GET THE LOWDOWN ON ULTRACAPACITORS

Now that you're armed with more capacitance than earlier generations of engineers ever dreamed of, what do you do with it?

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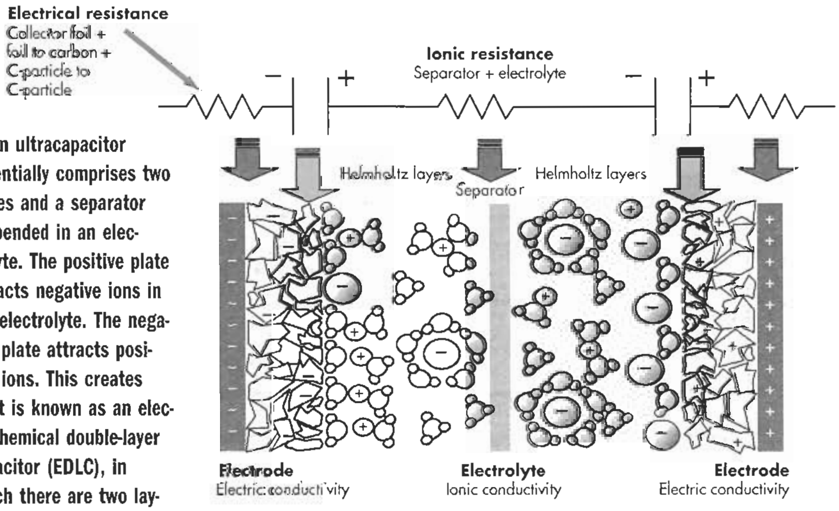
Call them ultracapacitors. Or supercapacitors. Whatever the name, they exhibit vastly greater capacitance than conventional caps. Singly, you can buy radial-lead board-mount devices rated for 5 to 10 F at 2.5 V, flashlight-battery size units rated for 120 to 150 F at 5 V, and larger single-capacitor cans good for 650 to 3000 F at 2.7 V. Note that all of those capacitance values are in farads. Not so long ago, a couple of thousand microfarads were a lot of capacitance.

Need more? You can buy off-the-shelf modules spec'd for 20 to 500 F, with voltage ratings from 15 to 390 V. If you understand how to balance them in series/parallel combinations, you can drive a bus with them—no, not two traces on a circuit board, but a passenger-hauling bus. (Although not very far, as hybrid propulsion systems, chemical batteries, and fuel cells are still in the picture. More on that shortly.)

What happened? In developing ultracaps, nobody discovered new laws of physics. In fact, the theory behind them goes back to Helmholtz. Like all capacitors, ultracaps are still about storing power in the form of an electrical charge between two "plates." The capacitance is directly related to the area of the plates and the permittivity of the material between the plates, and it's inversely related to the distance between them. After that, the story gets interesting.



1. An ultracapacitor essentially comprises two plates and a separator suspended in an electrolyte. The positive plate attracts negative ions in the electrolyte. The negative plate attracts positive ions. This creates what is known as an electrochemical double-layer capacitor (EDLC), in which there are two layers of capacitive storage.

Before we had ultracaps to provide astonishingly high values of capacitance, we had electrolytics. Ultracapacitors aren't electrolytics, but understanding the older tech is helpful in understanding the new tech.

Electrolytics are so named because one (or both) of the "plates" is a nonmetallic electrolyte on top of a metallic backing. During manufacturing, a voltage drives a current from the anode metal through a conductive bath to the cathode. That produces an insulating metal oxide on the surface of the anode—the dielectric.

One of the phenomena that happens inside electrolytics is the charge accumulation and charge separation that occurs at the interface when any electrode is immersed into an electrolyte solution. An accumulation of oppositely charged ions in the solution compensates for excess charge on the electrode surface. The interface is called the Helmholtz layer.

To understand ultracaps, stop thinking about flat plates (or flat plates rolled up into tubes) with a dielectric between them, much like peanut butter in a sandwich. In an ultracap, charging/discharging takes place on the interfaces between porous carbon materials or porous oxides of certain metals in an electrolyte.

The Helmholtz layers give rise to an effect called double-layer capacitance. When a dc voltage is applied across the porous carbon electrodes in an ultracap, compensating accumulations of cations or anions develop in the solution around the charged electrodes. If no electron transfer can occur across the interface, a "double layer" of separated charges (electrons or electron deficiency at the metal side and cations or anions at the solution side of the interface boundary) exists across the interface *(Fig. 1)*.

The Helmholtz-region capacitance depends on the area of those porous carbon electrodes and the size of the ions in solution. The capacitance per square centimeter of electrode double layers is on the order of 10,000 times larger than those of ordinary dielectric capacitors. That's because the separation of charges in double layers is about 0.3 to 0.5 nm, instead of 10 to 100 nm in electrolytics and 1000 nm in mica or polystyrene caps.

There's a catch to this "double-layer" characteristic, though. The double-layer configuration reduces the potential capacitance of a practical device because the ultracap consists of a pair of electrodes, each with half the total mass. In addition, the ultracapacitor is effectively two capacitors in series. Taken together, that means the ultracap achieves one quarter of the theoretical capacitance based on electrode area and ion size.

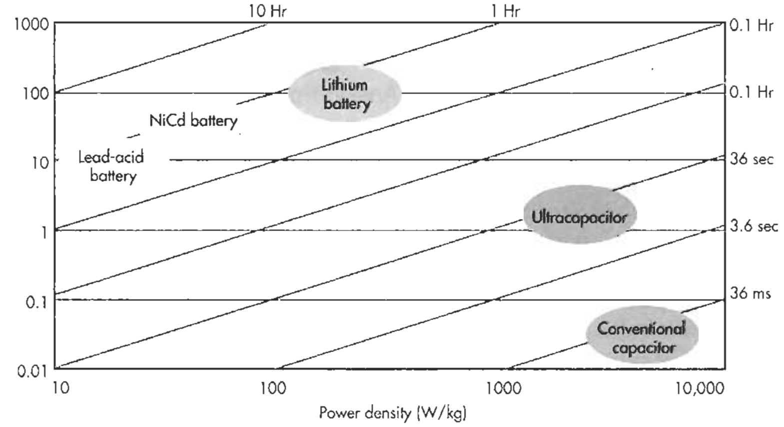
If you want to read the theory behind ultracapacitors in more depth, check out an article from the Electrochemistry Encyclopedia called "Electrochemical Capacitors, Their Nature, Function, and Applications" *(http://electrochem.cwru.edu/ed/encycl/art-c03-elchem-cap.htm)* by the late Brian E. Conway of the University of Ottawa's chemistry department. Conway was an important contributor to ultracapacitor research for several decades.

BATTERIES AND ULTRACAPS • The popular press likes to lump batteries and ultracapacitors together, obscuring a number of important differences:

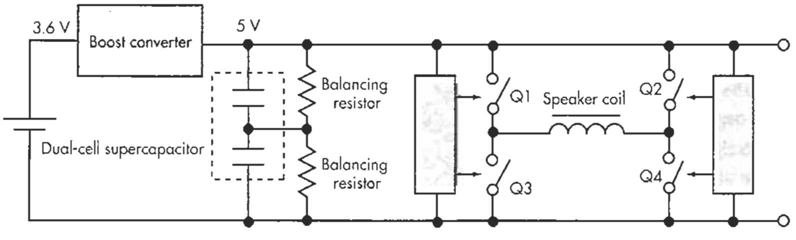
- Batteries store watt-hours of energy. Capacitors store watts of power.
- Batteries depend on chemical reactions with long time constants. They take a relatively long time to charge, and they're fussy about the profile of the current that charges them. Conversely, capacitors are charged by applying a voltage across their terminals, and their charge rate depends mostly on external resistance.
- Batteries deliver power in the form of a more or less constant voltage over long time periods. Capacitors discharge rapidly, and their output voltage decays exponentially.
- Batteries are good for only a limited number of charge/discharge cycles, and the number of cycles depends on how deeply they are discharged. Capacitors, especially ultracapacitors, can be charged and discharged repeatedly for tens of millions of cycles. (This is an important way that ultracaps differ from electrolytics—they aren't cycle-limited by the electrode plating that accompanies electrolytics' operation.)
- Batteries are big and heavy. Capacitors are small and light.

Many of these differences can be heuristically illustrated in a Ragone plot *(Fig. 2)*. Ragone plots have more analytical uses, but essentially, they're log-log graphs of energy density (in this case in Wh/kg) on the Y axis versus power density (in W/kg) on the X axis. Because they're log-log plots, discharge time can be represented as straight-line diagonal parameters.

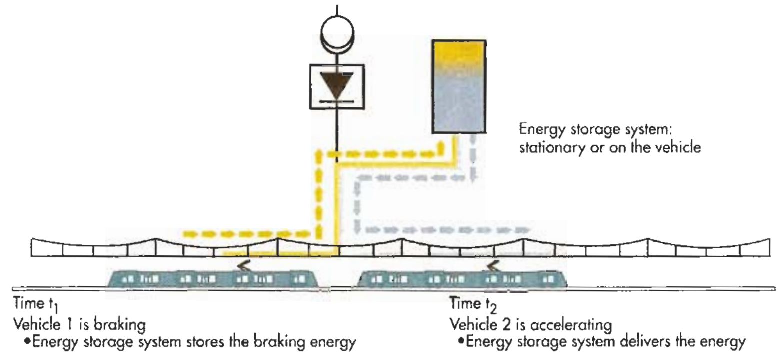
The Ragone plot helps illustrate the differences among different kinds of battery chemistry, clustered on the left, and capacitors on the right. Taken together as illustrated on the



2. A Ragone chart plots storage device energy density versus power density on a log-log coordinate system, with discharge times represented as diagonals. Among other things, it's handy for comparing batteries and ultracapacitors.



3. In automotive applications, ultracaps often are used adjacent to microcontrollers to protect them from momentarily sagging bus voltages. This application idea from Cap-XX goes a little further in using a small boost converter to "pump up" a pair of ultracaps that then supply power to the H-bridge in a class-D audio amp.



4. In transportation systems, ultracaps are useful in regenerative braking because of the speed with which they can store and deliver large amounts of power.

Ragone plot, those characteristics make batteries and ultracapacitors complementary to each other, rather than antagonists. In fact, that's how they're often used.

APPLICATIONS • The most basic applications for ultracaps lie in stabilizing dc bus voltages. Ultracaps have become widely used in automobiles to protect the various engine control units and other microcontrollers from voltage dips associated with the application of sudden transient loads. (Voltage spikes are handled differently.)

Those sudden loads often are associated with motors. But if the speaker output of the car's entertainment system is sufficiently robust, the load could come from audio peaks. In lieu of simply putting an ultracap on the 12-V input to the entertainment system, an application note by Australian ultracap-maker Cap-XX shows a way of increasing the voltage for a class-D output amplifier's H-bridge *(Fig. 3)*. It uses a small boost converter and stores the power needed for those occasional peaks in a pair of ultracaps.

Elsewhere in transportation, the ultracap's ability to absorb and discharge energy rapidly makes it far better than batteries for regenerative braking schemes. Most of these applications have been in public transportation *(Fig. 4)*.

The Bombardier rail cars in the light-rail system in Mannheim, Germany, use packs of 600 2600-F ultracapacitors for braking energy recapture. The stored energy is used to boost acceleration and to bridge non-powered sections and intersections. Operation there represents between 100,000 and 300,000 load cycles/year. This is an all-electric rail system, so recaptured braking energy reduces demand on the grid. In that regard, the prototype has demonstrated a potential for energy savings of up to 30%.

Mannheim installs the ultracaps on the rail cars themselves. An alternative is to install the ultracaps alongside the tracks. Demonstrating this approach, Siemens Transportation Systems uses ultracapacitors for regenerative braking in its Sitras SES system, which is used in Cologne's and Madrid's metro rail lines. In a typical trackside implementation, the ultracapacitors absorb the braking energy from all trains within a 3-km radius.

In hybrid transportation applications in the U.S., ISE Corporation's buses now run in Elk Grove and Long Beach. The buses accelerate more quickly than standard buses. At gross vehicle weight, the bus can accelerate from zero to 31 mph in 17 seconds and can reach a maximum speed of 62 mph. Preliminary data indicates better average fuel efficiency compared to competitive battery-based hybrid-electric drive systems. These ultracapacitor-plus-battery hybrid buses recuperate 38% of the propulsion energy, which translates into more than 3.9 miles/gallon of fuel-economy gain on average

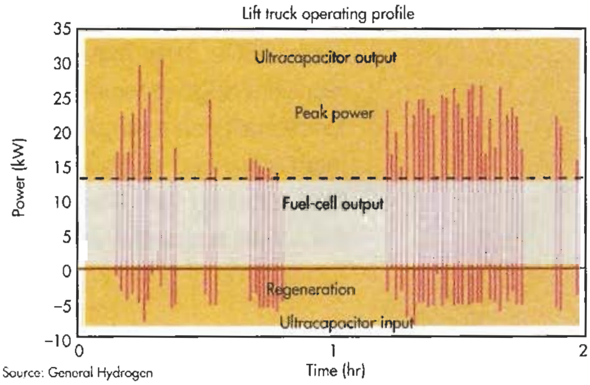
ISE developed its own thermally controlled modules, each of which uses 144 18-F ultracaps. The modules provide 360 V at 400 A. A pair of the modules is used in series to take the voltage to 720-V nominal (800-V peak). This dual-pack configuration allows charge/discharge cycles at power levels up to 300 kW and can store approximately 0.6 kWh.

Regenerative braking means capturing kinetic energy. These applications also recapture potential energy. One recent example is a forklift, but the much wider potential lies in building-elevator systems.

For forklifts, General Hydrogen offers retrofit and new "Hydricity Packs," fuel-cell systems sized for direct lead-acid battery replacement in conventional factory equipment. Its ultracapacitor bank stores power every time the loading fork descends with a pallet and releases it when power bursts are required for heavy lifting. Figure 5 plots typical power usage in a forklift, demonstrating the synergy between fuel-cell and ultracapacitor power.

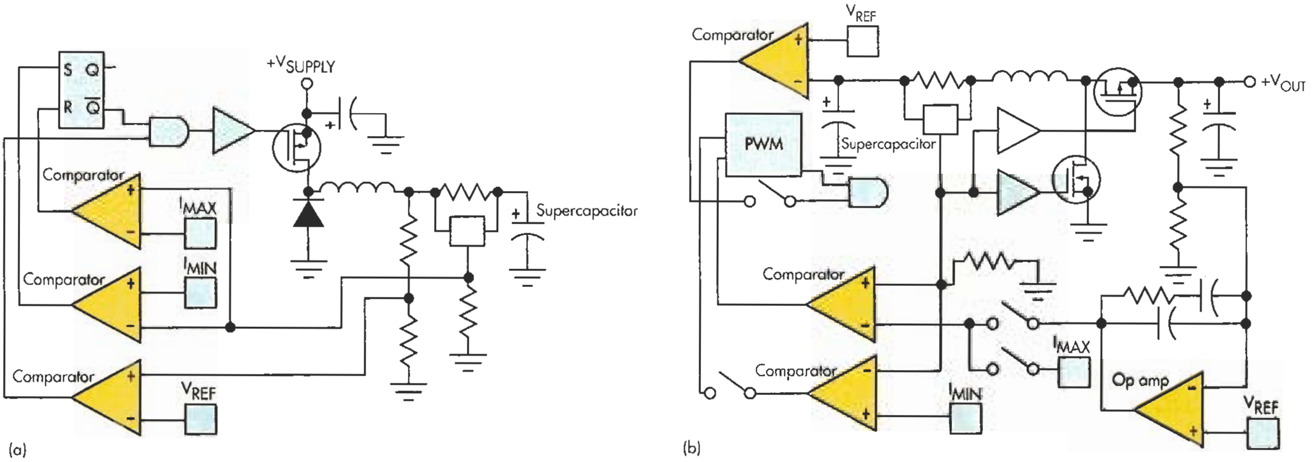
The short discharge time doesn't adversely affect some ultracapacitor applications. In European wind farms, the latest turbines have 160-ft blade diameters, with hubs 250 ft above the ground. In high winds, the blades must be feathered, lest the turbines over-rev. That requires high-torque pitch motors for each blade, along with a power source for those motors.

Although that looks simple enough for lead-acid storage batteries, the wind-turbine designers chose ultracapacitors. Batteries would need regular servicing, while ultracaps do



Source: General Hydrogen

5. Forklifts provide an opportunity to capture and store potential energy from descending loads, which can be used to boost other loads up to high storage areas. This time plot of fork-lift energy use shows how a hydrogen fuel cell and an ultracap array can share the load.



6. To make a system of batteries, solar panels, and ultracaps work together in a satellite system, designers at Microchip and AMSAT focused on charging the ultracaps using a modified switched-mode buck converter (a). Discharge via a boost converter would then flatten the ultracaps' normally exponential discharge curve. By clever design, the partners arrived at a buck/boost converter (b) that uses many of the same components.

not. Of course, the utility needs to employ some skilled service people to climb the towers. But it can get by with fewer of them if they can concentrate on serious maintenance work and not be continually clambering up and down thousands of towers just to babysit batteries.

CIRCUIT DESIGN • Combining ultracaps, batteries, fuel cells, and solar panels constitutes an interesting design exercise. Much of what follows comes from papers presented at the Power Electronics Technology conference in Dallas earlier this month and represents the state of the art.

In a paper titled "Storing Power with Super Capacitors," Thomas DeLurio of Advanced Analogic Technologies describes portable applications such as wireless data cards for GSM, GPRS, or WiMAX that require a peak current during data transmission of signals that exceeds what's available under PC Card, CF Card, or USB standards.

DeLurio also notes a similar problem with flash LED illumination in camera phones. "The challenge for designers is determining how to most efficiently interconnect the battery, dc-dc converter and super capacitor in a way that will limit the super capacitor charge current and continually recharge the capacitor between load events," he says.

The problem with ultracaps, DeLurio says, is their low equivalent series resistance (ESR). When the capacitor is initially discharged, it looks like a low-value resistor to the charging circuit. The resulting large in-rush current would essentially short-circuit the device's battery. Additionally, he notes, "Any circuit of this type also requires short-circuit, overvoltage, and current flow protection."

A designer could just use a series resistor to limit current, but that would result in an unacceptably long time for charging the capacitor. DeLurio describes a PC Card application in which sizing the resistor for PC Card host/card negotiation current limits would yield a charge time on the order of seven minutes.

Allowing a higher current to flow after host/card negotiation would reduce charging time. In fact, that concept could be extended to providing a means for switching in a succession of resistors as the capacitor charged up.

Yet this approach "requires that the timing of the switching points be closely controlled, which would demand very accurate and expensive resistors, or monitoring by additional voltage detectors," DeLurio says. "Furthermore, when the capacitor is fully charged and the PC card is removed, the energy stored in the capacitor would be sufficient to damage the connector pin."

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Instead, DeLurio introduces a new Analogic Tech "smart switch." The AAT4620 current-limited P-channel MOSFET power switch is designed expressly for wireless-card ultracap-power applications. It has two independent, resistor-programmable current limits and a power loop controlled by the AAT4620's die temperature.

Moving up the power scale, "Super-Capacitor Power Storage" by Keith Curtis of Microchip starts by noting the inefficiency of charging an ultracap using a linear charger. He then goes on to propose a modified dc-dc buck regulator *(Fig. 6a)* as the appropriate charging circuit because it can "regulate the charging current of the capacitor, independent of the output voltage... using the voltage feedback as the means of determining when the charge is complete."

The effect is somewhat like what DeLurio described, but more general. Explaining the circuit's operation, "Current... is regulated by comparing the current in the inductor against two fixed levels; one at the maximum desired current, and the other at the minimum," Curtis says.

"Initially, it will take the inductor very little time to ramp up from the minimum to maximum current, as the voltage across the inductor is at its maximum. The discharge time will be correspondingly longer, as the inductor has to discharge into a relatively small voltage," he notes. "As the charge in the capacitor increases, however, the voltage difference will drop—increasing the ramp-up time—and the capacitor voltage will rise, shortening the discharge time."

Curtis says that switching frequency is based on a "relaxation-oscillator, 555-timer-style system, using two comparators and a SR flip flop," so that the inductor component values will set the frequency.

He then uses similar logic to arrive at a switched-mode boost circuit for converting the capacitor output voltage into a reasonably constant load voltage. The upshot is that Curtis arrives at a combined buck/boost charge-discharge circuit in which a switching MOSFET replaces the flyback diode in the charging circuit *(Fig. 6b)*. A PIC microcontroller integrates control and most of the necessary peripherals.

Microchip worked with AMSAT-NA, the not-for-profit private organization that develops amateur-radio satellites. AMSAT's next big project, the Eagle satellite, is slated for launch in March 2009. To make Eagle function for decades, it will have a power system based on this work that combines solar panels, lithium-ion batteries, and ultracaps in an integrated power system that will optimize the use of each of those components.