designfeature *By Graham Prophet, Editor*

SUPERCAPS *FOR* SUPERCACHES

SUPERCAPACITORS, ULTRACAPACITORS, ELECTROCHEMICAL CAPACITORS, DOUBLE-LAYER CAPACITORS—ALL ALTERNATIVE NAMES FOR DEVICES FINDING AN EVER-WIDENING RANGE OF APPLICATIONS.

Energy-storing supercapacitors have electrical parameters and occupy a functional position between ordinary capacitors and batteries; you use the components primarily as power sources or reserves. Although you use them to store energy, supercapacitors' characteristics differ fundamentally from those of batteries. They are useful because their parameters exactly complement some of batteries' shortcomings and also the shortcomings of many other power sources. The "super" prefix refers to a supercapacitor's capacitance-value range; it's around three orders of magnitude higher than that of a conventional electrolytic capacitor in a similar package size. A supercapacitor is, however, still a simple capacitor—a two-terminal component (usually unpolarized) available in a variety of physical formats from surface-mountable coin cells for the smallest devices, to screw-terminal prismatic or cylindrical cans for the largest.

ENERGY/POWER DENSITIES

The idea of an energy cache comes into play for many common applications, especially those complementing batteries. Batteries achieve a high level of total energy stored (energy density). The rate at which they can yield this energy is limited, so they have a rather low "power density." You can most usefully express these units, depending on application constraints, as true density—the energy or power per unit volume—or energy/power per unit of weight. Supercapacitors mirror those parameters; they have a fairly low total energy stored (energy density), but they can quickly yield that energy, exhibiting a high power density (**Figure 1**).

In the simplest cases, therefore, you connect battery and supercapacitor in parallel. The supercapacitor "floats" at the same terminal voltage as the battery. When the load demands a sudden high current peak, it sees a very low supply resistance in the capacitor and a much higher one in the battery, so the charge in the capacitor supplies the current peak. The battery then restores that charge during the period when the load demands a low current.

Virtually all applications employ supercapacitors in the same way: compensating for the shortcomings of a primary power source. In one of the most familiar applications, the memory-maintenance battery on a processor board, the supercapacitor floats on the supply line and provides power to hold up SRAM or other volatile memory in the absence of main system power. In this case, the shortcoming of the power supply is its absence during the critical period. A supercapacitor's advantage over a rechargeable battery cell in this application is that you can treat it as any other component, without the finite life restriction of a battery.

A GSM (Global System for Mobile communications) cellular-phone system typifies a situation in which you supply pulse currents in conjunction with a power source—a battery, for example. Due to the "bursty" nature of the GSM signal, its power demand comprises short pulses of several amps with a much lower current between them. Rather than rate the battery to supply the whole current, you can use a supercapacitor to handle the peaks. Because of their physical dimensions, supercapacitors are not an option for today's handsets. But for the many applications (telemetry, for example) that use GSM transceivers in power- but not space-constrained situations, the combination can raise efficiency.

Moving up the power scale, the automotive environment provides a range of possible applications. In a conventional car, you can use a supercapacitor to assist with engine starting, reducing the "cranking load performance" rating of the main battery. You can also use the devices to provide local, point-of-load support for systems around the car. The dc motor that operates a window lift, for example, might peak at tens of amps (especially if it's stalled). The vehicle's main power system might be perfectly capable of providing that current peak, but if you augment it with a supercapacitor close to the motor, you can reduce the rating-and the weight—of power-supply wiring to the subsystem.

Step up again in power level, and you enter a regime in which the key word is "hybrid." One architecture for the "hybrid car" is that of an internal combustion engine driving a generator with an electric drive motor or motors to propel the vehicle. If you design such a system with a supercapacitor energy cache, the supercapacitor can supply the transient loads of starting and acceleration, and regenerative braking can recharge it. Aside from the efficiency of recovering the energy of braking, you would be able to run the internal combustion engine at nearly constant speed and power output. In this mode, I-C engines are at their most efficient; also, under the dynamic loads of acceleration, they emit their highest pollution levels.

AT A GLANCE

- ▷ Supercapacitors increase a power source's efficiency and ability to handle peak loads.
- ▷ Supercapacitors can significantly extend battery life in applications that require high current pulses.
- ▷ Use series/parallel arrays to operate at high voltages.
- ▷ Device ESR often limits low-power designs; total stored charge dominates high-power designs.

Likewise, in traction systems in trains and metro systems, supercapacitors may find further application. The opportunity for a cache on an individual vehicle is obvious, but a "systemwide" possibility also exists.

The term "hybrid" also applies to power-generation systems. Some proposals for future environmentally friendly systems rely heavily on supercapacitor caches to overcome either the primary energy source's inability to supply peak demand (such as fuel cells) or the inherent uneven supply characteristics (such as wind power).

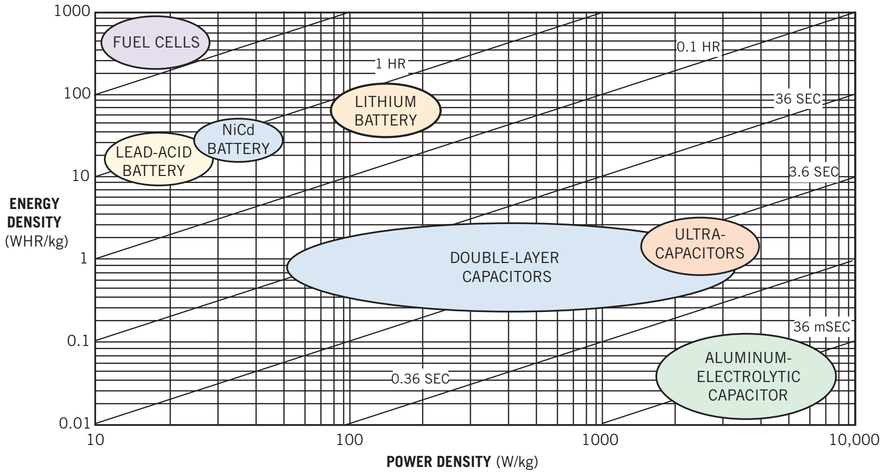


Figure 1 Graphing energy density against power density, conventional batteries occupy the top-left position, and conventional aluminum-electrolytic capacitors occupy the bottom-right. Supercapacitors bridge the space between. Diagonal lines are lines of equal discharge time into a specified load (courtesy Maxwell Technologies).

Somewhere in that power spectrum, then, you may find an application for a supercapacitor. You can also partition the spectrum into "standby supply" or "load leveling" (pulse- or peak-load absorbing) uses.

AVX, with its BestCap range, is one of the companies citing the GSM waveform as a good example of using a supercapacitor in a "light" power application. In such applications, BestCap can extend the effective life of the battery, says Scot Tripp, project director of technology development. The GSM signal requires a current pulse of as much as 2A for 500 µsec (at a 4-msec repetition rate); a conventional battery reaches its end-of-life (or end-of-charge-cycle) point when the voltage from the battery under this pulse load falls below the minimum level necessary for the circuit to operate. Using a supercapacitor means that the battery does not "see" this pulse, so you can use more of the battery's overall capacity before it reaches minimum voltage (**Figure 2**). A secondary benefit is that the pulse discharge of the battery reduces its efficiency; so, with a supercapacitor, the real capacity—not just the effective capacity—increases slightly. AVX claims that BestCap's use of an electrolyte that yields positive hydrogen ions, the most mobile species possible, leads to a very low ESR (equivalent series resistance) of tens to hundreds of milliohms (**Figure 3**).

The general process of designing with a supercapacitor begins with working out the energy you need from the device every discharge cycle, together with the knowledge of the acceptable endpoint voltage for correct circuit operation. You then look at the exponential dV/dt curve for the capacitor and the load you are supplying—as well as published graphs of your chosen device's available capacitance versus pulse width—to arrive at a component value. But, says Tripp, for many lower power applications, this process is barely worth the trouble: "It's much quicker to just try out one of the most popular sizes and monitor the voltage-discharge curve. With typical applications, you won't see the discharge curve at all. The initial drop due to the supercapacitor's ESR, as the capacitor begins to supply the pulse load, is much more significant; the actual capacitance value is somewhat irrelevant." AVX's most popular size devices are 30 and 60 mF. Limitations are that, because the devices have an upper temperature bound of 70°C, you cannot reflow-solder them, and there is a (reversible) rise of ESR below −20°C. AVX packages the devices as rectangular, sealed metal cans measuring 28×17 or 48×30 mm and ranging in thickness from 2.9 to 6.1 mm.

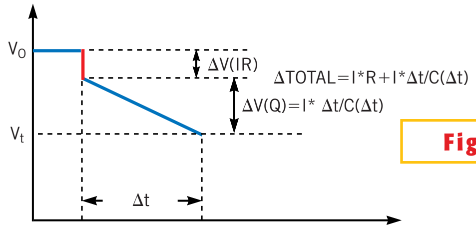


Figure 2

When you connect a load to the supercapacitor, you first see a voltage drop due to resistive losses in the unit's internal ESR (ΔV(IR)); then, you see the beginning of the exponential drop as the capacitor discharges into the load (ΔV(Q)) (courtesy AVX).

Cooper Bussmann also constructs its PowerStor capacitors differently from many devices on the market. The devices use carbon electrodes but in a foamed aerogel form, which also gives very low ESR. The company credits a new electrolyte formulation with extending the cell voltage to 2.5V. Cooper's field applications engineer Chris Likely notes that you can use the devices to overcome the current limits for power drawn over a PCMCIA connector, which is normally rated at 1A; a supercapacitor in the card means that you never see peak loads across the interface. Likely also cites an example in which derating the devices from 10^6 cycles at rated voltage to 10^4 cycles at 4.5V was regarded as acceptable: The device was used as the quickly charged energy reserve for a miniature "Hot Wheels" toy. PowerStor devices come in a number of series for low- and high-power applications.

Japanese company Elna produces a range of surface-mount coin-cell batteries for data retention in consumer products. It also manufactures screw-terminal can types reaching 4000F (at 2.3V, with an ESR of 3 mΩ, and measuring 89 mm in diameter and 130 mm long). Sales manager Hiro Imai notes that the lifetimes of these devices are approaching the demands of the automotive industry, but progress is still limited by temperature range, especially at the low end; the effective lower limit is −25°C. Nevertheless, Imai says, there is considerable interest in the 4000F unit; you can charge it at 100A. The derating curve is, he adds, logarithmic; a lifetime of 32,000 hours at 20°C reduces to 1000 hours at 70°C.

TRACTION APPLICATIONS

Concentrating on the high-power end of the supercapacitor spectrum, Epcos brands its products "UltraCaps" and has recently introduced a second-generation series of products (**Figure 4**). The com-

SUPERCAPACITOR FUNDAMENTALS

The basics of a supercapacitor are no different from those of any other capacitor, and the relationship you learned in high school is just the same: Capacitance varies directly with the area of the parallel plates and inversely with the distance between the plates of the capacitor. Supercapacitors achieve their very high values by maximizing the effective area of the "plates" in their structures and by reducing the effective separation between the plates to molecular dimensions. Most commercial devices employ carbon as an electrode material, exploiting that element's well-known ability to present a very high surface area in finely divided, granulated, or powder forms.

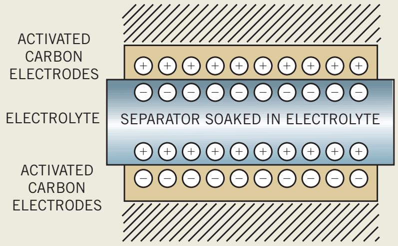


Figure A

When you place a potential on the terminals of a double-layer electrochemical capacitor, charge accumulates on the surface of the carbon electrodes and is balanced by ions drawn from the separating electrolyte (courtesy Epcos).

Electrical contacts comprise two carbon (cloth or powder) electrodes. You place a separator material between them that carries an electrolyte that readily provides high concentrations of mobile ions. When you place a potential across the resulting "sandwich," ions migrate toward charges of opposite polarity on the carbon electrodes (**Figure A**). The phase boundary between the electrode and the electrolyte is the dielectric layer of the capacitor and is only a few nanometers thick. Across this phase boundary are two layers of excess charge and opposite polarity, called the electrochemical double layer. The double layer constitutes a capacitor. This structure is mirrored on the other side of the separator layer but with reversed polarities. Internally, therefore, the structure is actually two capacitors that are series-connected via the conducting electrolyte.

As an electrochemical device, the supercapacitor has a significant ESR at dc; this parameter is key, and manufacturers are constantly striving to reduce it. Manufacturers often quote supercapacitor ESR at, say, 1 kHz, where it is at a minimum but may have little useful capacitance. You need to carefully interpret the data sheet to derive both capacitance and ESR at the exact point you propose to operate the component.

In designing in a supercapacitor, it is important to note that its main parameters vary with environmental and circuit conditions in a way that those of an electronic capacitor do not.

SINGLE VOLTAGE RATING

Most supercapacitors' construction enforces an operating voltage limit of around 2.3V, which some manufacturers are working to extend. If you want your design to operate at higher voltage, you must stack the devices in series and, as with any other capacitor, the effective capacitance decreases accordingly. Maintaining the same capacitance at higher voltage therefore requires an array of (individually) larger value devices or a series/parallel array; some manufacturers provide prepackaged arrays of supercapacitors in a single housing to achieve higher ratings. Some units, however, are rated for operation at, say, 3 or 4V. This exercise often involves simple derating, which trades life for the higher voltage. It is useful for applications such as toys, whose reduced lifetime is unlikely to be a constraint.

When you series-connect the capacitors, any mismatch between the individual units manipany produces both individual capacitors and fully designed arrays with passive or active voltage balancing for high-voltage/high-power applications. The capacitors, which Siemens has built into a drive train (the Elfa Drive), are already in use on the streets of Nuremberg, Germany. A hybrid city bus uses them to recover energy in regenerative braking and to return the energy to the drive train for acceleration from standstill. Epcos assembles 325 capacitors of 2700F at 2.3V into an 8.3F capacitor operating at as much as 650V. The company bases new-generation cells on a new electrode and case design, and rates them at 2.5V with a 2.8V peak; they operate over −35 to +70°C. The highest value device is a 5000F unit that weighs just 850g and offers a power density of 7.4 kW/kg, energy density of 5.1 Wh/kg, and ESR of 250 μΩ. You can charge or discharge it at as much as 500A. Peak power density comes in a 200F unit that reaches 16 kW/kg with an ESR of 2 mΩ and a maximum current of 50A.

Epcos product-marketing manager Thomas Dietrich notes that these large traction arrays will require cooling if you use them in the full automotive temperature range—not because they generate much heat internally but to keep their operating conditions within limits while still meeting automotive-environment specifications. Epcos has full Spice-modeling data for the components, can carry out full simulation, and publishes a worksheet detailing the complete design process—including assembling arrays and adding voltage balancing. The company's active balancing circuits use an accurate voltage reference and partially discharge any cell in a stack that is subject to an overvoltage (see **sidebar** "Supercapacitor fundamentals"). From the array's terminals, this process appears as a slightly increased rate of self-discharge.

Figure 3

Using a proton polymer separator in its construction enables AVX's BestCap to achieve ESR values of 20 to 230 mΩ and to extend the useful operating range to maintain as much as 60% of nominal capacitance at pulse widths of 2 to 3 msec.

Maxwell Technologies' Boostcaps come in values of 4 to 2700F at 2.5V. Maxwell recently hosted a daylong seminar on Boostcap applications, yielding papers on automotive uses in cars and buses, including the "mild-hybrid," 42V vehicle architecture, as well as in railway, tramway, UPS, telecommunications-backup, and energy-generation applications. Maxwell's Web site contains a full worksheet for selecting its devices, which it specifies using a 5-sec discharge to 50% voltage rate. It is sometimes difficult to compare products in this sector, because not all devices are specified with identical conditions, and you may need to infer like conditions by interpolating from graphs.

Maxwell business manager Bobby Maher notes that operating the devices at a high frequency—and, for these high-power applications, 100 Hz is high—reduces the available capacitance, but it also reduces ESR. With 42V automotive electronics seemingly receding, Maher sees considerable interest in the mild-hybrid architecture with distributed power support for steering and braking systems. You need 150 to 300F to support the higher power systems, he says, and 5 to 10F for units such as solenoids and door locks. Boostcaps operate usefully at −40°C, though with increased ESR; the company quotes self-discharge at around 30 days to 50% voltage. You can support UPS systems through 5-sec glitches, Maher adds, and a fast-growing application is in power-generating windmills. With power for the windmill's control systems separate from its generated power, you need to support high peak loads to drive the blade-feathering motors.

In contrast, NEC-Tokin concentrates on backup applications reaching 1A, spanning high-impedance uses such as SRAM and timer support, complete microsystem support, and low-impedance applications, such as actuators and valves. Values span 10 mF to 100F, and the construction allows maximum voltage ratings of 12V. NEC's latest introductions are its HV series, which offers 10 to 100F at 2.7V for small motor drives and energy storage in solar-powered systems, and the FG1C series, which takes the company into the large-capacitance

fests itself as unevenly distributed voltage across the capacitors. (By definition, the charge on each will be the same.) There is, therefore, a danger of exceeding the rated voltage on one of the stacks. Most manufacturers' data sheets do not indicate a catastrophic failure mechanism for a supercapacitor taken over its rated voltage; rather, you will see a reduction in lifetime. To combat this problem, you can employ voltage balancing across the stack with either passive or active techniques. Passive balancing involves a resistor network in parallel with the capacitors, in effect setting voltage levels across the capacitors by a resistive divider chain. Active balancing uses semiconductor switches to hold the voltage across any single capacitor within preset limits (**Figure B**).

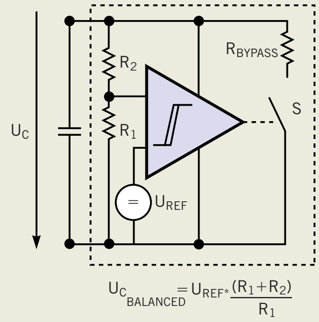


Figure B

In a capacitor array with active balancing, each cell has a comparator, switch, and bleed resistor to prevent the capacitor from exceeding its voltage limit (courtesy Epcos).

POLYMER CAPACITORS

A completely separate strand of supercapacitor research is actively investigating the use of conductive polymers as a charge-storage media. By storing ions in the bulk of polymer materials, rather than on a surface, researchers believe that you can achieve even higher capacitance values. In a manner somewhat analogous to doping in semiconductor materials, polymers can provide sites to accept ions within the organic molecules that comprise the polymers; conduction mechanisms roughly analogous to semiconductor electron/hole propagation provide the conductivity. Researchers are exploring numerous mechanisms and materials, including some hybrids of polymer and existing supercapacitor techniques, such as the use of carbon nanotubes together with the polymer polypyrrole. Among the challenges this technology faces is the ability to achieve commercially useful lifetimes. However, the largest supercapacitor charge-storage capacities yet reported have been in polymer systems.

(100F at 15V) range and offers low ESR of 20 mΩ at 1 kHz for automotive and traction applications.

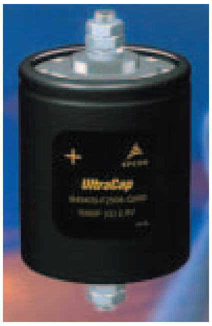


Figure 4

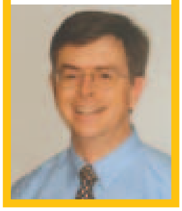
The second generation of Epcos' UltraCap series upgrades electrode and case design with a format designed for incorporation into multicapacitor, series/parallel banks.

Korean supplier NessCap is also concentrating on the automotive sector, although it also produces cells ranging from coin size upward. Its EDLC series ranges from 3 to 5000F, and uprated voltages to 2.7V are available; the company builds modules with multiple cells incorporating active and passive voltage balancing. Fully electric car evaluations have used these modules to augment conventional batteries, which are the main energy reserve. NessCap also produces the intermediate technology of its EnergyCache range. This technology, unlike most supercapacitor structures, employs an electrolyte system that depends on a faradic-oxidation/reduction charge-storage mechanism, so it conceptually lies between other supercapacitors and batteries. It claims higher power density than either and is available in 50, 120, or 2500F for 2.3V operation.

Other products also use internal structures and manufacturing techniques to achieve performance points somewhere between conventional capacitors and supercapacitors. Evans Capacitor's Hybrid device is a polarized capacitor with a tantalum wet anode but an electrochemical-supercapacitor cathode to provide energy densities of as much as $2J/cm^3$ and 0.5 J/g. The company says these hybrids exhibit low ESR, low leakage, and excellent frequency response. Unlike most supercapacitors, they can be supplied to operate to 125V (the higher voltage performance deriving from the electrolytic part of their nature) and come in capacitance values to 0.22F (at 6.3V). Evans also manufactures an electrochemical capacitor called "Capattery," in values reaching 1.5F at 5.5V, or 0.75F at 11V.

Panasonic's GoldCaps comprise several ranges of pc-board-mounting capacitors with values of 0.1 to 2F at 2.3 or 5.5V, targeting a variety of data-retention and -backup functions. The company recently added the Ultra-Power (UP-Cap) device, which it aims at emerging 42V automotive applications. It specifies these devices, which come in cylindrical-can format, at 500 to 2500F and 2.3V and claims a lifetime of 2000 hours at 2.3V and 60°C. Panasonic's automotive-device-marketing specialist Matthias Frey, describing the use of an array of 40 to 50 capacitors in a vehicle, anticipates that the technology will reach the full 75°C rating that the automotive industry would like to have by 2005 or 2006. Panasonic is currently building capacitor arrays to explore automotive applications as special custom projects.□

You can reach Editor Graham Prophet at +44 118 935 1650, fax +44 118 935 1670, e-mail gprophet@reedbusiness.com.



FOR MORE INFORMATION...

For more information on products such as those discussed in this article, go to www.edn.com/info and enter the reader service number. When you contact any of the following manufacturers directly, please let them know you read about their products in *EDN*.

AVX	www.avxcorp.com	*Enter No. 334*
Cooper Bussman (Cooper Electronic Technologies)	www.cooperET.com	*Enter No. 335*
Elna	www.elna.co.jp or www.elna-america.com	*Enter No. 336*
Epcos	www.epcos.com	*Enter No. 337*
Evans Capacitor	www.evanscap.com	*Enter No. 338*
Maxwell Technologies	www.maxwell.com	*Enter No. 339*
NEC-Tokin	www.nec-tokin.net/now/english/index.html	*Enter No. 340*
NessCap	www.nesscap.com	*Enter No. 341*
Panasonic	www.maco.panasonic.co.jp	*Enter No. 342*
Siemens	www.siemens.com	*Enter No. 343*

SUPER INFO NUMBER

For more information on the products available from all of the vendors listed in this box, enter no. 344 at www.edn.com/info.