WHITE PAPER

ULTRACAPACITORS HELP TO OVERCOME THE PROSPECTIVE ENERGY REQUIREMENTS OF VEHICLES

Dr. A. Schneuwly, Dipl. Ing. J. Auer, Dr. J. Miller
Maxwell Technologies SA

Maxwell Technologies, Inc.
Worldwide Headquarters
9244 Balboa Avenue
San Diego, CA 92123
USA
Phone: +1 858 503 3300
Fax: +1 858 503 3301

Maxwell Technologies SA
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Brucker Strasse 21
D-82205 Gilching
Germany
Phone: +49 (0)8105 24 16 10
Fax: +49 (0)8105 24 16 19

Maxwell Technologies, Inc. -
Shanghai Representative Office
Rm.2104, Suncome Liauw's Plaza
738 Shang Cheng Road
Pudong New Area
Shanghai 200120, P.R. China
Phone: +86 21 5836 5733
Fax: +86 21 5836 5620

info@maxwell.com – www.maxwell.com

1. Abstract

Ultracapacitor power cells have been introduced into the marketplace in relatively large volumes since 1996 and continue to experience steady growth. In recent years ultracapacitors have become more accepted as high power buffers for industrial, aerospace and transportation applications as standalone pulse power packs, or in combination with conventional lead-acid batteries and advanced chemistry batteries.

The automotive industry is creating new demands for electrical power within vehicles – both as part of the power train in hybrid and electric vehicles, and to power the increasing level of electronic components in cars. Cars are becoming more sophisticated, evolving towards an intelligent electrically-powered platform with many more subsystems and accessories, requiring a substantial increase in the need for electric power. A stable 14V board net is required to ensure a continuous and always adequate board net performance.

Several ultracapacitor based innovative board net and hybrid drive train concepts have been designed with consistently positive results with regards to efficiency and consumption. Ultracapacitors, thanks to their specific properties, are ideally suited to overcome the prospective energy requirements of vehicles. This paper presents recent advances in ultracapacitor technology with regard to the use in automotive applications, and discusses start-stop, micro hybrid and board net stabilization architectures using ultracapacitors actually in development at OEMs and tiers.

2. Ultracapacitors

Ultracapacitors are based on an electric double layer technology that has been understood for over a hundred years, but only available for commercial applications for about ten years. They rely on an electrostatic effect, which is purely physical and therefore highly reversible. Charge and discharge occurs upon the movement of ions within the electrolyte. This energy storage process is in contrast to all battery technologies, which are based on chemical reactions. With no chemical bonds being made or broken, cycle life of over 1 million cycles has been demonstrated with minimal degradation. Ultracapacitors are compact in size and can store a much higher amount of energy than conventional capacitors while also being able to deliver at a much higher power than batteries. Maxwell Technologies offers BOOSTCAP® ultracapacitors on the market with capacitance ranges up to 3000 Farads. To facilitate adoption of ultracapacitors for applications which require integrated packs consisting of multiple ultracapacitor cells, Maxwell provides fully integrated power packs that satisfy the energy storage and power delivery demands of large systems. The module is a self-contained energy storage device, comprised of individual ultracapacitor cells, cell interconnect system, and an integral active cell balancing circuitry. Units may be connected in series to obtain higher operating voltages, parallel to provide additional energy storage or a combination of series/parallel arrangements for higher voltages and energy. When connected in series, unit to unit voltage balancing is also available. The module packaging is a heavy-duty aluminum extruded enclosure ensuring optimal heat dissipation and is a permanently sealed device requiring no maintenance. Low internal resistance of the energy storage modules enables low heat generation within the modules during use. As with any electronic components, the cooler the part operates the longer the service life. In most applications natural air convection should provide adequate cooling. In severe applications requiring maximum service life, forced airflow may be required.

Figure 1: Maxwell BOOSTCAP® ultracapacitor products

Batteries are well established energy storage components in the automotive domain. But they are only partially able to fulfill the requirements of future board nets. Batteries are not able to handle the dynamic peak power demands efficiently, and reduced lifetime is the result. This has created an increasing demand to use ultracapacitors to cover short term peak power demands. Combining ultracapacitors and batteries results in an energy storage device with high energy availability combined with high power and high efficiency. The benefits of ultracapacitors in such applications arise from their wide operating temperature range of -40°C to +65°C, minimal maintenance, relatively high abuse tolerance to over charging and over temperature, high cycling capability on the order of one million charge-discharge events at 75% state-of-charge swing and reasonable price. Ultracapacitors today store approximately a tenth the energy of nickel metal hydride batteries but are capable of more than ten times the power.

Ultracapacitors are best suited to perform in those applications that require short bursts of power, interspersed with longer durations of low power requirements. Many systems can use two components to achieve an optimal solution for both power and energy. One model is a cache of power; the ultracapacitor is sized for maximum peak power, while the primary energy storage is a large device sized for maximum continuous power. The primary energy storage can be a fuel engine, high-energy batteries, or a fuel cell. System designers size the ultracapacitor for the difference between maximum continuous and maximum peak power, to take full advantage of both components.

3. Efficiency and cycle capability of ultracapacitors

Analysis shows that today’s ultracapacitors, possessing ultra-low ESR and hence high efficiency at relatively high power levels, can deliver efficiency of 90% or better. Figure 2 is the result of such analysis for a typical ultracapacitor cell (3000F BCAP3000) undergoing constant power testing. The result is 95% or better efficiency for pulse time intervals ranging from 8s at 10% of matched load power, P_{ml}, to 2s at one fourth P_{ml}, to 1s when the power loading is 40% of P_{ml}. Matched load power is defined in (1) and results when the terminal load equals the cell (or pack) internal resistance, ESR.

Energy efficiencies under high loading conditions are summarized in Table 1 for a power D cell™ (310F, 2.5V, 2.87mOhm). At matched load power levels half the stored energy is dissipated internally and half delivered to the load (i.e., efficiency is 50%). For constant power levels well below matched load conditions the ultracapacitor efficiency trends toward 100% and for cells designed for passenger vehicles the overall efficiency will be as shown in Figure 2, in the range of 95% to 98%. High efficiency means more compact modules and improved product integration, less cooling system burden so that air cooling suffices and reduced overall installation cost. Power ultracapacitor products such as the one illustrated in Figure 1 are state-of-the-art in high specific power (approaching 20kW/kg), low cost (~$12/kW) and high efficiency (>95%). Improved efficiency in energy storage means transportation systems having improved fuel economy, reduced emissions and uncompromised performance.

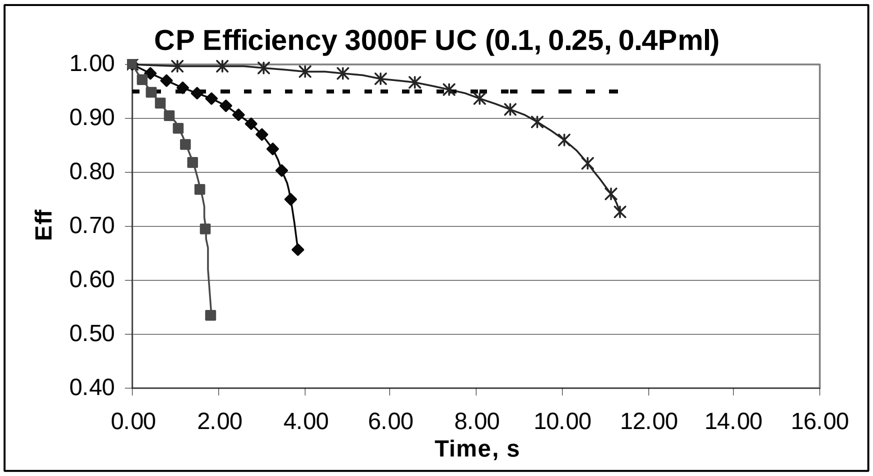


Figure 2: Ultracapacitor constant power discharge time for >95% efficiency (8s at 0.1Pml, 2s at 0.25Pml, 1s at 0.4Pml)

Power loading	Load Watts [W]	Voltage cut-off Uco, [V]	Time to Uco [s]	Useable Energy [J]	Delivered Energy [P*t]	Energy Eff.
0.1 P_{ml} =	34	0.45	31	1260.6	1054	0.83
0.4 P_{ml} =	135	0.9	6.56	1230.5	885.6	0.72
1.0 P_{ml} =	336	1.42	1.78	1180	598.1	0.507

1.6 P_{ml} =	538	1.8	0.653	1120.6	351.3	0.313

Table 1: Summary of power D Cell™ ultracapacitor performance under constant power discharge

Ultracapacitors rely on an electrostatic effect, which is purely physical and therefore highly reversible. This elementary operating mode allows to achieve high cycle life. Today's ultracapacitors from Maxwell reveal high cycling capability on the order of one million charge-discharge events at 75% state-of-charge swing (Figure 3).

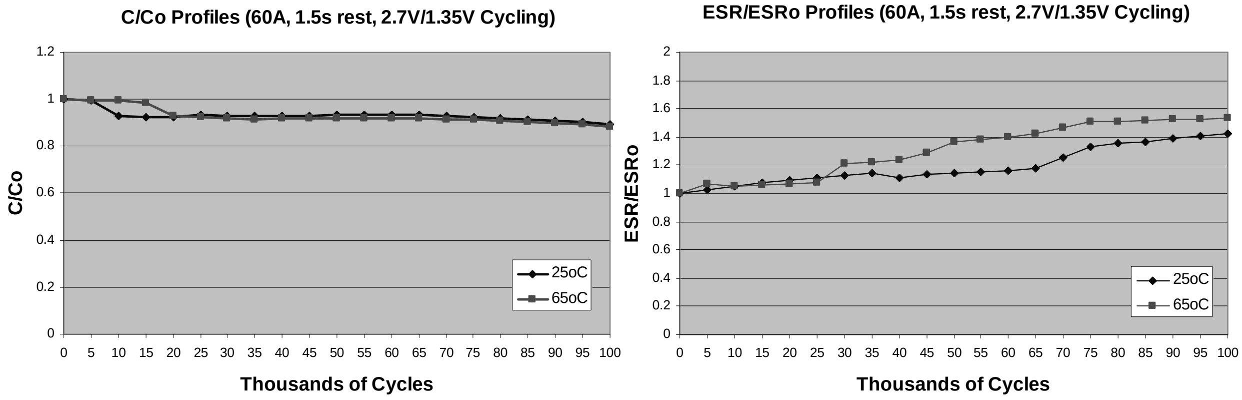


Figure 3: Maxwell Technologies BCAP0650 P270 capacitance (C) and internal resistance (ESR) change in function of cycle number. Cycling is performed between 2.7 and 1.35V (50% DOD), rest time charge/discharge 1.5s

Table 2 presents the cycle capability at 80% DOD (depth of discharge) for different energy storage technologies. Ultracapacitors clearly dominate the cycle capability ranking with values above 1M cycles; even the most advanced battery technologies just achieve values in the order of 15k cycles. While the cycle capability at higher DOD almost remains unchanged for ultracapacitors, it drastically decreases for batteries. On the other hand batteries reveal much higher energy densities (up to 70Wh/kg) than ultracapacitors

(5Wh/kg). Nevertheless, by combining cycle capability with energy density, the resulting energy throughput in Wh-cycles is by far the largest for ultracapacitors.

Technology	Cycle Capability at 80% DOD [# Cycles] (Wh-cycles)
Ultracap	$>10^6$ $(4x10^6)$
VRLA	$3*10^2$ $(7x10^3)$
NiMH	$4*10^3$ $(1.5x10^5)$
Lithium	JCS $2.5*10^3$ $(1.4x10^5)$ A123 $5*10^3$ $(2.8x10^5)$ AltairNano $15*10^3$ $(8.4x10^5)$

Table 2: Cycle capability and energy throughput for different energy storage technologies

These attributes make ultracapacitors an ideal energy storage solution for automotive applications requiring high cycle capability, such as start-stop, board net stabilization or micro hybrid systems.

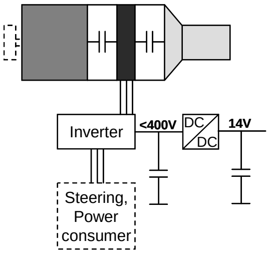
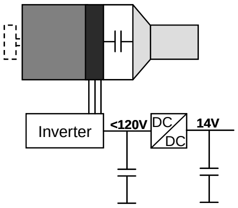
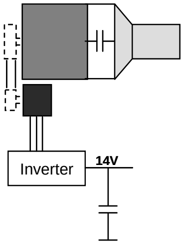
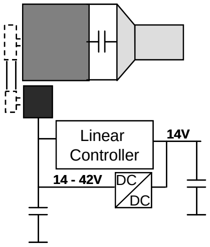
4. Hybrid power train systems

In the past 5 years, the costs of electronics in a car have increased by 8%. The reason is the rapidly growing number of electrical functionalities in the car, for example Park Distance Control (PDC), front window defogger, premium hi-fi packages, electrical seat adjustment, daytime running light, modern communication systems and seat heating, electrical steering, electrical braking system, electromagnetic valve gear and electrical pumping systems. Each year, the total power requirements of electrical systems and functions increase by 100 to 150W.

In today's vehicles, 100W of demand for electrical energy typically causes additional fuel consumption of 0.1 l/100 km. The growing demand for electrical systems thus opposes the objective of the automotive industry to continuously reduce fuel consumption and CO_2 emission. To still reach their objective, car manufacturers follow many different routes. For instance the electrical board net is designed for higher power requirements, start-stop functions are introduced and hybrid drive train systems are developed.

Accordingly, the energy management requirements in the car are increasing continuously and there is an increasing demanding for new and powerful energy storage concepts. Ultracapacitors have proven to be an ideal augmentation to hybrid power trains as an electrical peak power unit. The reason for the acceptance of ultracapacitors in vehicle propulsion systems and board net stabilization requirements is their high pulse power capability, fast transient response, and high efficiency during discharge and recharge, plus full-charge cycling in excess of 1 million cycles. They will last the lifetime of a car with no maintenance, and offer better performance at extreme temperatures than batteries.

Hybrid drives promise considerable potential savings in terms of fuel consumption and emissions. Micro hybrid- and mild hybrid vehicles enable consumption reductions (NEFZ) of up to 12% and 20%, while full hybrids allow reductions of up to 25%. Depending on the hybrid application, batteries and ultracapacitors both show advantages as well as disadvantages. Among the companies that have announced programs for using ultracapacitors in vehicle power trains include such big names as BMW, VW, Audi, Honda, Nissan and Toyota, along with many others, some still at concept stage and others ready to go into production. An overview of different hybrid systems, showing their functional principle as well as the main functions is given in Table 3.

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

* with modified series start ** with additional power electronics

Table 3: Different hybrid systems and functional principle

4.1 Start-Stop

Whereas costly hybrid applications are flourishing worldwide mainly thanks to strong hybrid applications at the leading edge of technology, companies such as Valeo decided to focus its efforts on affordable hybrid solution, excluding complex hybrid electrical architecture or non standard electrical machines.

Valeo introduced the first generation of StARS µ-hybrid (Starter Alternator Reversible System) start-stop system in 2004, today in serial production with Citroën. StARS performs a comfortable start-stop function in complete transparency for the driver. The belt driven starter-alternator system shuts down the engine during idle phases and restarts the engine quickly (down to 350 ms) and silently on request. This results in no fuel consumption, gas emission, vibration and noise at standstill.

Following the first generation of belt driven starter alternator next generations with integrated electronics, from pure stop-start technology to stronger functionalities such as regenerative braking was developed.

The most recent solution is the StARS +X system. It provides a cost effective architecture for bigger engine capacities with extra functions such as regenerative braking. As shown on Figure 4, the electrical architecture of the Valeo StARS +X system consists of the following components:

- A StARS electrical machine with its control unit
- A bidirectional DC/DC converter, and
- An ultracapacitor pack

Thanks to a smart and cost-effective architecture close to 14V standards, a number of comfort and safety features are provided within the vehicle together with significant savings in fuel consumption and CO2 emissions. This arrangement is called the 14+X architecture, X being a value at which the starter generator machine can raise its voltage or be driven in both generator and motor modes. A dedicated ultracapacitor storage system allows to optimally store the recovered kinetic energy of braking phases for later “free” use. 5 kW generation in regenerative braking mode is available to power electrical loads (fast cabin and seats heating, e-cooling fans, and de-icing systems). When installed on large gasoline engines or Diesel engines, the system eases the cranking by supplying 14+X Volts at the starter-alternator terminals. The system can supply extra 4kW continuous power for peak loads. It is also able to provide some light torque assist to enable the combustion engine working in optimum operating ranges with adapted load balance. Moreover, standard 14V network quality through ripple filtering with DC/DC converter and high energy dependability namely for any by-wire function are ensured within the vehicle through the dual energy storage capability of the 14+X architecture. The combination of start-stop and regenerative braking features leads to fuel consumption reduction of up to 12% in a NEDC cycle with a gasoline engine and more in city driving cycles. Start-stop was recognized as one of the important levers of fuel consumption reduction whereas other functions such as boost and regenerative braking are really linked to storage system availability. Whereas mild- and full-hybrid applications usually rely on costly automotive battery technologies such as NiMH or Lithium-ion, the StARS +X system is based on ultracapacitor technology featuring high cycle life and energy efficiency and allowing maximum power availability at low cost. Valeo simulations and results prove that the StARS +X system will allow 80% of the performance of a current mild hybrid for 20% of the vehicle on-cost.

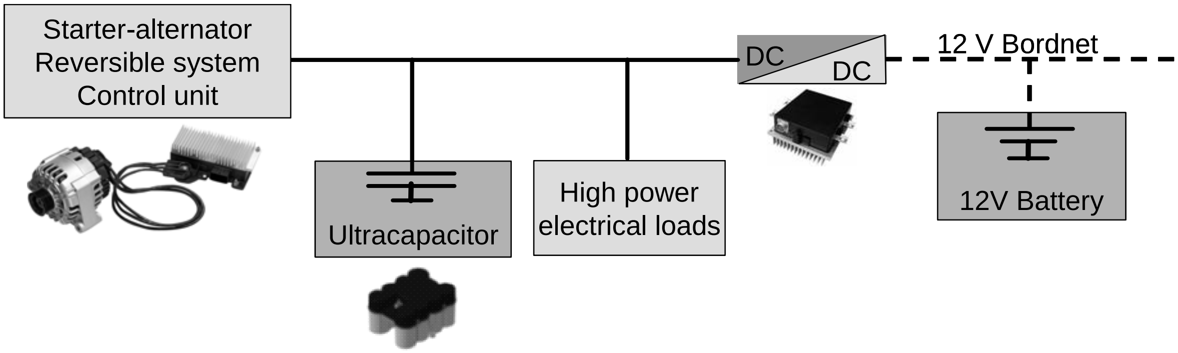


Figure 4: Valeo StARS +14 system

4.2 Micro hybrids

Alcoa has developed a special, cost-effective micro-hybrid architecture which realizes considerable fuel savings through intelligent distribution of the electric energy conversion phases. The concept allows energy supply of a start-stop-system, recuperation and passive boosting. At the same time this architecture enables for peak demand coverage of supplementary energy consumers like electrical power steering and rapid heating. The electric current is predominantly produced in phases of optimum operating conditions, temporarily stored in an energy storage system, and then delivered as required to the consumer via the board net (Figure 5). In this way, the level of fuel consumption can be maintained or even reduced despite additional energy consuming devices. Alcoa has developed a safety concept for the electrical system that ensures complete control and maximum protection for micro- and mild hybrids.

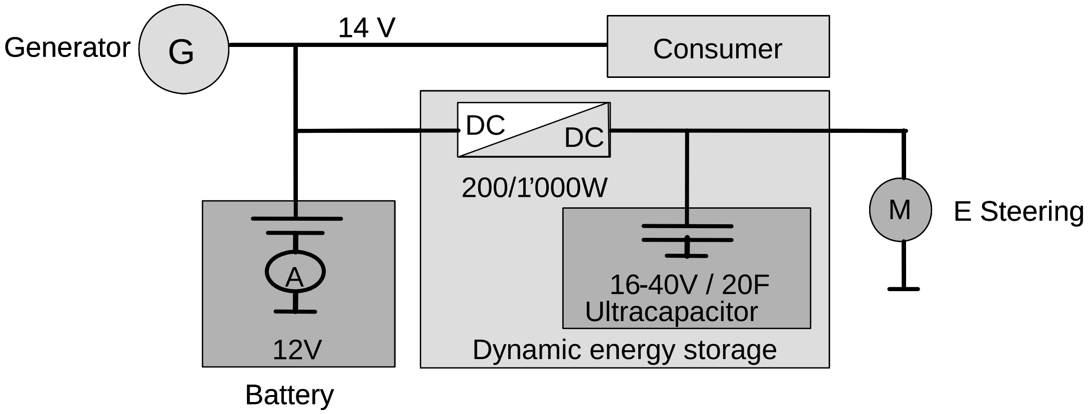
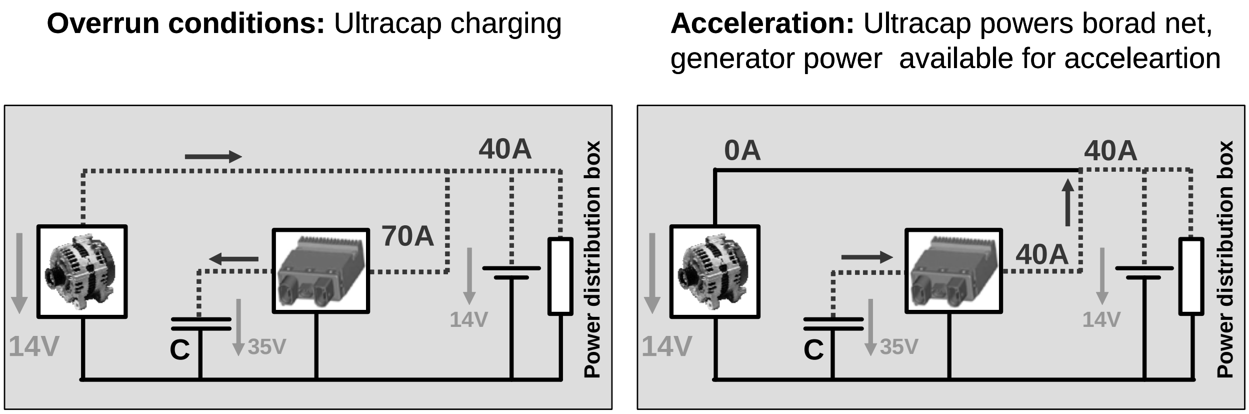


Figure 5: Alcoa micro hybrid concept

Positive operating conditions happen during braking and acceleration. A dynamic energy storage system consisting of a bidirectional DC/DC converter and an ultracapacitor module is ideally suited to store the electrical energy. Depending on the driving phase, the ultracapacitors are charged or re-charged, as shown in Figure 6. In overrun conditions, the capacitor is charged via the DC/DC converter in boost mode. The maximum charge load is typically 1'000 W for a period of 15s.

During acceleration, the board net is supplied with the energy stored in the capacitor via the DC/DC converter in buck mode, whereby the generator current is considerably reduced and the available drive torque for acceleration increased. The normal de-charging capacity is typically 500 W. This is adequate to meet the energy requirements of a regular board net. In the short term it can be increased considerably to deliver currents of up to 100 A for assistance during motor start.


Overrun conditions: Ultracap charging

Acceleration: Ultracap powers borad net, generator power available for acceleartion

Figure 6: Recuperation function

The required ultracapacitor storage device has a capacity of 20 F at a variable operating voltage range of 16 to 35 V. The storage system with integrated bidirectional Buck/Boost-DC/DC converter developed by Alcoa and shown in Figure 7 offers 1’000 W power output, redundant design with multi phases and optional bypass supporting x-by wire functions such as electrical steering. The air convection based cooling design and CAN interface. The temperature range is -40 to 75 °C. Based on a very low internal resistance an efficiency of more than 97% can be achieved. The cooling is done via convection on the system housing.

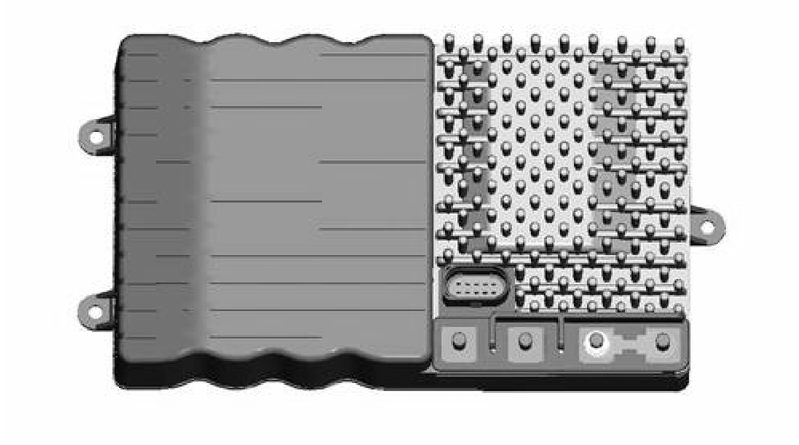


Figure 7: Alcoa ultracapacitor storage system with integrated bidirectional Buck/Boost-DC/DC converter.

The micro hybrid concept typically achieves a reduction in power required of up to 0.9kW or 12Nm near idle running. Based on the electrical storage potential it is possible to achieve fuel savings of up to 0.56l/100km (NEFZ 0.22l/100km) in the city. A start-stop function enables additional fuel savings. A longer life cycle of the battery and a cost-efficient quick heating system are further customer benefits.

4.3 Mild hybrids

Mild and full hybrid vehicle have a combustion engine that functions as the primary power source, and an electric motor with a power storage system that functions as the secondary power source. Designers are able to size the combustion engine for cruising power requirements thanks to the presence of the secondary power source that handles the peak power demands for acceleration.

For high-performance car models, the BMW Group has developed an excellent example of the drive concept in the BMW Active Hybrid. At the IAA 2005, this illustrated for the first time intelligent hybrid technology in the form of a Concept X3 EfficientDynamics.

The core element is the active gear, which without requiring additional space houses the electric motor including electronics. It is primarily fed from a high-performance capacitor, not from a conventional battery. Batteries have a high internal resistance, which also increases dramatically with advanced discharge. A high internal resistance means high energy loss during charging, whereby a large part of the energy which has been won back when braking is lost. On the other hand, the internal resistance of ultracapacitors is practically zero – independent of the charge condition. In practice, this means that the cycle of charging and dis-charging can be repeated as often as required with a high coefficient.

The BMW Concept X3 EfficientDynamics has ultracapacitors integrated in the door sills (Figure 7). This installation is optimum in terms of the driving dynamics of the vehicle and the point of view of best space usage. The total capacity of the ultracapacitors of 190 kW suffices to drive the vehicle totally electrically for short periods of time, for example when parking or maneuvering. With a quoted specific power density of around 15kW/kg, the ultracapacitors substantially offer more than the 1.3kW/kg available from a nickel/metal hydride battery. Given the same weight, voltage and power supply, the ultracapacitor offers an efficiency of 98%, compared to 84% from a NiMH battery, operates well at low temperature and is not subject to internal thermal run away (and risk of fire) like the NiMH batteries.

Figure 8: BMW X3 with 190kJ ultracapacitor tube modules in the door sills

The combination of electric motor and combustion engine shows interesting characteristics. While the combustion engine can develop torque only from a minimum revolution speed, the electromotor achieves its full torque right from standstill. The result is a noiseless, full acceleration from a lower RPM range. As soon as the car moves, the clutch closes, the combustion engine starts and powers the vehicle. The electric motor takes on the job of the starter for the combustion engine. These generally short electromotive operating periods have one more advantage: the energy quantity which needs to be provided by the electric storage is accordingly low, making it ideal for the use of ultracapacitors. Immediately after discharging, before the next time it is required, the energy storage will be recharged. For this purpose the electric motor will be primarily switched in braking and overrun conditions on generator mode. Thus this concept offers two advantages: higher performance at noticeably lower fuel consumption. In the European driving cycle, a consumption reduction of up to 20 percent has been achieved.

4.4 Board net stabilization, distributed power

As well as power trains, the modern car has high demands for electrical power, particularly short peaks in demand for systems like powered braking and steering or fast de-icing systems. These base level loads have dramatically increased from 1 or 2 kW in the 1980s to over 6 kW today and the dynamic loads have gone from 2kw to over 18kw in high end modern automobiles. In a 14-volt system, this requires currents from 500 to 1,500 amps for several seconds.

If a short-term demand causes a voltage drop on the board net (the power distribution supporting the logic boards), the control electronics may stop functioning due to low voltage cut-off. With 50 to 100 control modules competing with 50 to 100 electrical actuators and motors in a modern car, this is a major reliability and safety issue. Electronic fuel controls may stop, causing the engine to stall, and lights and sound systems may fluctuate. In the worst cases, the car will require towing to a service centre to be reset.

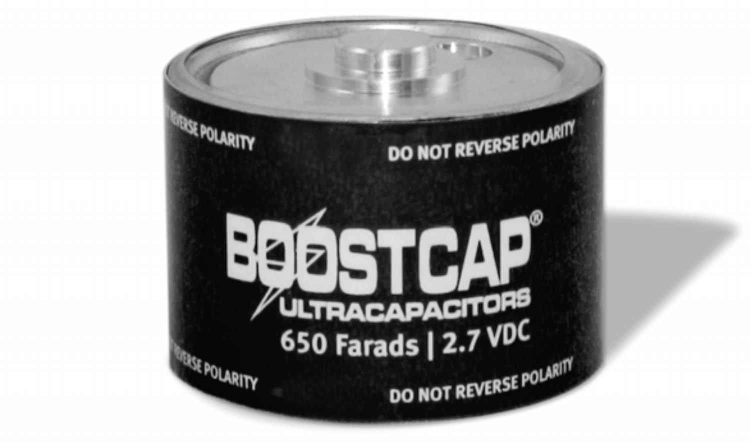


Figure 9: Maxwell Technologies BCAP0650 power ultracapacitor typically used for board net stabilization

Board net stabilization is one of the best and easiest to implement applications for ultracapacitors. The short-term power demands that cause voltage dipping can be buffered with a 14V power module designed with enough energy storage to “ride through” or supplement peak power demands. This offer replaces the need for a second battery, takes less weight and space, is not a maintenance item, lasts the life of the car, and performs reliably at –40°C. The cost in high volume is about the same as a second battery and associated cabling, and the life cycle cost to the consumer is lower. Power cells such as the ones shown in Figure 9 are designed for board net stabilization and are currently being designed into energy storage packs by tier1 for several automotive manufactures as the solution for voltage dipping.

Ultracapacitors can also be used to support higher demand intermittent power applications, such as electrical power steering and braking. These applications usually demand 1 to 2 kW for a second or two, then a smaller demand for several more seconds. To meet safety requirements, the ultracapacitor module has sufficient energy to perform this operation 5 to 10 times without recharging. Most of the time, power steering is quiescent, drawing little power for actual steering. When called upon, the power requirement is a brief, high power pulse of less than one to two seconds. The profile for a typical electrically powered steering event is a one- to three-second ramp to approximately 2000 watts for several hundred milliseconds, which quickly returns to quiescent. In centralized power architecture, the power required can be supplied by the central energy storage, but this would require a very heavy and costly power cable. The voltage drop due to the high current could require that either the cable or the energy storage system be oversized.

5. Ultracapacitors for heavy transportation applications

Hybrid power train systems also apply to heavier vehicles on our roads, such as trucks and buses. Public transportation such as trains and trams also stands to benefit from adopting a hybrid power train approach. In case of buses and trucks pollution and fuel consumption can be reduced, as well as cutting noise. In case of trams and trains primary energy demand can be reduced significantly, allowing longer, more or higher performance vehicles on an existing track.

The obvious energy storage device might be a rechargeable battery, but in fact they have some serious limitations for this kind of application. Batteries are heavy, large in size, have a limited charging rate and potentially high maintenance. They also can suffer degraded performance at low temperatures or when operating under deep cycling conditions. Ultracapacitors on the other hand provide high power, wide charge acceptance, high-efficiency, cycle stability, and excellent low-temperature performance.

Heavy transportation vehicles place particular demands on energy storage devices: they must be very robust and reliable, with a long lifetime and low maintenance requirements. They must be able to operate efficiently under harsh conditions, operate at high voltages of typically 750V and they must be able to deliver high peak currents. They must also be able to work on a high duty cycle and cope with frequent deep discharging. Finally, they must be straightforward to integrate into a vehicle design.

Maxwell has addressed these issues with its BOOSTCAP® ultracapacitor HTM (Heavy Duty Transportation) module for ultracapacitor-based braking energy recuperation and torque assist systems in transportation applications (Figure 10). The HTM125 module is based on BOOSTCAP® power cells rated at 3,000F which have a very low internal resistance, resulting in excellent efficiency during charging and discharging. Up to 12 modules may be linked in series to deliver a total operating voltage of 1’500V. Balancing interconnectivity between modules is fully integrated within the module and requires no additional hardware, facilitating its integration into the system.

A key factor in the energy storage system is thermal management. With efficient cooling, higher continuous currents are possible without compromising reliability. The dimensions and design of the 125V module were chosen for best efficiency and cooling behavior when operated at very high currents of up to 150A continuous and 750A peak. The module design ensures that there is only a 15°C temperature rise above ambient at maximum continuous current. The layout of the module results in a very stable temperature distribution over all cells in the module, resulting in greater reliability and longer life.

In addition to managing high current, the module is built to withstand the harsh environments and extremely demanding duty cycles that are typical with heavy transportation applications. The HTM module is designed to perform reliably through one million or deeper charge/discharge cycles, which equates to 150,000 hours or more than 15 years of operational life. It is undergoing extensive testing against rigorous transportation industry standards

Proprietary material science and packaging technology are reducing manufacturing cost, so that the price of the modules competes favorably with other energy storage designs. The HTM125 module is sealed from the elements in a rugged, splash-proof, IP 65-compliant, aluminum chassis, and weighs less than 50kg. The module can store more energy per unit volume, deliver more power per unit volume and weight and last longer than any other commercially available ultracapacitor pack solution.

Ultracapacitors have been proven to have a successful effect over a period of years in a number of bus applications, both full electric and hybrid electric, and in light rail vehicles.

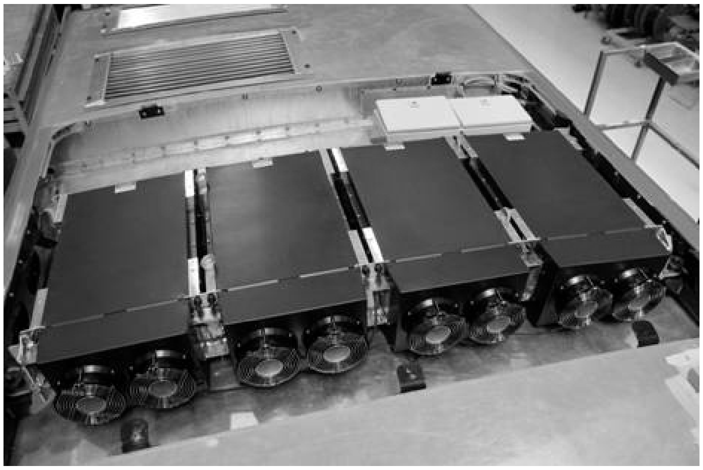


Figure 10: HTM125 modules installed on the roof of a Scania hybrid bus. Beside a single HTM125

6. Conclusions

Ultracapacitors can provide high efficiency, long cycle life, high power capability, durable design, wide temperature range, and low maintenance. Their features allow engineers to break new ground in the development of innovative architectures for handling the power requirements of new electric systems. Targets concerning capacity, efficiency and life time can therefore be better achieved. In use with hybrid electric power trains, ultracapacitors show clear advantages over conventional energy storage technologies. Their efficiency of more than 90 percent is particularly noteworthy, and ensures recuperation with highest efficiency. The energy stored during braking can be used for acceleration without any losses.

In recent years, growing demand for ultracapacitors in the electronics and industrial markets has spurred materials and design advances leading to dramatic cost reduction, making ultracapacitors affordable for a wide range of automotive and transportation applications. Many innovative concepts have been implemented in vehicles and their performance and consumption results are throughout positive.

7. Literature

[1] J.M. Miller, M. Prummer, A. Schneuwly: ”Power Electronic Interface for an Ultracapacitor as the Power Buffer in a Hybrid Electric Energy Storage System”, Maxwell, Power system Design Europe, July 2007

[2] A. Schneuwly: ”Energiespeicher (nicht nur) zum Treibstoff sparen”, Maxwell, Interview Automobil Elektronik, Juni 2007

[3] A. Schneuwly, M. Prummer, J. Auer: „Neue Energiespeicherkonzepte im Kraftfahrzeug“, Maxwell, Conference Baden-Baden, 2007

[4] Fredrik Morsing, “Ethanol: an excellent fuel for sustainable urban transport”, Scania, UITP public transport congress in Helsinki 21-24 May, 2007

[5] J. Winkler, S. Esch: “Mikrohybrid ohne Starter Generator mit den Funktionen Schnellheizung und Rekuperation”, Audi, Conference Baden-Baden, 2005

[6] D. Richard, Y. Dubel: “Valeo StARS Technology: A Competitive Solution for Hybridization”, Valeo, 1-4244-0844-X/07, IEEE 2007

[7] M. Fenkart, “Double Layer Capacitors – Energy Storage Components in Hybrid Vehicles“, BMW, 5th Boostcap day, Forum Freiburg, 2005