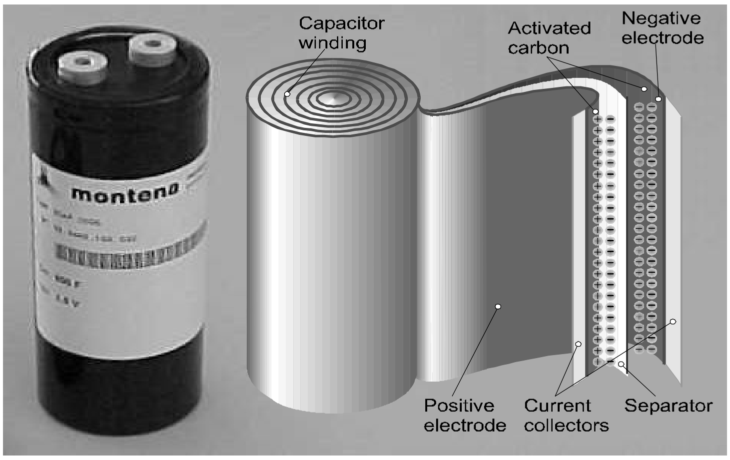


Figure 2: Electrochemical double-layer capacitor

BOOSTCAPs® rely on an electrostatic effect, which is purely physical and therefore highly reversible. Charge and discharge occurs upon movement of ions within the electrolyte. This energy storage process is in contrast to all battery technologies, as they are based on chemical reactions. Consequently, there are some fundamental property differences between BOOSTCAPs® and battery technologies, which are long shelf life, an extended useful life and a high cycle life. These advantages result in an almost maintenance-free storage device.

2.3. Cell construction

Double-layer capacitor devices differ generally in two methods of construction, the monopolar cell design and the bipolar cell design. The bipolar devices reveal high voltages, low resistance and low capacitance. Such double-layer capacitors are built up by stacking several single cells in series into one case. The sealing of such devices is very sophisticated.

The monopolar device shows very high capacitance due to a high surface area. The voltage of such devices is identical to that of the single cell. Monopolar double-layer capacitors are assembled by winding or stacking in parallel electrodes, current collectors and separator foils. Stacking processes are used by several manufacturers which assemble separate electrode and collector foils in the device. In this case, it is important to have a very good mechanical contact between the electrode and the current collector. By applying a controlled high pressure on the stack, low internal resistance can be obtained. The disadvantage of the stacking technology is a low productivity and therefore high production costs. Stacked devices allow a prismatic design.

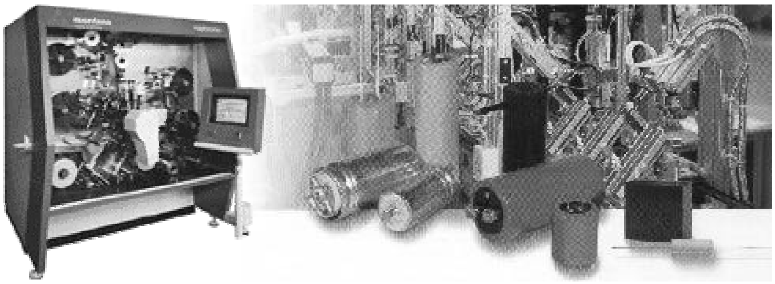


Figure 3: Montena winding machine and assembly line

Manufacturers assembling electrodes deposited directly on a current collector are usually using winding processes (Figures 2, 3). Advantages of the winding technology are a very reliable process, a high productivity and therefore low costs. Montena has many years experience in the winding technology. Today the fastest and most reliable winding machines worldwide are produced. Thanks to this technology BOOSTCAPs® are today produced in a cylindrical shape with variable sizes and dimensions. Due to a precise control of all winding parameters such as the foil length and the foil tension a very low dispersion of the devices performances is achieved (see chapter 4.3).

2.4. Future design trends

The winding technology shows also advantages for future BOOSTCAP® designs. First we can up- and downscale the dimensions of actual available cylindrical capacitor design almost at will, and second it is also possible to produce capacitors with prismatic design. Therefore capacitors are wound during the manufacturing process on a bigger core diameter and the product is then pressed to a flat capacitor winding. This technology is already well known for other capacitor technologies. The flat design will offer additional liberty for the assembly of modules from individual devices.

3. BOOSTCAP® features

3.1. Available cells

Today, Montena manufactures double-layer capacitors of different sizes and designs. The top of the range when it comes to power and energy density is represented by the BOOSTCAP® BCAP0010 capacitor. With an internal resistance below 0.45 mOhm at 1 kHz this capacitor is predestined for power applications of any kind. The following table shows the range of BOOSTCAP® products and their characteristics.

	BCAP0009	**BCAP0011**	**BCAP0007**	**BCAP0008**	**BCAP0010**
Rated Capacitance [F]	**400**	**800**	**1400**	**1800**	**2600**
Capacitance Tolerance [%]	±20	±20	±20	±20	±20
Rated Voltage [V]	2.5	2.5	2.5	2.5	2.5
Surge Voltage [V]	2.8	2.8	2.8	2.8	2.8
Series Resistance ESR (DCC, 25 °C) **[mW]**	3 (2 @ 1kHz)	2 (1.8 @ 1kHz)	1.4 (0.9 @ 1kHz)	0.9 (0.6 @ 1kHz)	0.7 (0.45 @ 1kHz)
Matched Power Density (2.5 V) **[W/kg]**	4'000	4'000	4'500	6'500	6'600
Max. Current [A]	130	200	300	450	600
Specific Energy Density (2.5 V) **[Wh/kg]**	2.5	3.3	4.3	3.9	4.3
Weight [g]	140	210	280	400	525
Volume [l]	0.128	0.177	0.255	0.3	0.42
Operating Temperature [°C]	-35 to 65	-35 to 65	-35 to 65	-35 to 65	-35 to 65
Storage Temperature [°C]	-35 to 65	-35 to 65	-35 to 65	-35 to 65	-35 to 65
Life Time (25 °C) **[y]**	10	10	10	10	10
Cyclability (25 °C, I = 20 A)	500'000	500'000	500'000	500'000	500'000

Table 1: Characteristics of BOOSTCAP® double-layer capacitors

3.2. Future performance trends

The double-layer capacitor performance development goals are a long lifetime, an increase of the rated voltage, an improvement of the operating temperature range and an increase of the energy and power densities. The rated voltage will be increased up to 3 V within the next years. To easily access automotive applications a temperatures range from –35 up to 105 °C will be of advantage. The energy and power density goals for BOOSTCAP® double-layer capacitors have been fixed at 10 Wh/kg and 10 kW/kg.

What is expected from the research and development are the increase of the electrolyte decomposition voltage and ionic conductance, the increase of the electrode accessible surface, chemical and mechanical stability as well as electronic conductance and the separator electronic insulation level and ionic conductance. A main activity is actually the development of new electrolytes based on the combination of novel organic solvents and improved conduction salts, permitting not only a higher rated voltage and a higher conductivity but also a larger operating temperature range.

4. BOOSTCAP^{Ò} Properties

4.1. Ragone diagram

The Ragone diagram is a chart, which gives the relation between the specific energy and the specific power of a storage system at given frequency [2]. Figure 4 shows the power density vs. the energy density of BOOSTCAPs$^{®}$ double-layer capacitors calculated from electrochemical impedance spectroscopy measurements over the frequency range from 10 kHz to 10 mHz. The curves reveal the excellent performance of the capacitors. Due to the very low internal resistance the devices show a very high power density. At higher frequencies values up to 10 kW/kg are possible, at lower frequency an energy density of up to 4.8 Wh/kg is achieved.

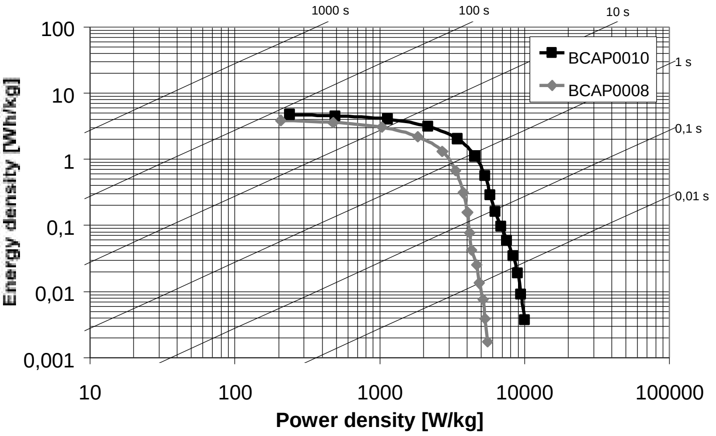


Figure 4: Ragone diagram of BOOSTCAPs$^{®}$

4.2. Aging behavior of BOOSTCAPs^{Ò}

Different techniques are usually used to characterize the aging behavior of double-layer capacitors under electrical aging conditions [3]. Among them, cycling tests consist in charging and discharging the component at constant current between two values of potential. DC life test is also a test of endurance which is more simple to implement than cycling. The component is continuously polarized at a constant voltage and a constant temperature, often the maximum value of use, so it is maintained at a constant state of full-charge during weeks.

4.2.1. Cycling of BOOSTCAPs$^{®}$

Cycling performances of BOOSTCAPs$^{®}$ have been tested at room temperature using an original monitoring apparatus. The device allows the cycling even if a high current and thus high power is needed. Figure 5 shows the time behavior of BCAP0010 under a current stress of 130A between 2.3 and 1.15 V, with a 25 seconds rest time after every charge and discharge and a BCAP0010 under a current stress of 100 A between 2.7 and 1.8 V, with a 5 seconds rest time. The former cycling is a simulation of a use under normal conditions and the latter of utilization under extremely hard conditions.

The measurements done with a maximum charge voltage of 2.3 V show a capacitance decreased to about 90% of the initial value after 100'000 cycles. If the decrease was stronger at the beginning of the experiment, it became always slower with the number of cycles. According to this tendency, it can be assumed that the target performance of less than 20% of capacitance loss after 1 million of cycles will be reached with a maximum cycling voltage of 2.3 V. In the same time, the ESR increased very slightly from 0.49 to 0.53 mOhm (+ 8 %).

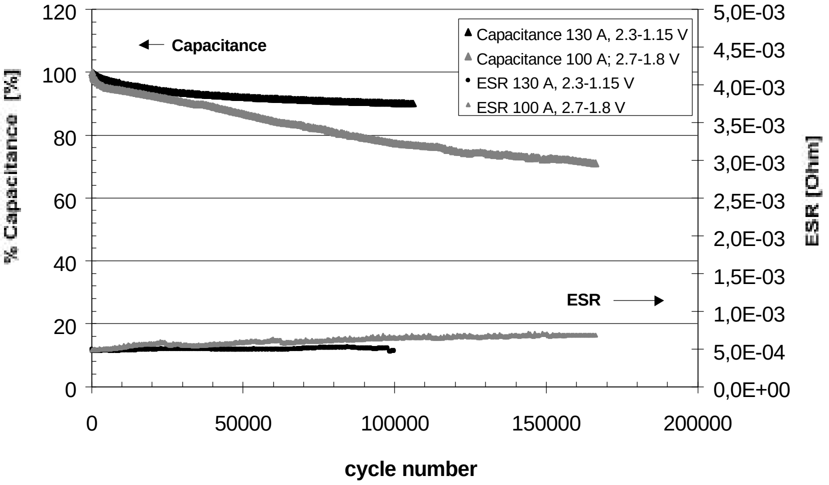


Figure 5: BCAP0010 performances during cycling tests

The measurements show, that even at a high voltage of 2.7 V and a short rest time a high cycle number of up to 100'000 cycles is achieved before the capacitor capacitance decreased by 20 % compared to its initial value. The ESR under this conditions shows merely a slight increase from 0.49 to 0.69 mOhm (+ 40 %) after more than 150'000 cycles.

4.2.2. DC life tests

BCAP0010 were stored at a constant temperature under different voltages continuously supplied by power sources.

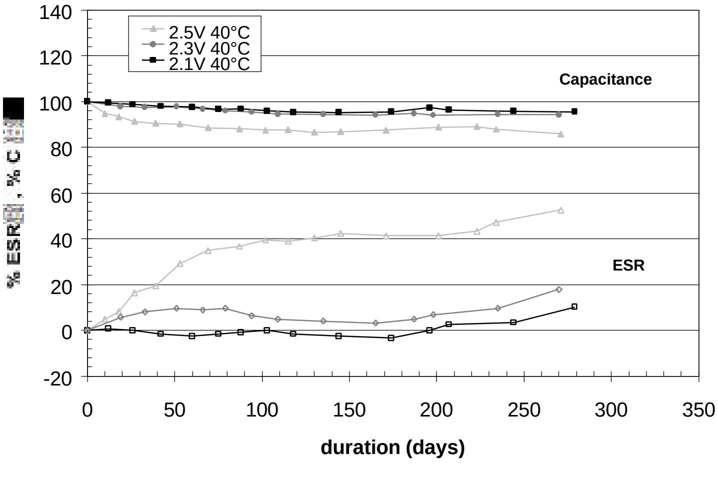


Figure 6: BCAP0010 capacitance and ESR behavior during DC-life tests at 40 °C.

Periodically the components were let at room temperature and capacitance and ESR were measured. Figure 6 shows the behavior of capacitance and ESR for components polarized at 2.1, 2.3 and 2.5 V at a temperature of 40 °C. During the first measurements the capacitance is decreasing slowly. In the same time, the ESR has increased slightly. These phenomenon is accentuated at higher voltages and, based on equivalent measurements, at higher temperature. This confirms the influence of the voltage and the temperature on aging conditions. Nevertheless, it seems that the strongest part of the degradation of double-layer capacitors stand during the first weeks. Then, after about 40 days, a kind of stabilization can be seen, at more than 90% of the initial value of capacitance, even at 2.5 V.

4.3. Performance dispersion

The continuous improvements of the production techniques and sustained automation of the production equipment allowed an important improvement of the performance dispersion of finished devices. Today BOOSTCAPs® double-layer capacitors reveal not only an excellent performance but also very close performance values of the devices.

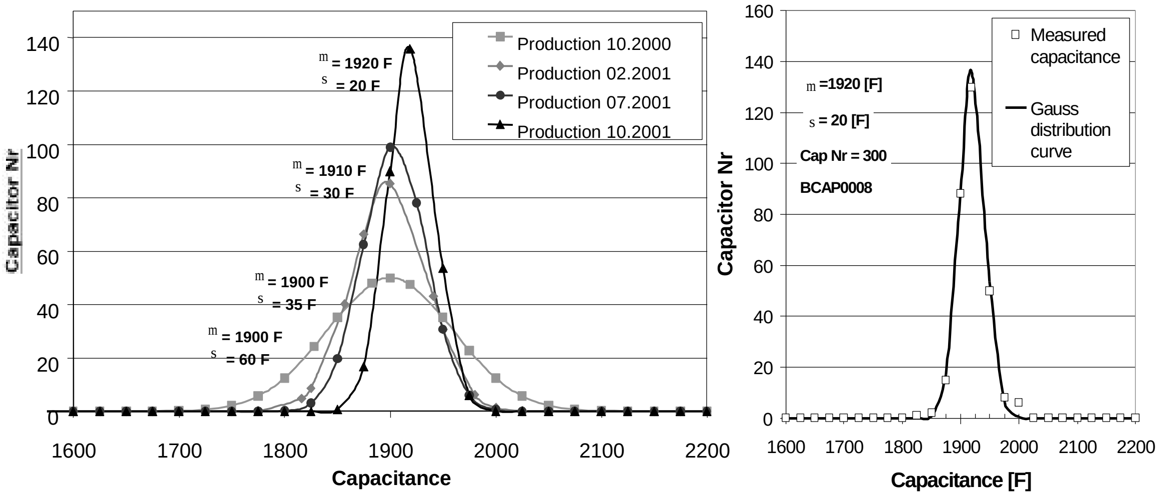


Figure 7, 8: Capacitance dispersion evolution, actual BCAP0008 capacitance dispersion

The evolution of the capacitance dispersion during the last few months is shown in Figure 7. The curves show that not only the standard deviation has been decreased but also the mean capacitance value could be increased. This is mainly due to the increased electrode surface which has been achieved with an improved control of the winding parameters thanks to automated winding equipment. Today, an excellent dispersion performance has already been obtained (Figure 8).

5. System design and voltage balancing

The specially compact design of double-layer capacitors allows a combinations of individual devices to form modules according to customers specifications. Today, standard modules with voltages of 14, 28 and 42 V are available. Each module shows the typical characteristics of the individual device, namely a high energy and power density. Different modules which have been built up according to customer specifications are shown in Figure 9. All of them are equipped with an active sharing device for voltage balancing of the individual BOOSTCAPs®, which protects the capacitors from being overloaded.

Figure 9: BOOSTCAP® modules with active voltage balancing electronics

In addition to the wide range of applications, double-layer capacitors offer various possibilities for combined use with accumulators or traditional capacitors. Storage units for electrical energy can be manufactured with operating lives of more than 10 years, which need no maintenance of the BOOSTCAPs®. Additionally, a reliable operation at very low temperatures and low voltages is guarantied. Most importantly, the long operating life of the capacitors results in their ability to carry out 500'000 loading and unloading cycles.

5.1. Voltage balancing

Due to the different capacitance values and self discharge behavior of the devices and the accelerated aging of individual capacitors in case of temperature gradients on the module, the total voltage over a series connection will not be equally distributed between the different capacitors. If this effect is not compensated a local over-voltage could appear over one of several double-layer capacitors with a risk of destruction of this component. In addition, the stored energy wouldn't be optimized. Therefore a voltage sharing device is used if capacitors are connected in series.

5.1.1. Existing voltage balancing solutions

A common way to equalize the voltages in a series association of capacitors is to connect across each of them a resistor. The values of the resistors are fixed by various criteria. The main criteria to consider is to fix a dynamic of the voltage sharing equal to the dynamic of the charge process of the double-layer capacitors. This allows to avoid any overshoot of the individual voltages. The main disadvantage of this solution is the power dissipated in each resistor. There is always a current flowing in the resistor-network, deteriorating the self discharge behavior of the system.

A circuitry similar to the resistor balancing uses zener diodes across each capacitor. Those zener diodes have to limit the voltages of the capacitors, in order to fix the maximum value to 2.5 V. There is no power dissipation as far as all the voltages are less than the limit voltage. But the power dissipation can be important if many devices reach their voltage limit.

An other possibility is to couple each device with its own dc/dc-converter to a main dc-link. This most expensive solution offers a maximum isolation of each capacitor. Therefore a very good availability can be achieved. Because of the separated current control, it is useful for high currents.

The circuitry shown in Figure 10 uses an active charge equalization device based on a back-boost topology, which ensures no over-voltage, and a maximum energy stored with a high efficiency. The charge of neighboring double-layer capacitor can be equalized by measuring the tensions and controlling the corresponding transistor-switches. Here a selective charge equalization is possible but a direct one from the firsts to the lasts capacitors of a serial module is impossible.

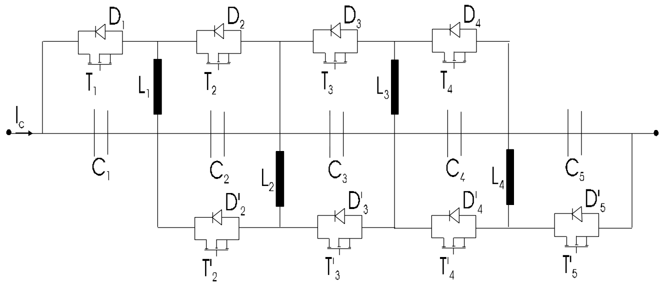


Figure 10: Electronic schema of the active voltage sharing based on a backboost topology [4]

Finally, an interesting voltage balancing solution is the so-called virtual parallel (VP) circuitry, named due to the parallel structure of the circuitry [5]. The VP as power-circuitry shown in Figure 11 has the advantages that the capacitors are stressed according to there parametric deviation, so that they are self-controlled. The devices are coupled together to the power link by means of pulsing the dc voltage of the capacitors with a clock-signal with an identical duty cycle. Therefore only one control unit for a huge number of double-layer capacitors in the same module is necessary. Neither a reverse of polarization nor an overload can happen. Furthermore, energy storage of different technologies, e.g. batteries, can be used in the same storage system. A breakdown of one storage element does not touch the running system, which explains the low trouble-proneness of this solution.

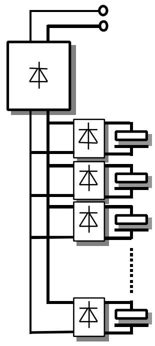


Figure 11: VP as power-circuitry

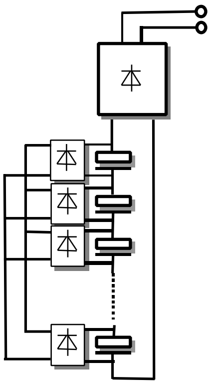


Figure 12: VP as equalizing-circuitry

If the VP is used in the version of an equalizing-circuitry (Figure 12), the devices are additionally wired by a parallel path. That effects a permanent and direct charge equalization. The equalization-path can here be designed only for a limited current. The double-layer capacitors with a higher energy level serve energy to the equalization circuit automatically, those with a deeper source voltage receive this energy. Here too, only one unique intelligence for the whole module is needed.

6. Automotive applications

BOOSTCAP® double-layer capacitors are ideal wherever high bursts of power are needed. Existing and new applications include automotive engineering, rail traction, telecommunication, uninterruptible power supplies, renewable energy resources, industrial electronics and medical engineering.

Onboard electrical systems, power steering, electromagnetic valve control, integrated starter-generators, catalysts preheating as well as hybrid electric and fuel cell drives are just a few examples of the many automotive applications possible. In the following, actual applications and test data under realistic automotive profiles are presented.

6.1. BOOSTCAPs® used in a hybrid fuel cell vehicle application

6.1.1. Introduction

In the last few years new propulsion hybrid drive trains have been intensively studied. An interesting concept is a fully electric hybrid drive train which consists of a primary constant power source such as a fuel cell or a battery and a secondary peak power source, e.g. double-layer capacitors [6]. The primary power source handles continuous load requirements, such as cruising and basic electric needs. The secondary power source is sized for short-duration load leveling, absorbing the kinetic energy from braking and release it later to accelerate the vehicle, resulting in energy savings of up to 25 % [7] and increased mileage of the vehicle. Because these short-duration events are experienced many thousands of times throughout the life of a vehicle, they are very well suited for the long life of the BOOSTCAP® double-layer capacitors. Their cycle lives are much longer than those of batteries, so it may never be necessary to replace the energy storage medium. Therefore the life-of-system costs are reduced, and adverse environmental effects are diminished.

In collaboration with the Paul Scherrer Institute and other partners, a hybrid fuel cell vehicle is built up with BOOSTCAPs® [7, 8]. The fuel cell, which acts as primary power source, is sized for the continuous load requirement. The BOOSTCAP® bank, which acts as the secondary power source, is sized for peak load leveling events [9] such as engine starting, acceleration and braking. These short duration events are experienced many thousands of times throughout the life of the vehicle and require relatively little energy but substantial power.

6.1.2. BOOSTCAP® module assembly

In the actual activities a BOOSTCAP® module was assembled out of 140 pair wise connected single cells (Figure 13). In order to minimize interface corrosion effects between the electrical contact and the capacitor, aluminum bars were chosen for the electrical connectors. Contact resistance turned out to be higher when using different metals e.g. copper contacts on aluminum capacitor mounts. To meet the given target for the series resistance it was necessary to treat all contact surfaces to remove the insulating oxide layer and to increase the contact area. A supplementary active voltage balancing electronic was mounted to equilibrate the cell voltages inside the BOOSTCAP® module. The capacitor module was mounted into a metal housing, shaped according to the space requirements of the car. Furthermore the box was equipped with a cooling system consisting of fans and air distribution channels where required.

Figure 13: The fully assembled BOOSTCAP® module in its storage box

6.1.3. Measurements and performance data

The total mass of the module was 84 kg, made up of 55 kg BOOSTCAP® cells, balancing electronic and electrical contacts and 29 kg for the metal housing, contactors, fuses and supplementary electronic components e.g. power electronic- and CAN-bus-components. The total volume of the BOOSTCAP® module was 80 liters. All measurements were carried out in a engine laboratory on a dynamic test bed.

The total series resistance ESR of the module was 56 mΩ. To measure the energy content and the power of the module, a constant power supply or demand were generated by the dynamic test bed and the electrical engine to charge or discharge the capacitors between half (90 V) and full (180 V) rated voltage. The module was capable of providing a constant power of 25 kW during 15 seconds of discharge from full to half rated voltage, as shown in Figure 14. This is equivalent to an energy content of 105 Wh @ 25 kW.

To verify the thermal properties of the module and its cooling system, the module was charged and discharged with 15 kW load (corresponds with a charge-/discharge-time of 30 seconds) generated from the test bed and the electrical engine. In a duty-cycle of 50 % the BOOSTCAP® module showed a maximum temperature increase of 15 °C after 2700 s of cycling with 15 kW. During the following 1800 s break the temperature dropped about 10 °C.

Despite the great number of series connections, it was possible to keep the series resistance ESR of the module low, which contributes to the high power capability and to a good efficiency, both essential for the use in a drive train system. The chosen cooling system seems to be sufficient to keep the module temperature at a tolerable level during cycling and helps to cool the capacitors to a lower temperature during breaks, which leads to a lower self discharge and a longer lifetime of the capacitors.

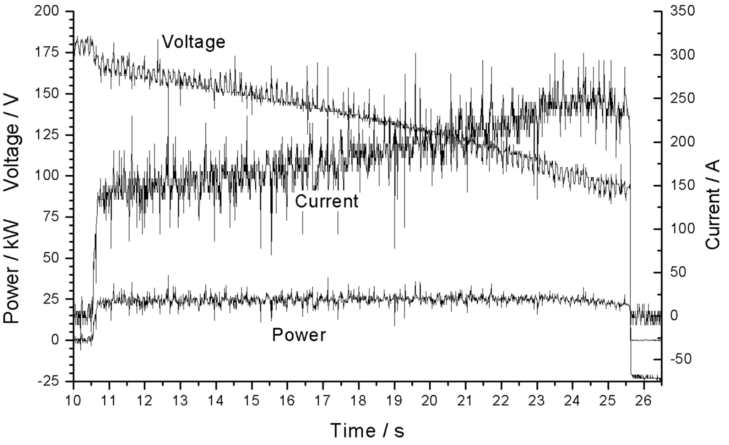


Figure 14: Measured current, voltage and calculated terminal power during a constant 25 kW discharge of the BOOSTCAP® module.

6.2. Performance test of a scaled down BOOSTCAP® module for a hybrid drive train

6.2.1. Introduction

The power consumption from a battery driven electrical vehicle, driving on a chosen route under hard conditions was measured. With this data the power division for a hybrid drive train was calculated. The drive train consisted of a constant power source (e.g. fuel cell or battery) and a peak power source in form of a double-layer capacitor module. In the following experiment the behavior of the capacitor module was studied. To meet the possibilities of the used test bed, the size of the used BOOSTCAP® module was linearly scaled down.

The calculated and down scaled power profile for the test cycle is shown in Figure 15. During the first 1900 seconds the module is rarely used, due to the topography of the chosen route, but in the last part the charge and discharge activity, from subsequent breaking and acceleration processes, of the module is on a considerable level. The aim of this experiment was to prove the capability of the BOOSTCAP® module to deliver and store the calculated demanded and given power during this driving cycle. Furthermore, this method allows to verify and to compare different calculated power distributions between the constant power source (e.g. battery or fuel cell) and the peak power source for the described hybrid drive train on the capacitor side.

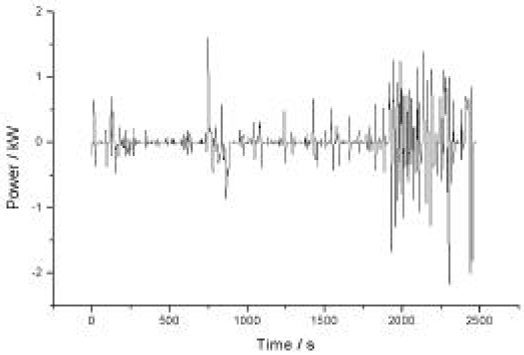


Figure 15: Calculated power profile for the down scaled BOOSTCAP® module, negative power means charge and positive means discharge of the module

6.2.2.Experimental

The used BOOSTCAP® module consisted of 10 pair wise connected single cells (BCAP0012), leading to a terminal voltage of 12.5 V. The module was equipped with a voltage balancing electronic to keep the serial units on the same voltage level and to avoid partial overcharge of certain units. To observe the thermal properties, the module was mounted in an insulating Styrofoam box, to avoid thermal loss during the cycling. The surface temperature of the cells and the power part of the balancing electronic were observed with two thermocouples.

From the power profile (Figure 15), a current profile was generated to serve as the input data for the test bed, composed of a power supply (Topcon, 100VDC / 320A), an electronic load (Höcherl & Hackl, 120 V / 500 A), a data acquisition system (Agilent data acquisition/switch unit), and a personal computer as control unit. The time resolution was 0.5 s for the data acquisition and 2 s for the current setting of the test bed. With the measured current and terminal voltage on the capacitor module the power behavior during the driving cycle was calculated.

6.2.3. Performance results

The experiment showed, that the theoretical assumptions for the power management of the drive train were reconfirmed and the BOOSTCAP® module was able to deliver the power peaks and to store the predetermined power of the driving cycle. A representative part of it is shown in Figure 16, the differences between the predetermined power and the effective power are smaller than 5 % of the default value and only on the discharge side apparent. This difference arises due to insufficient response of the electronic load in the test bed.

The performed temperature measurements during the cycling with subsequent acceleration and braking periods showed a slight increase of the temperature of only about 3.5 °C and this without cooling of the module (Figure 17). Thus the temperature increase inside the module is a minor problem and can be solved with conventional cooling methods. The higher temperature level measured at the balancing electronic is due to losses in the power part devices, which occurs immediately after applying a voltage to the module. Therefore this temperature already increased during the charging of the module to its starting point of the driving cycle.

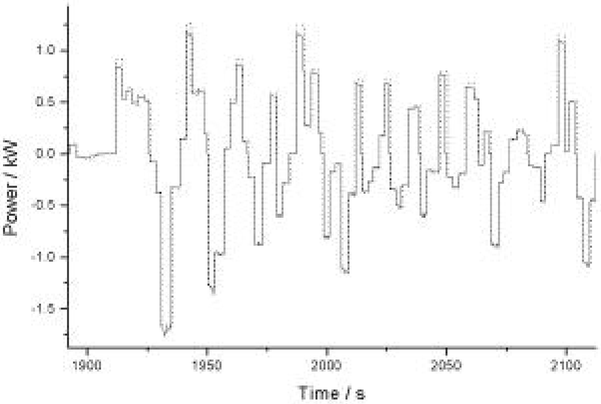


Figure 16: Representative part of the driving cycle, exhibiting the differences between the predetermined power (doted line) and the effective power (solid line) of the BOOSTCAP® module.

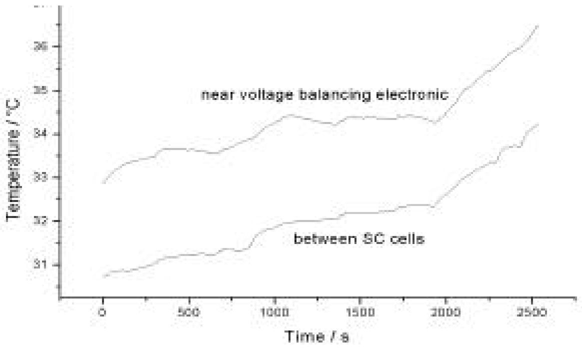
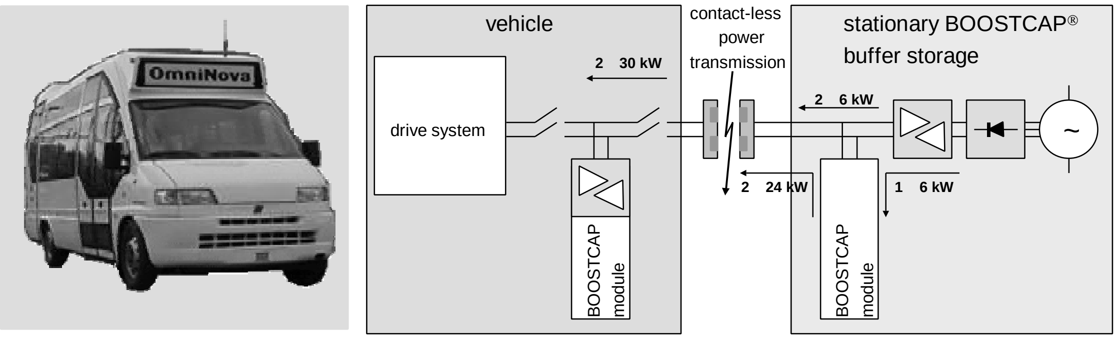


Figure 17: Temperature increase during cycling of approximately 3.5 °C for both thermocouples.

6.3. Fast charge shuttle bus

Buses are being closely watched as pioneering vehicles of environmentally friendly transportation. Until fuel cells go into volume production, combustion engine-electric drives represent the most interesting drive systems to reduce the emission levels of buses. In collaboration with the University of applied science of central Switzerland and other partners from industry and economy, a minibus called Tohyco-Rider based on the combination of a combustion engine with an electric power train is realized [5]. A picture of the minibus is shown in Figure 18. The concept is schematically shown in Figure 19. The objective is to equip a 4.5 t minibus with a BOOSTCAP® module that absorbs the kinetic energy from braking and release it later to accelerate the vehicle. Double-layer capacitors are the ideal components for the use in minibuses because the energy consumption is very high. The total mass of the module is about 400 kg, made up of BCAP0007 cells. Calculations show that the capacitor module weigh about 500 kg less than a comparable battery module. Moreover, due to the longer useful life of capacitors, the module costs could be much deeper for double-layer capacitors.

During the day, the minibus will operate in a city in the electrical mode at zero emission only with the energy from the capacitor module on a stretch of about 5 km with several stations. After each turn the capacitor bank will be charged by inductive, thus contact-less power transmission. As a result of the stationary BOOSTCAP® buffer storage, the recharge of the module on the vehicle can be done in a very short time of approximately three minutes. The loading-up power of altogether 30kW can be supplied to 80% by the static capacitor buffer. As a result, power peaks are reduced in the net. In the evening, the minibus replaces big buses serving the lines in the surroundings of the city in the hybrid mode.



Figures 18 and 19: Tohyco-Rider minibus and concept for the minibus energy supply, way 1: net buffer is loaded, way 2: loading of the minibus

6.4. 42 V electrical subsystem and integrated starter generators

The development of innovative automotive systems is determined by the demand for comfort improvement, cut in fuel consumption, reduction of environmental pollution and increase in efficiency. A result is the substitution of mechanical by electrical systems such as electric steering, electromagnetic valve control, electric water pump, electromechanical braking, electric air conditioning, catalyst preheating etc. as well as the introduction of new drive train functions like start-stop and recuperative braking. The storage of braking energy can also be usefully applied for vehicles with internal combustion engines, especially for the improved alternators used as braking generators, so-called integrated starter generators [10]. Conventional lead-acid batteries cannot furnish the energy in the seconds range because of the slow chemical processes. Double-layer capacitors work quiet differently: They are predestined to store the energy generated within a very short time and release the energy with high efficiency, even in cold weather. Future 42 V electrical subsystems will be able to furnish the power demands in the range of 8 to 20 kW [4]. Thanks to their long life and high cycle life BOOSTCAPs® are ideal for the variable power loading required of new subsystems.

6.5. Transportation applications

On a larger scale, double-layer capacitors are well suited to many transportation applications. The endless cycles of acceleration, followed by braking, of mass transit train, subway, and metro systems are ideal for BOOSTCAP® technology. In conclusion, double-layer capacitors could play a large part in revolutionizing the entire transportation industry, an industry which needs power technologies that respond to changing consumer demands for environmentally sensitive, high performance and low-cost products.

Several projects are actually running in the field of transportation applications. For example tram supply without catenary [11] and voltage drop compensation for weak distribution network [12]. In industrial electronics, double-layer capacitors can be used in uninterruptible power supplies, elevators [13], pallet trucks etc. BOOSTCAPs® can be combined into large modules with integrated balancing that span outages in all power categories. In power electronics they are particularly suitable for backup in operation independent of the line voltage.

7. Realistic cost estimates

During the next years, the costs of double-layer capacitors will decrease significantly. This is possible due to different reasons. First, the nominal voltage of BOOSTCAPs®, currently rated at 2.5 V, will be increased to 3 V within the next five years. In this way, the costs of a module built up from several devices will be reduced by approximately 25 %. Second, an additional cost reduction can be expected as production quantities increase. The world market for double-layer capacitors is estimated to increase up to 500 Mio US$ within the next 5 years [14]. High production volumes will permit to purchase the capacitor materials at much higher volumes and therefore lower prices. Mainly the electrode price as the key material in a double-layer capacitor is depending strongly on the ordered quantity. Third, an important cost reduction is obtained due to the automation of the whole production process. Here the winding technology used for the production of double-layer capacitors offers a big potential for cost reduction. Thanks to these improvements, the future costs per energy content of BOOSTCAPs® will come down to 10 US$ per 1000 F. In addition, module costs will decrease due to higher production volumes and new low-cost voltage sharing technologies. Double-layer capacitors will then be used in many applications which are currently still powered by accumulators or batteries.

8. Conclusion

Double-layer capacitors are ideal wherever high bursts of power are needed. They are an optimum storage medium for absorbing and releasing large amounts of energy within the seconds range. These properties predestine BOOSTCAPs® for automotive applications, where they can save energy from braking and release it for acceleration, thus reducing fuel consumption, environmental pollution and increase efficiency. In addition they can contribute to the improvement of car comfort thanks to their ability to furnish the high power demands needed for the substitution of mechanical by electrical car systems.

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