WHITE PAPER

AUTOMOTIVE ELECTRONICS

Adrian Schneuwly
Business Unit Manager, BOOSTCAP®

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

Ultracapacitors drive new efficiencies for powertrains

Electric and hybrid vehicles have been under development for as long as anyone can remember, but have so far failed to become widely adopted. There have been some fundamental problems of energy storage and delivery that have yet to be successfully and cost-effectively overcome. Many of these issues can be traced to the limitations of batteries – heavy, large in size, with a limited charging rate and potentially high maintenance.

Recently, newer designs have taken advantage of the benefits of another component: the ultracapacitor. Integrating ultracapacitors with other energy devices solves many challenges that are not solved efficiently using a single energy storage device. For example, combining high-energy lead-acid batteries and ultracapacitors can create a system that has the excellent energy, self-discharge, availability, and low cost associated with lead-acid technology, and the high charge acceptance, high-efficiency, cycle stability, and excellent low-temperature performance of the ultracapacitor.

System designs can take advantage of the power of ultracapacitors to conserve energy by allowing the engine to stop while the vehicle is not moving and then to be restarted nearly instantly on tip in of the throttle. The design also allows regenerative braking energy to be captured thereby significantly increasing efficiency and reducing pollution. The use of engine start/stop and regenerative braking has been estimated to produce between 7 and 15% increased fuel efficiency while reducing pollution by an even greater percentage.

Announced programs for integrating ultracapacitors into vehicle powertrains include big names such as BMW, VW, Honda, Nissan and Toyota, amongst many others. These vehicles run the gamut from concept to production-intent, and include systems for hybrid trucks, buses, and passenger vehicles are underway.

Problems with hybrid vehicles

Let's look at Hybrid Electric Vehicle (HEV) technology, which combines the best characteristics of fuel-driven engines, electric motor drives and energy storage components. Their solution has been designed with 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. Additionally, regenerative

braking energy is captured by the secondary power system and that energy is applied for further acceleration or for the basic energy needs of supplementary electrical systems by using the secondary source.

Using only batteries to provide the electrical power storage has drawbacks in the hybrid application.

- Batteries have difficulty functioning in cold weather.
- Batteries require a sophisticated charge equalization management.
- Batteries have limited cycle life under extreme conditions, which results in high cost replacement throughout the life of the vehicle. A new battery has to be purchased and installed; the old battery has to be removed and disposed. Battery disposal can be problematic unless the manufacturer has a recycling program.
- Batteries are limited in their ability to capture and provide bursts of high power during short duration events such as acceleration and regenerative braking. This high power limitation reduces the efficiency of the hybrid electric drive system design.

The Solution

Ultracapacitors can fulfill many of the functions of batteries in this application, but with dramatically higher reliability and overall performance. They significantly improve power management in hybrid electric vehicles and extend battery life. In addition, ultracapacitors allow for lower emissions, better fuel-efficiency and advanced electrical drive capabilities. Redesigning a power system to use ultracapacitors can allow the HEV to recapture and reuse braking energy. Compared to conventional diesel engines: reduction of fuel consumption is estimated at greater than 50%; reduction in particulate emissions is greater than 90%; and reduction of nitrogen oxide emissions is 50%.

Looking beyond hybrid vehicles, another example where the ultracapacitor has a valuable role is designs based on a fuel cell. These are efficient and dynamic enough for automotive use with a few drawbacks. There is no existing infrastructure for hydrogen delivery, hydrogen is not easy to handle safely, and the tanks are rather large in volume and must be very strong to withstand the very high pressures of storage and potential accidents. Even though the fuel cell is capable of being dynamic enough to handle transients, it is large and costly if sized to meet the maximum load. Therefore, it is more cost-effective to have a hybrid design with a fuel cell and a bank of ultracapacitors. The ultracapacitors are capable of handling very dynamic loads such as initial acceleration and have the added benefit of absorbing braking energy.

What is an ultracapacitor?

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.

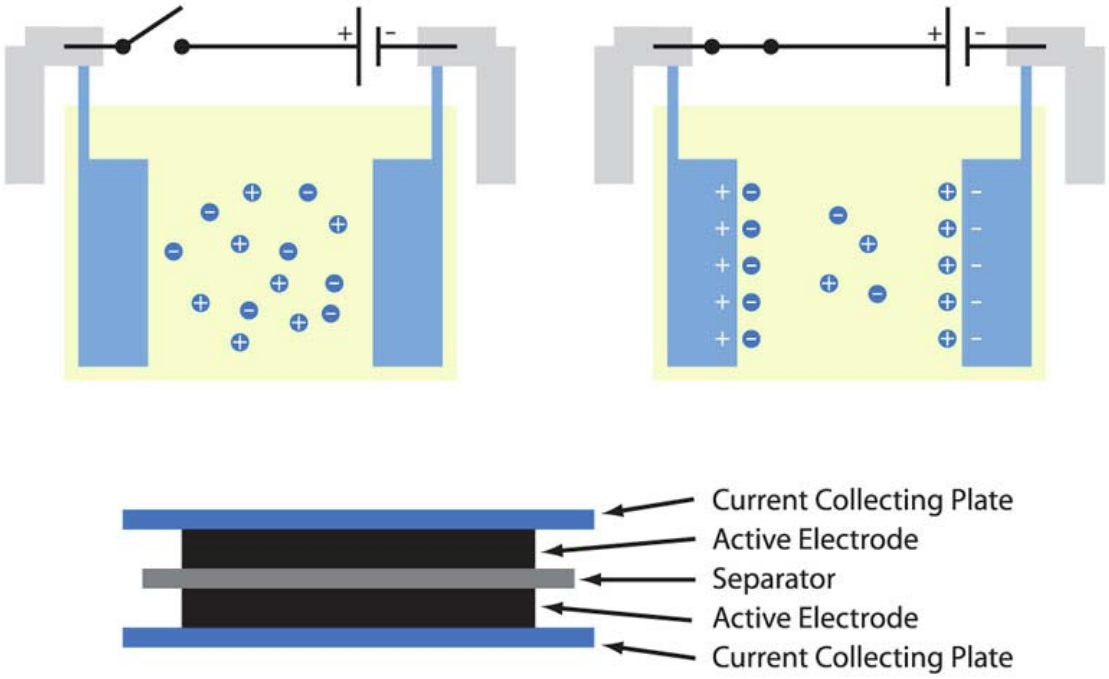

Figure 1: Ultracapacitor construction

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 2700 Farads, and they can release that energy at both a high and low rate.

What are the advantages of ultracapacitors as compared to batteries?

- They function well in cold weather, down to –40° Celsius, whereas without heating, batteries do not operate well below 0° degrees Celsius.
- They are extremely safe because a pack with equalization is discharged over night.

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

- They have a long life cycle, basically built to last the time of the machine into which they are incorporated. This means that they are maintenance-free which ultimately results in costs-savings. This is particularly important for applications where life-cycle cost is of high value, such as embedded power modules, hybrid buses and trucks.
- They are more efficient than batteries; 84-95% as compared to an average of below 70% for batteries in this application.
- They are very environmentally friendly as they are 70% recyclable and do not include any heavy metals which are detrimental to the environment.
- Ultracapacitors offer up to ten times the power of batteries, which plays an important role in boosting the acceleration of a vehicle.

Ultracapacitors are best suited to perform in those applications that require short bursts of power, interspersed with longer durations of low power requirements. Engineers continue to learn how to design systems that use two different components to achieve an optimal solution for both power and energy. One model is that of 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 (Figure 2). 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.

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

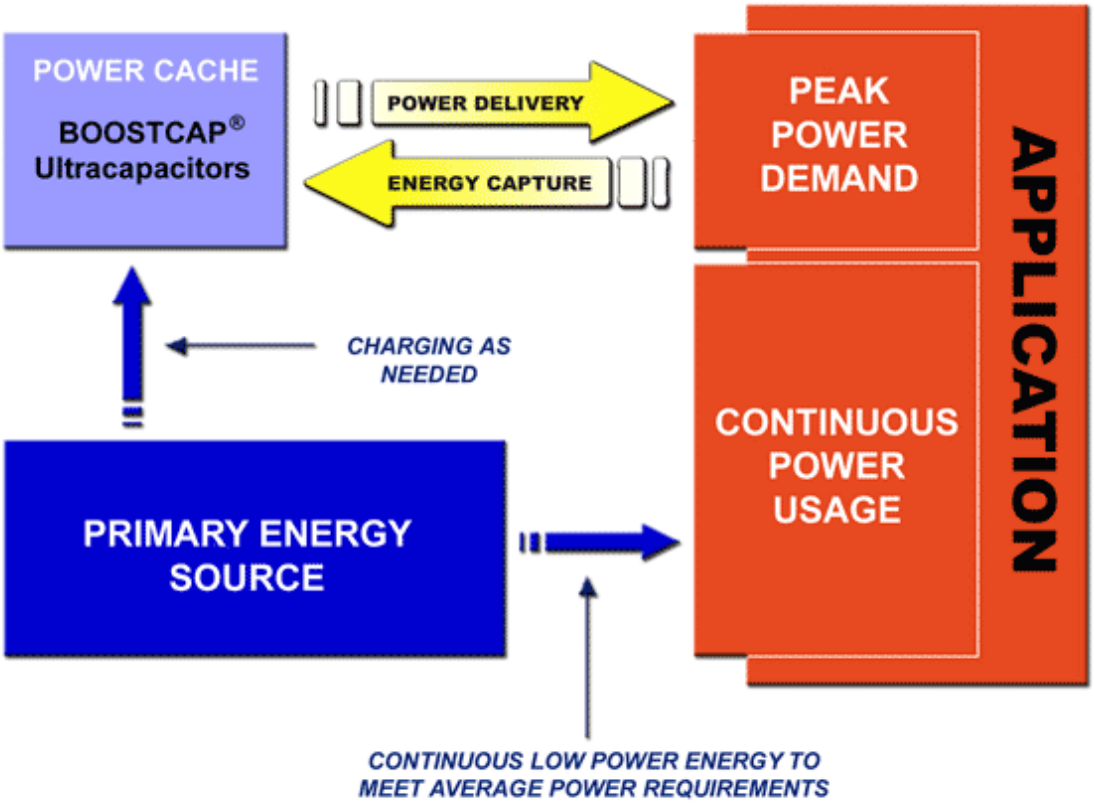

Figure 2: Ultracapacitor Application Model

Numerous automotive firms are well into the production design cycle for ultracapacitor-based powertrains and subsystems, as they recognize the advantages and availability of the ultracapacitor to meet their business and technical requirements. Ultracapacitors are becoming a standard energy storage option. Ultracapacitors are globally available, cost-effective, perform well in automotive systems, and are considered a peer to any other option for commercial energy storage requirements.

Boxout: Case study: ISE Corporation powers buses in Long Beach

ISE Corporation and Maxwell Technologies are engaged in a joint technology development to design ultracapacitor-based energy storage systems for the transportation industry. The goal is to develop a safe, reliable, maintainable and cost-effective product.

So far, this has resulted in the unique ISE power pack rack design that allows easy access, simplicity, maintainability, and structural integrity. The system will be used on over 70 buses to be delivered to Long Beach in 2005.

The features of this joint ISE-Maxwell system, which uses 144 of Maxwell's BOOSTCAP BCAP0010 2600F ultracapacitor cells, are:

- completely integrated contactors, voltage measurement, Ground Fault Indication (GFI) and temperature monitoring,
- programmable GFI threshold,
- total system weight of 120kg,
- all low voltage controls accessible from the outside,
- a vehicle interface that meets CAN J1939, power and ignition,
- designed to discharge itself over 12 hours,
- measured cycle efficiency range of 84-95%,
- integrated cooling system,
- fully assembled pack,
- an ESR of 0.07 Ohm,
- SAE J1939 communications.

The benefits of using Maxwell's BOOSTCAP ultracapacitors have been 100% reliability, low lifecycle cost, improved acceleration, and high regenerative braking power capture. Since the integration of the ultracapacitor system into the first prototype bus there have been no serious issues and the systems have functioned reliably at temperatures from –25°C to 45°C. The response of the drive system is significantly better than that of a standard bus and fuel economy is improved through the efficient capture of more braking energy.
As Tom Bartley, the New Business Manager at ISE Corporation put it, "Due to their excellent power characteristics, ultracapacitors increase the performance, reliability and durability of on-board energy storage and provide a key link in accelerating the societal impact of environmentally-friendly transportation."

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

Picture: Bus for Long Beach, USA with ultracapacitor power system

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