Ultra Capacitors

Application in Onboard Power Supplies

Ultra capacitors, also known as ultracaps or supercaps, are short-term electrical storage elements which are considered in part to be competitive with batteries (so-called long-term storage elements) in on-board electrical systems. Maxwell Technologies explains the advantages and limitations of this storage technology and discusses its integration particularly in on-board electrical systems which lend themselves to a combination with batteries (electrical hybrid). In doing so the company addresses potential, which will be transformed within the scope of new developments to benefit ultracap technology.

1 Introduction

Political circumstances, emissions legislation and not least social change, exemplified by increased environmental awareness, will change the automotive industry and its products forever. Significantly more efficient and energy saving vehicles are necessary. The challenge is to be able to continue to provide them with maximum safety, perceptible comfort and good performance which will continue to be sufficient for future requirements. The electrification of the power train and components which have differing characteristics, from hybrid drives to all-electric driven automobiles, are favoured solutions. Here, electrical energy storages are seen to be a source of hope but also a bottleneck. To rely upon long-term storages such as high-voltage lithium-ion batteries alone is too short-sighted. In the context of new drive concepts the combining of batteries and supercaps is being considered or specifically, how the systems can used to compliment each other in a meaningful way. In this respect, in the following article various scenarios and their potential **Figure 1** are considered and additional areas of application for short-term storages discussed.

2 Ultra Capacitors

2.1 Electrochemistry

Ultra capacitors, **Figure 2**, also known as electrical double-layer capacitors (EDLC), are based on two electrodes of activated carbon which are separated by an insulating layer. To enable an ultra capacitor to function at all, the carbon electrodes (Helmholtz double layers) are saturated with an electrolyte. The electrolyte contains ions with differing charges which accumulate on each reverse polarised electrode when a potential is applied. To allow the dissociation of the ions the insulating layer between the two electrodes has to be pervious for the mobile charge carriers. Due to the extremely large surface area of up to 3.000 m^2/g, of the activated carbon with layer thicknesses of 100 to 150 microns, present-day ultra capacitors can possess capacitances of several thousand farads. The extremely small charge separation allows exceptionally high performances to be provided with a cell voltage of 2.7 volts (dependent on type of cell) for a short period (effective period to max. 30 sec.). The carbon for the electrodes, the crucial components, is obtained by Maxwell from coconut shell, an ecologically suitable, sus-

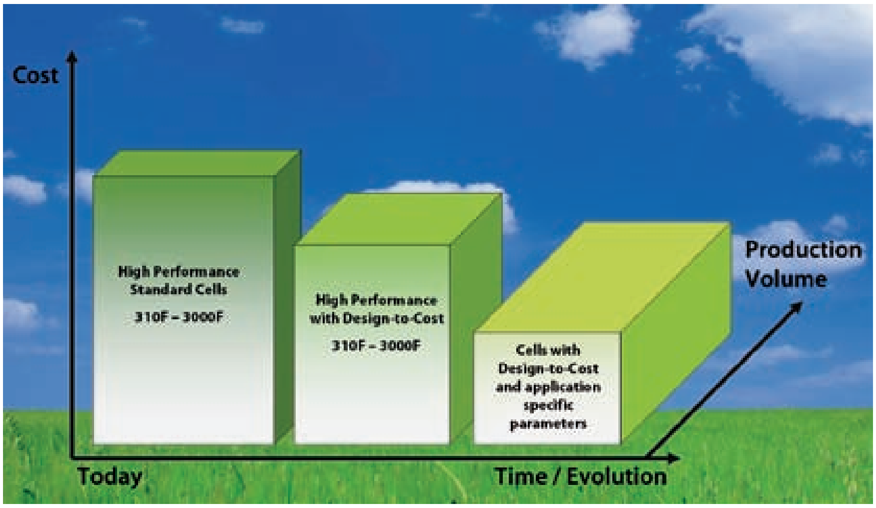


Figure 1: Evolution of ultracaps in terms of cost and technology

The Authors

Jürgen Auer
is Head Automotive at Maxwell Technologies GmbH in Gilching (Germany).

Christoph Wieser
is Key Account Manager Automotive at Maxwell Technologies GmbH in Gilching (Germany).

tainable and environmentally-friendly resource which is in almost unlimited supply.

2.2 Characteristics

For the above-mentioned vehicular applications it is essential that the performance from the ultra capacitor storage is available at the precise moment it is required.

This means that the voltage level at which the capacitor is charged frequently has to be maintained over exceptionally long periods of time. A low self-discharge rate, by which ultracaps are distinguished, **Figure 3**, is therefore a prerequisite which a power storage has to fulfil in order to perform under extreme conditions. Starting the engine after a long period of inactivity and under the most unfavourable conditions can be required at any time. Where battery performance is weak it is particularly the ultra capacitor which has to provide the necessary power. Figure 3 shows that the self-discharge rate is highest in the first few hours after switching off the power source. Ions which have permeated the electrode to a lesser extent detach themselves relatively easily. Subsequently however the ultra capacitor exhibits an almost linear and extremely low self-discharge. One refers in this case to an intrinsic self-discharge over periods of time of up to several thousand hours. Responsible for this are those electrons which are located in the deeper layers of the electrode and which have a longer distance to cover to reach its surface.

It can be observed that the temperature has a significant effect on the abruptness of the self-discharge. Whilst at high temperatures from approx. 50 °C the self-discharge is highest, this rate is significantly lower at room temperature. Indeed, at -40 °C no further reduction in cell voltage can be observed after an initial decrease. This almost absence of intrinsic discharge can be traced to a reduced mobility of the ions at very low temperatures. For this reason the ultra capacitor provides excellent performance specifically at low temperatures where other storage technologies exhibit clear weaknesses.

3 High-current Applications in the Automobile

Vehicle technologies of the future and their on-board electrical systems will have to be able to store and release currents of far more than 1,000 A within a short period of time (a few milliseconds). In particular in hybrid vehicles such currents occur cyclically and in high quantities. Here, recurrent braking and boosting, frequent stop/start procedures as well as the supply of high-performance consumers, subject the on-board electrical system to unique stresses. For example during operation of a micro-hybrid vehicle, energy storage elements are subject to as many as 700,000 stop/start cycles and more than 1 million regenerative storage events. Furthermore a system of this kind has to provide well over 200,000 cycles to support the on-board electrical system for power consumers. On-board electrical systems built to present-day technical and design standards are not able to cope with these kinds of loads over the lifetime of a vehicle. It is exactly here that the ultra capacitor finds its ideal application, a fact which cells with a capacity of 650 F from Maxwell Technologies have proven during several years in applications as well as in extensive tests for use in automobiles and other possible industrial applications. In the course of this ultra capacitors were tested and subjected to peak currents of up to 12,500 A. These tests were carried out using different load profiles and over numerous charge and discharge cycles. The following effects were observed:

- After thousands of cycles an expected increase in the internal resistance and a normal decrease in capacitance can be observed.
- Even at such high currents the Maxwell electrode does not suffer any damage and the pore structure of the carbon powder used remains unchanged.
- The loads result in an increased self-heating of the cell whereby the ambient temperature assumes an even higher significance for the service life.

In order to store a charge in an ultra capacitor the ions in the electrolyte form electrostatically charged pairs on the porous surface of the carbon powder when a potential is introduced. If the charging and discharging processes are carried out with high currents this results in an extremely dynamic movement of the ions. This can result in the charge carriers being blocked in the pores of the carbon powder thus gradually clogging them. As a result, part of the surface re-

Figure 2: Maxwell 650 Farad ultracap

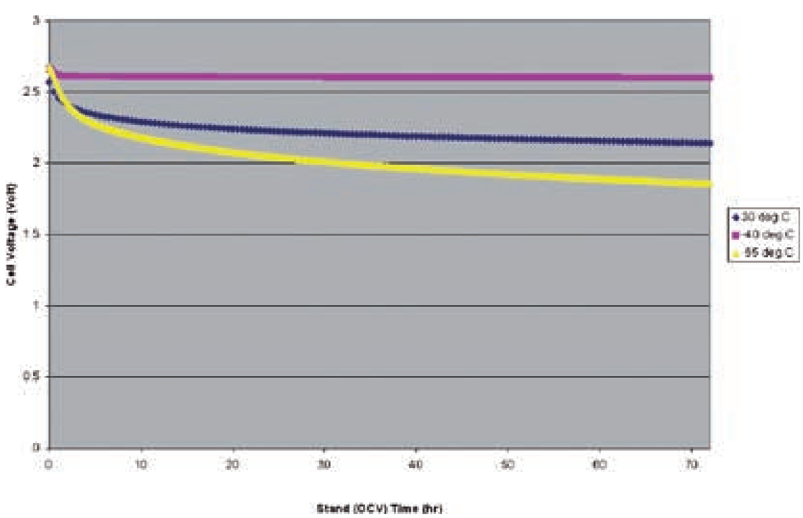


Figure 3: Self discharge curves of Maxwell MC-cells at different temperatures

quired for energy storage is lost and the capacitance of the capacitor reduces. If the operation of the capacitor is interrupted for a brief period or the load reduced, the process can be partially reversed. Basically the application and ageing behaviour of ultra capacitors is linked to two conditions.

The specific operating temperature as well as the specified maximum cell voltage should not be exceeded. If as a result of a failure of the control electronics, a malfunction in the charging unit or any other fault, the capacitor is overloaded, irreparable damage is caused resulting in accelerated ageing.

Current projects in the area of onboard network stabilization, stop/start, as well as in hybrid vehicles, show that the use of ultra capacitors for power storage provides significant advantages. No other storage technology is able to provide the vast number of brief but frequently occurring peak performances efficiently. At the same time cells are utilized with a capacitance from 310F up to 3,000 F fitted into modules in a voltage range below that of present on-board network voltages and up to 42 V systems. The relatively simple convection-cooled design of the standard capacitor module as well as the designated location (e.g. cockpit area, water tank, boot) are selected so that operation over the whole life of the vehicle can be achieved.

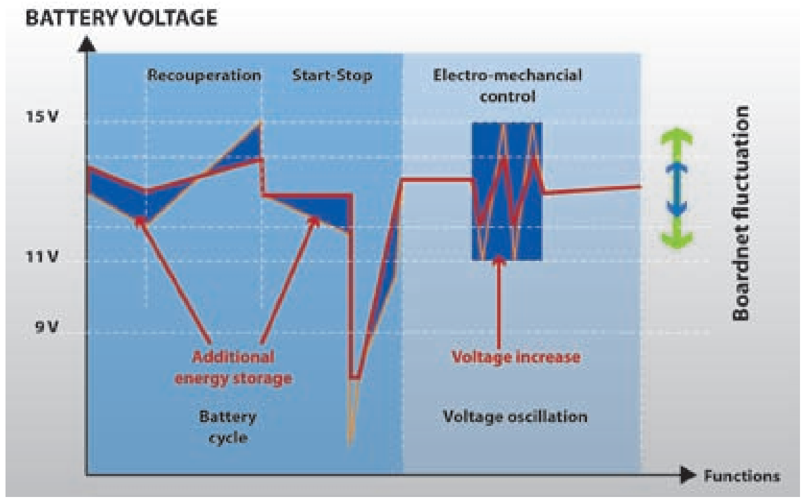


Figure 4: Influences on the board net

4 Decentralised Energy Supply Systems

Modern vehicles depend more and more on electronic subsystems as the increase in number of functions continues to accelerate, **Figure 4**. X-by-wire functions such as power steering, electric brakes, rapid-action heating, electric and air-conditioned seats, heated seats, sat-nav and infotainment systems, place high demands on a vehicle's energy supply system both individually and in total. As a result of increased energy consumption and redundancy requirements for safety-critical systems such as electrically power-assisted steering, magnetic valve control, electrical door openers and electrical braking functions, automobile engineers have to develop new architectures for power supply systems.

Current architectures have weak points in the handling of multiple high switch-on currents such as those described. The availability and reliability of electrical energy for stable functions as well as during malfunctions and accidents must be taken into account when planning future energy supply systems. This is particularly important for the energy supply to processor-supported systems in vehicles. As far as this is concerned a poor quality energy supply could result in shutdown of devices and ultimately to standstill of the complete vehicle. An answer to the demand for more power and redundancy for the critical systems and the safety systems in automobiles is a system architecture with modular and decentralised power supply modules. Local ultra-capacitor modules reduce the voltage drop in power supply systems by providing power locally whilst the average power requirement is taken from the primary power supply system of the vehicle. By this means the high peak loads can basically be disconnected from the primary power supply of the vehicle. Furthermore a redundant power supply is necessary for so-called X-by-wire functions in case of interruption of the supply from the main power supply system. Local power supply modules on critical loads, for example in the vicinity of electrical power steering systems or an electro-hydraulic brake module, provide automobile designers with additional redundancy for these safety-critical applications.

To provide a central energy supply, a separate cable must be taken from the central control box (with fuses, relays and switches) to the device which is to be supplied. Each cable must conduct the full power load and given the current state-of-the -art of vehicle design, sometimes achieve this via long and complicated routes. Local energy supply structures can be used to increase the ruggedness of systems whilst at the same time reducing the cost, weight and complexity of the power network. By this means the energy is available where it is required and is then distributed via a limited number of common energy buses. The control signals are also distributed via a limited number of common communication buses. Current and signal are transported to a local distribution node in which intelligent electronic controls and possibly an energy storage element are integrated. The local processor controls the local energy consumption without the need for laying several cables via lengthy routes to each individual device.

There, where power is periodically required, an energy storage device such as an ultra capacitor on the local distribution node can supply it whilst the vehicle's energy bus only has to provide the average amount of energy required. A local energy storage device of this type also significantly reduces the size of the bus for the main energy supply. The integration of a local energy storage device has also proven itself for better protection of controllers from energy supply prob-

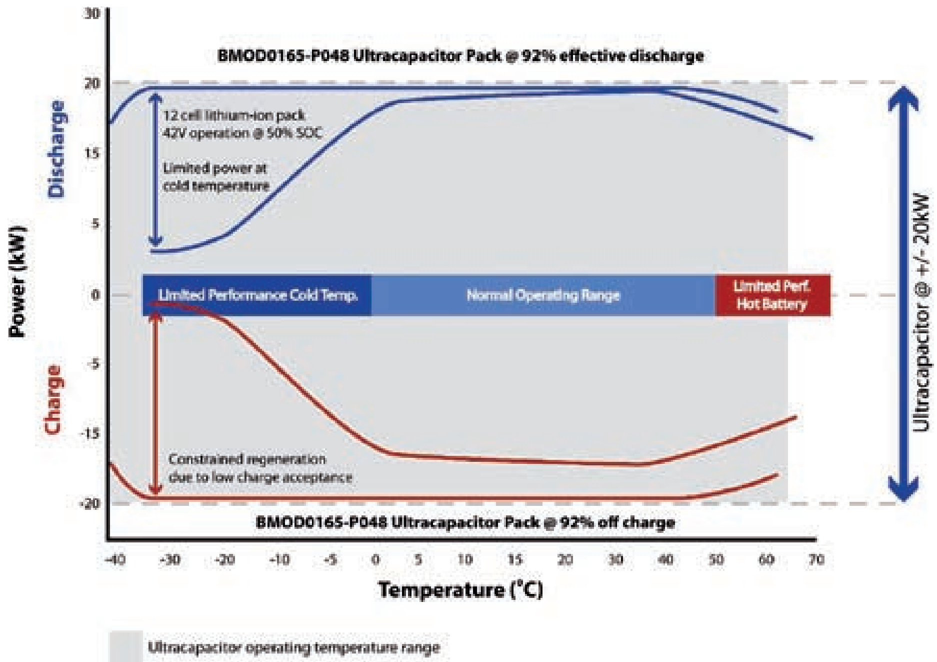


Figure 5: Efficiency of ultracap modules and battery modules at different temperatures

lems. The use of a back-up energy supply source in the switchbox is a precaution which provides fewer malfunctions and reliable switching-off. This kind of back-up concept is already common practice in present-day computer-based industrial and commercial systems.

5 The Combination of Ultra Capacitors and Batteries

The battery represents one of the main sources of malfunctions in vehicle electrical systems according to the automobile club ADAC breakdown statistics and also in line with internal information from the automotive industry. The increasingly universal use of stop/start and recuperative functions in the mainstream market as well as the general rapid increase in demand for electrical power in vehicles makes huge demands on present-day batteries. Consequently there is a need to look for solutions which will satisfy future demands on an energy storage device. One solution to the problem can be the separate consideration of the average energy requirement and the short-term power requirement call off. As a result of its specific characteristics (very high power density > 25 kW/kg, efficiency >95 % at temperatures from -40 °C to +65 °C, **Figure 5**, high cycle stability, internal resistance lower than battery technologies by factor ~10) the ultra capacitor is predestined for combining with batteries to provide a total energy storage with clear advantages:

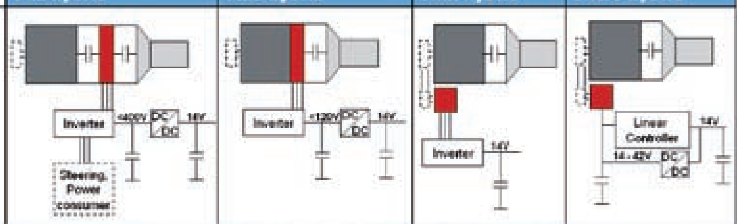
- Utilization of energy-optimized batteries which are more economical to manufacture
- Battery design for continuous energy requirement to enable fundamental use of low-cost types.
- The energy storage can be reduced in size and is therefore lighter.
- Increase in total efficiency of the storage and the vehicle thereby improving the CO_2 performance
- Increase in service life of the battery, minimisation of claims under the manufacturer guarantee and thereby reduction in quality-related costs

The most diverse consumers in the vehicle can gain from the combination of ultra capacitors with batteries. High-performance consumers are supplied with power locally or from a central energy conversion system (possibly at a higher voltage level) or the complete on-board network supported during voltage fluctuations. The necessity for on-board network support arises now for micro hybrids with recurring start procedures. Depending on the state of charge of the ultra capacitors the starting of the combustion engine using only the energy stored in them is possible in some systems. The ultra capacitor provides new possibilities as a local back-up storage device for safety-critical systems such as electrical door and hatch closing systems too.

The combination offers significant development potential via the various development stages of the hybrid to the fuel cell powered or electric vehicle. The most diverse systems can be utilized here depending on the application or hybrid stage, **Figure 6**. The incorporation of a few cells with the simplest electronics for local or high-voltage applications in the vehicle, to more than one hundred ultra capacitor cells connected in series which connected via energy-management electronics to an energy storage device, provide the power to drive full hybrids and electric vehicles. When used in fuel-cell powered vehicles the ultra capacitor primarily provides coverage of the peak loads as well as the provision of energy during start-up of the fuel-cell system.

6 Limitations of the Ultra Capacitor – Future Developments

Most of the present day product portfolio of ultra capacitors from their various suppliers is standardized in respect of capacitance, voltage range and tempera-



	System			
	Full hybrid	Mild hybrid	Mini hybrid	Micro hybrid
Function				
Start-stop	✓	✓	✓	✓ *
Recuperation	✓	✓		✓
Passive "boost"	✓	✓		✓
Active "boost"	✓	✓		
El. driving	✓			
Power assist	✓ **	✓ **		✓

* with modified series starter ** with additional power electronics

Figure 6: Stages of systems with ultracaps in relation to level of electrification in a vehicle

ture ranges. Geometrically the present 60 mm diameter of the cells with capacitance from 650 F to 3000 F constitute a standard.

As well as endeavouring to overcome the present limitations of ultra capacitor technology (T_{max}= +65 °C; U_{max} = 2,70 V; 1 Mio. cycles; Tau = 0,5 s; performance; volume; mass) however, the question should also be asked as to whether these "all-round products" always represent the perfect or most economical solution for the afore-mentioned automotive applications. As a rule the widespread and high-volume utilization in the transport and automotive sectors cause economies of scale which even in the short term result in significantly lower costs for ultra capacitors. However these cells were developed as standard products which have to be suitable for a diversity of applications in the areas of regenerative energy, the rail and transport sectors, telecommunications and consumer industries. But, of all industries it is the automotive sector which clearly surpasses many of the above-mentioned industries as far as cost sensitivity is concerned and in this connection demands specialized design-to-cost developments as a prerequisite for high-volume use in future hybrid variants.

Here, product and technology in the field of ultra capacitors provide sufficient potential for working even more closely together with automobile manufacturers and system integrators in the future. It is for example conceivable that cells are developed with lower cycle stability which nonetheless outlive the total life of a vehicle but which, with respect to their mechanical construction, are significantly more cost effective. A far larger energy capacity can also be achieved if at the same time a greater time constant and the related higher resistance can be accepted for specific applications. Be that as it may, even under demanding operational and application conditions the ultra capacitor always constitutes a reliable storage medium. Furthermore, ultra capacitors allow exact SOH (state of health) measurement to be made. Simple system designs allow maltreatment of cells, if at all possible, to be reduced or eliminated. By this means the greatest possible reliability is provided for the entire service life. ■