Ultracapacitors and Batteries for Energy Storage in Heavy-Duty Hybrid-Electric Vehicles

Abstract: Ultracapacitor packs are now offered as a standard energy storage option on ISE Corporation hybrid-electric drive systems, currently 18 in service and over 50 more on order. They are available, safe, and offer high power performance at very high efficiency. A standard ThunderPack II™ is described along with its performance on an urban transit bus at better than 84% efficiency. However, ultracapacitors have low energy density compared to batteries. ISE has limited experience with combining a lead acid battery pack and a nickel sodium chloride (Zebra) battery pack with an ultracapacitor pack. Continuing projects include the combination and road testing of a high voltage ultracapacitor pack and a commercially available nickel metal hydride (Cobasys NiMH) pack on a hybrid-electric truck. The interactions are analyzed with respect to power, energy, environment, and life cycle costs. These results could be significant for energy storage markets and applications.

Hybrid-Electric Vehicle Application

A hybrid-electric drive system achieves efficiency improvements (higher fuel mileage and lower operating costs) over a standard drive system by storing and reusing braking energy that would otherwise be lost as heat and by using more efficient electrically driven accessories rather than power-take-offs from the engine. However, the replacement costs of the energy storage media can significantly affect the vehicle overall life cycle cost. The system trade-off has been: save fuel by using the batteries heavily to store braking regeneration energy, but pay higher battery replacement costs; or use the batteries lightly to lower the replacement costs, but save less fuel.

ISE's main interest in an energy storage system for a heavy-duty hybrid-electric drive is to save fuel by recycling as much of the braking regeneration energy as possible, maintain or improve upon standard vehicle acceleration performance, have some all-electric drive range, and not incur energy storage replacement cost penalties. From a system perspective here is what ISE would like to have:

Stored Energy: 10kWh minimum, 25kWh preferred
Voltage: 720 maximum, 600 nominal, 400 minimum
Power: 200kW maximum for 10 seconds, 150kW continuous for 60 seconds
Energy Density: 30kg/kWh maximum (300kg for a 10kWh battery)
Warranty: 5 years of operation @ 200 x 2.5kWh cycles/day, 330 days/year
(330,000 cycles @ 25% Depth of Discharge for the minimum 10 kWh stored energy)
(330,000 cycles @ 10% DoD for the preferred 25kWh stored energy)

System to include: battery, NEMA 4x enclosure, BMI (integrated battery manager), GFI (ground fault interrupter), contactors, and cooling interface

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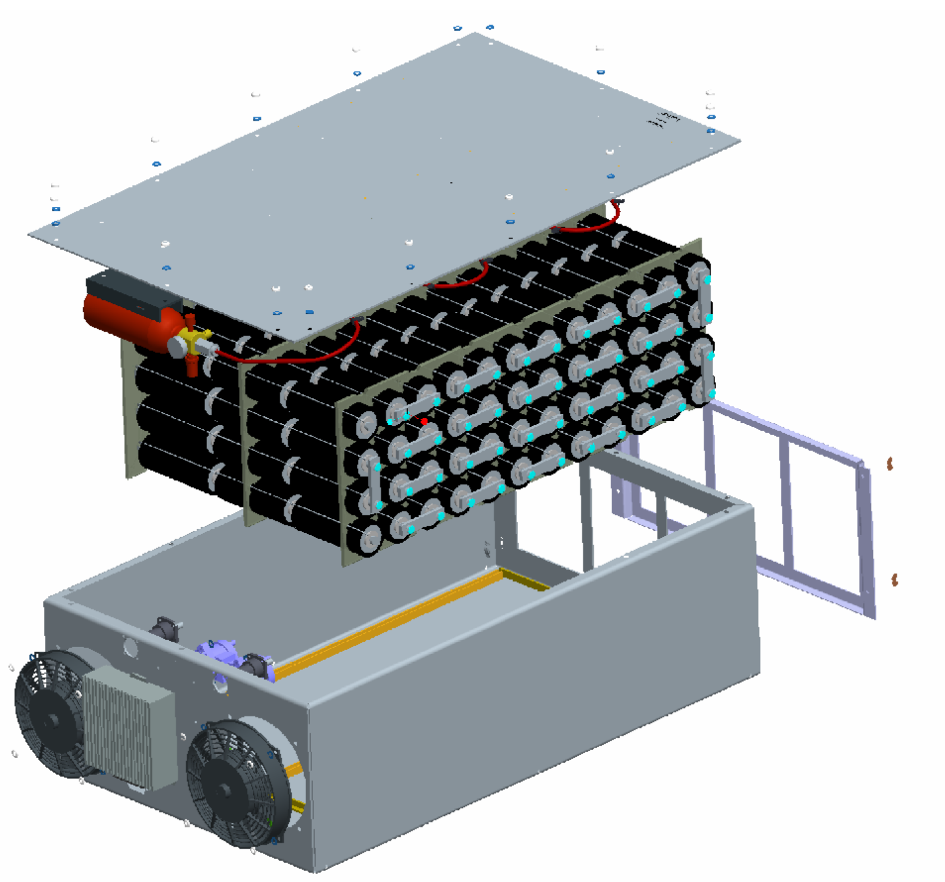
Ultracapacitors

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 was to develop a product that is: **Safe, Reliable, Maintainable, and Cost Effective**.



The result is the unique ISE rack design which allows easy access, simplicity, maintainability, and structural integrity.

The ISE ThunderVolt ThunderPack II™ represents the latest advance in **high power** density ultracapacitor energy storage technology. For hybrid-electric vehicle applications, where maximum energy recapture and durability are needed in a small package, ThunderPack II™ offers an attractive new alternative. In addition to offering weight and volume reductions, ultracapacitors can last significantly longer than batteries. The ThunderPack™ system employs a unique integrated system to equalize the charge levels of the 144 ultracapacitors in the pack to optimize overall vehicle energy management. Two ThunderPack II™ packs can be placed in series to allow use on higher voltage systems to 720V nominal (800V peak). This dual pack configuration allows charge/discharge cycles at power levels up to 300kW and can store about 0.6kWh. The ThunderPack II™ offers several important safety features, which include over temperature protection, a "Safe on Disconnect" integrated contactor, a fire suppression system, and an optional integrated precharge circuit to match battery pack and ThunderPack II™ voltages. ThunderPack II™ is also thermally controlled to keep the ultracapacitors within an optimal temperature range. ThunderPack II™ can also be used to handle fluctuating power demands in stationary distributed power systems, helping to stabilize electrical loads on the principal power generation source or grid.

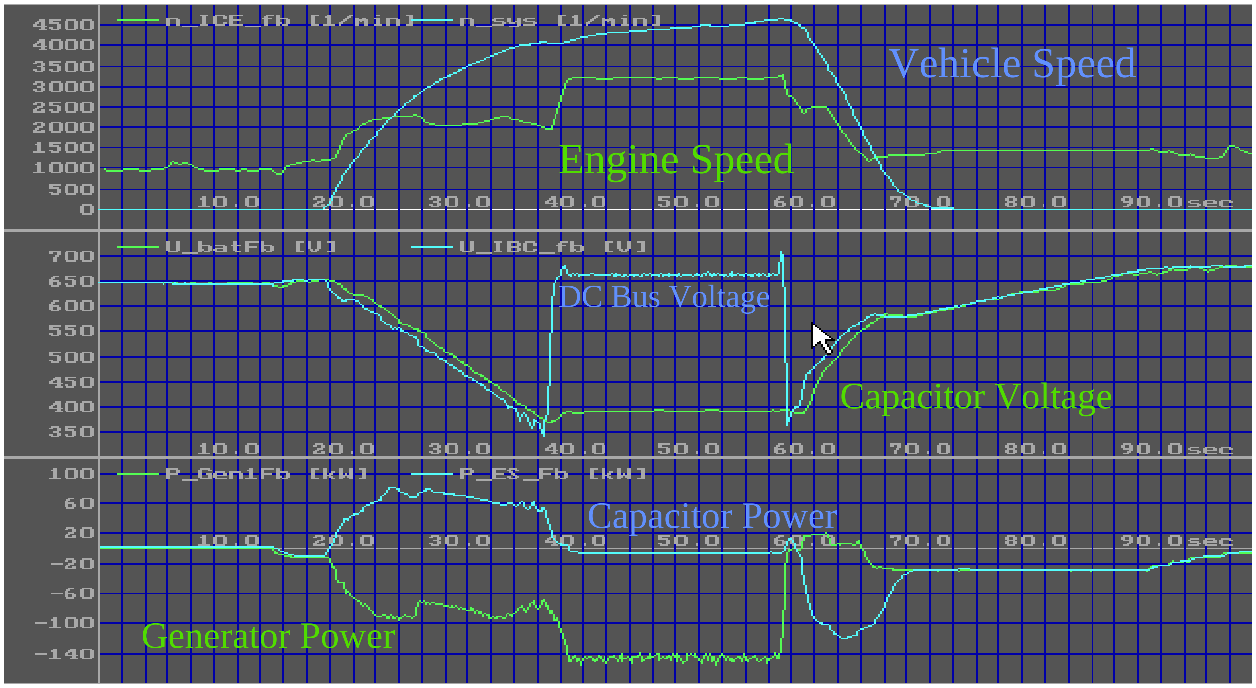
Nominal Voltage	360V*
Peak Voltage	403V**
Rated Current	400A
Capacitance	18.05F
Total Energy Stored nominal / max.	0.325kWh / 0.407kWh
Leakage Current	5mA nominal
Operating Temperature	-35 to 65 °C
Weight	240lbs
Dimensions wxlxh	24"x40"x12"
Standard Pack	144 Capacitors
Fire Suppression System	Heat Activated Halotron System

Model	BCAP0010
Capacitance	2600F
Series Resistance	0.7 mΩ at DC
Voltage-Continuous	2.5V
Voltage Peak	2.8V
Rated / Max Current	400A / 600A
Long Cycle Life	> 5x105 cycles

Capacitors are known to accept high power levels and store energy quickly. Ultracapacitors are high power, low energy devices with high power density and cycle life, but cannot store the energy needed for long term or extended range all-electric operation. Ultracapacitor packs for hybrid vehicles offer the storage and delivery of hundreds of kilowatts at efficiencies greater than 84%. Ultracapacitors have a greater than 500,000 charge/discharge cycle life and a -35 C to +65 °C operating temperature environment. In heavy-duty hybrid vehicle applications ultracapacitor packs are projected to have a 10 to 12 year life. Furthermore, known economies of scale manufacturing techniques could reduce future ultracapacitor cost by more than 60%.

Urban Transit Bus Performance

The following trace diagram shows actual performance data during a bus start up acceleration, a short cruise and a braking regeneration stop. The horizontal axis is time in seconds. For about the first 16 seconds the vehicle is idling at a stop. About 2 seconds before the vehicle starts to accelerate from the stop the engine generator kicks in a little more energy to the ultracapacitor pack to raise the DC bus voltage slightly above 650 volts. At 20 seconds the driver pushes the accelerator and the vehicle accelerates with about equal power from both the generator and the capacitors for about the next 20 seconds as the capacitor bank is emptied. When the DC bus voltage drops below 350 volts the capacitors are switched off, the engine speed increases to a new level and the generator supplies all the drive power at about 650 volts on the DC bus for a slight increase in vehicle speed for about 20 seconds until the driver applies the brakes at about 60 seconds into the trace. Then the generator is turned off causing the engine speed to decrease, the capacitors are turned back on, the DC bus voltage drops back to 350 volts and the drive motors become braking regenerators to recharge the capacitors at a peak of over 120kW as the vehicle slows to a stop at about 70 seconds. Shortly before a complete stop the generator is turned back on to add to the capacitor recharge.



Considerations when using ultracapacitors

For batteries, the output voltage remains somewhat constant over the stored energy state-of-charge (SOC). The main characteristic of ultracapacitors is the wide variation in voltage with the stored energy SOC according to **energy (watt-secs) = ½ C V^2;** where **C** is the capacitance in Farads, **V** is in volts. A simple **RC** model, where R consisted of the load (useful energy) and the equivalent series resistance (wasted energy-heat), was used to analyze and predict the power and efficiency performance. The results compared closely to the actual traces presented above.

The difference in voltage swings presents a challenge to the hybrid-electric system designer.

- Solution A: A DC-to –DC converter can be used to boost the ultracapacitor voltage.
- Solution B: The system components operate over a wide voltage range and must be designed accordingly.

The energy capacity is limited and will not support long grades or high speed operation. The engine has to be sized for maximum vehicle performance and braking resistors are needed to support downhill braking regeneration (retardation).

Electric Drive-350VDC Swings

Siemens DUO-Inverter operates with a 350VDC swing from 700VDC to less than 350VDC to power AC induction vehicle drive motors from a Maxwell/ISE ultracapacitor pack. A pair of ISE ThunderPack II™ ultracapacitor packs containing Maxwell BOOSTCAPS® connected in series supply the high power electrical discharge required for the acceleration of a 40,000 pound heavy duty hybrid-electric vehicle. Because ultracapacitors require a wider voltage swing than batteries for a high power discharge, the wide operating voltage range of the Siemens ELFA DUO-Inverter is a perfect match for Maxwell ultracapacitor energy storage applications. Rated at two times 120kVA the Siemens DUO-Inverter is the high power interface between DC energy and the AC induction electric motors. For mobile hybrid vehicles this arrangement works with either generator or fuel cell supplied electricity. For fixed installations ultracapacitors combined with inverters can help to reduce peak power demands and the associated extra costs, and supply instantaneous high power for an emergency switchover from the electric power grid to a local backup power source. ISE Corporation is the preferred Siemens United States distributor for ELFA generators, motors and inverters.

<u>ISE Ultracapacitor Pack</u>
Total Energy Stored: 0.407kWh
150 kW Charge/Discharge Current
4 Wh/kg Energy Density
1.5kW/kg Power Density
Expected life 10-12 years
System Cost : 100 $/kW
Life Cycle Cost: 100$/kW

<u>ZEBRA Battery Pack</u>
17.4kWh Usable Energy
32kW Charge and Discharge Power/Module
87 Wh/kg Energy Density
0.16kW/kg Power Density
Expected life 2.5-5 year
System Cost: 375 $/kW
Life Cycle Cost: $1125/kW

Hybrid-Electric Vehicle Batteries

Batteries are typically moderate power, high-energy devices. Battery-only energy storage systems have good energy storage capability, but are limited with respect to power density, efficiencies (typically less than 75%), cost, cycle life (typically less than 1,000 charge/discharge cycles), and slow discharge. Batteries usually have a thermal management system to operate beyond a -3 C to +35 C temperature environment. Lithium batteries may solve some of these problems but at a high cost.

Battery life (and replacement costs) in a hybrid-electric vehicle is usually defined by the number of 100% charge/discharge cycles. Reducing the depth of discharge (DoD) increases the number of cycles in a battery's life. This relationship varies from somewhat linear to exponential. For example in a squared relationship, limiting the DoD to 10% would increase the number of lifetime charge/discharge cycles by a factor of 100. Thus, the life of a 1,000 cycle battery increases to 100,000 cycles. This characteristic is how the Toyota and Honda ca afford to offer extended life battery warranties with their hybrid-electric vehicles.

For an urban heavy-duty hybrid-electric vehicle that operates in stop-and-go traffic, part of the hybrid control strategy is maintaining an energy storage SOC level that will accommodate braking regeneration charging and acceleration discharging. An optimal SOC level is highly drive cycle dependent, but without priory knowledge of the upcoming traffic and topology some mid level is usually chosen. Other than the hybrid drive manufacturers, Bowling Green State University and the University of Michigan have developed optimized hybrid control strategies. The battery use trade-off between fuel economy and replacement costs should be considered in this strategy.

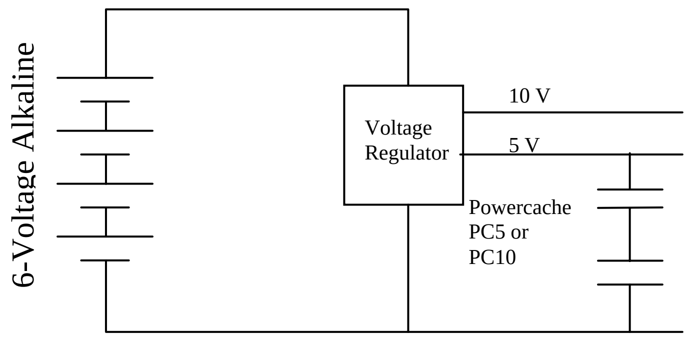
Batteries and Ultracapacitors

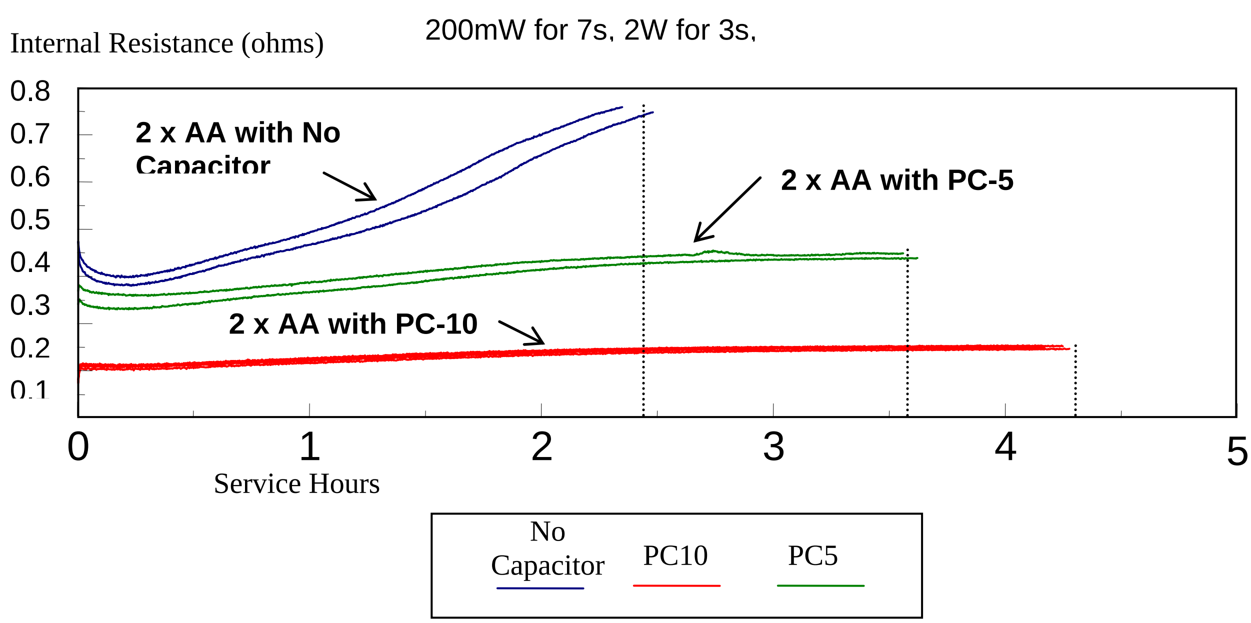
Hybrid-electric ground vehicles require an advanced, compact, high energy-density electrical storage system to provide both high power and high energy. A combination of multiple types of energy storage, such as batteries combined with ultracapacitors, may provide the best overall performance and offer superior power, energy and cycle life. The concept of combining the two systems offers potential advantages of both, while minimizing the disadvantages of either type of technology to meet the demand of storing and releasing energy. There is potential to improve the performance, reliability, and extend the operating environment of all hybrid-electric power trains, especially for heavy-duty vehicles. Typical advantages are longer range for quiet operation, better acceleration, higher fuel mileage, and lower maintenance.

Encouraging Results

Maxwell Technologies performed the following experiment that connected four AA alkaline batteries in series to power a voltage regulator similar to the use in small electronic devices like a digital camera. Ultracapacitors were connected across the load. The internal resistance of two AA batteries was measured while the discharge cycle was repeated at 200 milliwatts for seven seconds followed by two watts for two seconds. In the best case the service life of the batteries was extended by at least 80%.

Internal Resistance





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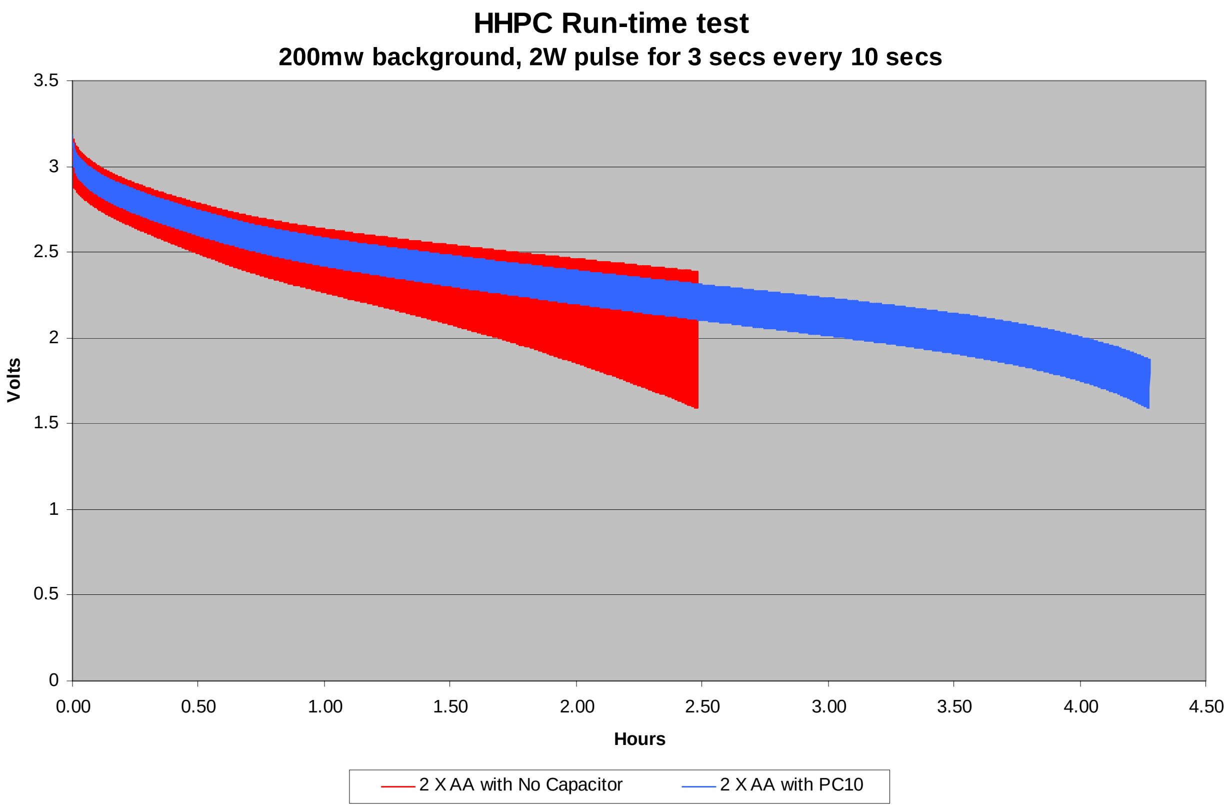
Run-Time

Another experiment measured the voltage over time of two AA batteries in series with and without a parallel ultracapacitor. Every ten seconds a two watt discharge was added to a 200 milliwatt discharge background. In addition to narrowing the distribution of the results the ultracapacitor appeared to extend the battery run time about 70%.



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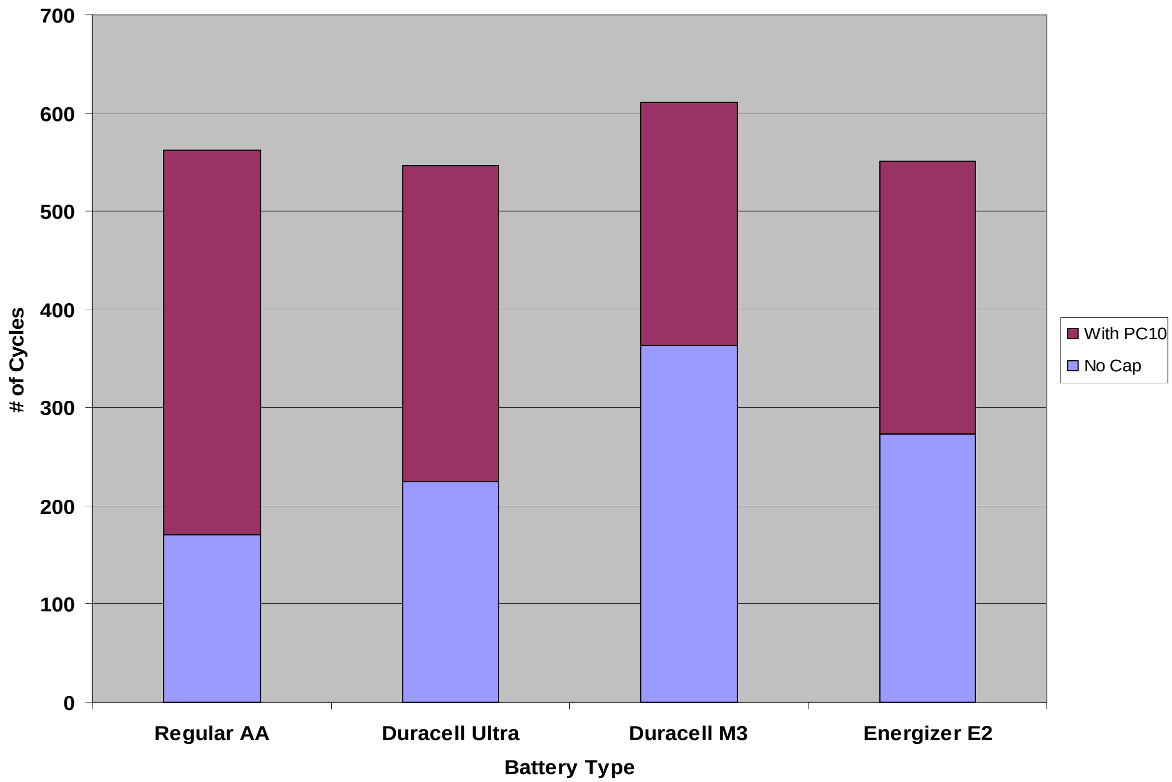
Diversity

Finally the experiment was repeated for four different battery manufacturers to see if there was any effect due to the chemical manufacturing process. The results indicate that the ultracapacitors tended to have an equalizing effect n the performance. The worst batteries were helped the most while the best batteries were helped the least.



Conclusions

These tests were intended to be indicative, not conclusive. They were also intended to introduce some increased power pulses because ultracapacitors would probably have little if any effect on a slow continuous discharge. As would generally be expected, seem to have a power averaging effect that extends battery life. A speculative conclusion would be that battery chemistry during discharge deteriorates more rapidly the higher the discharge power. One might also speculate that the same is true for recharging rechargeable batteries. Thus, anything that can be done to minimize battery charge/discharge power peak would extend battery useful life. This would also be consistent with the speculation that battery internal resistance and high current levels create local heating and internal hot spots that tend to more rapidly wear out the chemistry.

Over charging and over discharging are known to create heat and destroy batteries. If there is less and less chemical reactants available at the extremes of operation then operating batteries over some mid range in the DoD could be thought of as averaging the chemistry with best molecules, lowest internal resistance, and correspondingly less heat and hot spots. Again, the averaging effect of ultracapacitors should extend battery useful life.

Ultracapacitors and Batteries On A Hybrid-Electric Bus

ISE carried out two different projects that combined ultracapacitors and batteries in an energy storage system on a hybrid-electric urban transit bus. Both projects were unique opportunities in the course of hybrid drive developments and preliminary results were encouraging, but neither project had sufficient time and resources to optimize the design or completely evaluate the performance of the combination.

The first instance of combining ultracapacitors and batteries on the same vehicle was conducted using two series connected ISE first generation ultracapacitor packs operating in a direct parallel connection with a 600 volt lead acid battery pack on a gasoline hybrid-electric drive system for a 40 foot, 40,000 lb urban transit bus. This first installation performed well for a few weeks, but was terminated prematurely when the seals leaked on some of the first generation ultracapacitor canisters. Unfortunately, no useful quantitative data was collected. However, the caps reduced the battery power spikes in charging and discharging and the electric driver system was smoother. The high current handling of the caps seemed to protect the batteries against the inertia of the vehicle.

The second experiment used rudimentary controls to connect the ultracapacitor packs with nickel sodium chloride battery pack in the hybrid-electric drive system of a hydrogen fuel cell powered 40 foot, 40,000 lb urban transit bus. Although initial all electric testing was accomplished which shows great promise for the combination, that vehicle is still undergoing fuel cell integration into the drive system so the full evaluation has not been performed.

Future Projects

Funding for planned projects has been delayed, but ISE is currently integrating hybrid-electric drive system in a prototype demonstration vehicle that uses Cobasys NiMH batteries for energy storage. This project is a future candidate for evaluating the combination of batteries and ultracapacitors. The objective is to develop some useful models to evaluate fuel savings versus battery life and replace cost as a function of the capacities of the battery pack and the ultracapacitor pack (initial costs).

The control mechanism for a hybrid battery-ultracapacitor energy storage system is a challenge because each technology starts with different physical, electrical, and chemical characteristics that result in different power, energy, voltage characteristics, and charge/discharge methods. The interactions between these systems are not immediately obvious or predictable without a careful study and verification through hardware validation. The challenge lies in controlling the combination of both types of energy and power storage to meet the supply demands from the vehicle electric traction system.

A complete control system evaluation required for the power management and distribution from batteries and ultracapacitor energy storage systems has not been accomplished. A hybrid combination of multiple types of energy storage, such as batteries combined with ultracapacitors, may provide the best and most cost effective overall performance for and offer superior power, energy and cycle life and enhanced producibility because of wider use and economies of scale. The concept of combining the two systems offers potential advantages of both, while minimizing the disadvantages of either type of technology to meet the demand of storing and releasing the energy as needed for heavy-duty vehicles. There is potential to enhance the performance, reliability, and producibility of high power energy storage at reduced costs. Typical advantages are higher pulse power with higher cycle life and lower maintenance.