Technology Brief 8: Supercapacitors as Batteries

As recent additions to the language of electronics, the names ***supercapacitor***, ***ultracapacitor***, and ***nanocapacitor*** suggest that they represent devices that are somehow different from or superior to traditional capacitors. Are these just fancy names attached to traditional capacitors by manufacturers, or are we talking about a really different type of capacitor? The three aforementioned names refer to variations on an energy storage device known by the technical name ***electrochemical double-layer capacitor*** (EDLC), in which energy storage is realized by a hybrid process (Fig. T8-1) that incorporates features from both the traditional electrostatic capacitor and the electrochemical voltaic battery. For the purposes of this technology brief, we will refer to this relatively new device as simply a supercapacitor. The battery is far superior to the traditional capacitor with regard to energy storage, but a capacitor can be charged and discharged much more rapidly than a battery. As a hybrid technology, the supercapacitor offers features that are intermediate between those of the battery and the traditional capacitor. The supercapacitor is now used to support a wide range of applications, from motor startups in large engines (trucks, locomotives, submarines, etc.) to flash lights in digital cameras, and its use is rapidly extending into consumer electronics (cell phones, MP3 players, laptop computers) and electric cars (Fig. T8-2).

Capacitor Energy Storage Limitations

Energy density W' is often measured in watt-hours per kg (Wh/kg), with 1 Wh $= 3.6 \times 10^3$ Joules. Thus, the energy capacity of a device is normalized to its mass. For batteries, W' extends between about 30 Wh/kg for a lead-acid battery to as high as 150 Wh/kg for a lithium-ion battery. In contrast, W' rarely exceeds 0.02 Wh/kg for a traditional capacitor. Let us examine what limits the value of W' for the capacitor by considering a small parallel-plate capacitor with plate area A and separation between plates d. For simplicity, we assign the capacitor a voltage rating of 1 V (maximum anticipated voltage across the capacitor). Our goal is to maximize the energy density W'. For a parallel-plate capacitor $C = \epsilon A/d$, where ϵ is the permittivity of the insulating material. Using Eq. (4.121) leads to

$$W' = \frac{W}{m} = \frac{1}{2m} CV^2 = \frac{\epsilon A V^2}{2md} \qquad \text{(J/kg)},$$

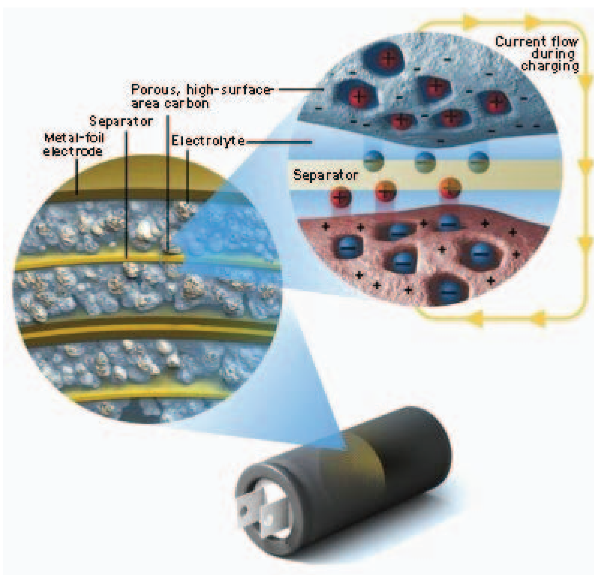

Figure TF8-1: Cross-sectional view of an electrochemical double-layer capacitor (EDLC), otherwise known as a supercapacitor. (Courtesy of Ultracapacitor.org.)

Figure TF8-2: Examples of systems that use supercapacitors.

where m is the mass of the conducting plates and the insulating material contained in the capacitor. To keep the analysis simple, we will assume that the plates can be made so thin as to ignore their masses relative to the mass of the insulating material. If the material's density is ρ (kg/m^3), then $m = \rho A d$ and

$$W' = \frac{\epsilon V^2}{2\rho d^2} \qquad \text{(J/kg)}.$$

To maximize W', we need to select d to be the smallest possible, but we also have to be aware of the constraint associated with dielectric breakdown. To avoid sparking between the capacitor's two plates, the electric field strength should not exceed E_{ds}, the dielectric strength of the insulating material. Among the various types of materials commonly used in capacitors, mica has one of the highest values of E_{ds}, nearly 2×10^8 V/m. Breakdown voltage V_{br} is related to E_{ds} by $V_{\text{br}} = E_{\text{ds}} d$, so given that the capacitor is to have a voltage rating of 1 V, let us choose V_{br} to be 2 V, thereby allowing a 50% safety margin. With $V_{\text{br}} = 2$ V and $E_{\text{ds}} = 2 \times 10^8$ V/m, it follows that the smallest value d should have is 10^{-8} m, or 10 nm. For mica, $\epsilon \simeq 6\epsilon_0$ and $\rho = 3 \times 10^3$ kg/m^3. Ignoring for the moment the practical issues associated with building a capacitor with a spacing of only 10 nm between conductors, the expression for energy density leads to $W' \simeq 90$ J/kg. Converting W' to Wh/kg (by dividing by 3.6×10^3 J/Wh) gives

$$W' = 2.5 \times 10^{-2} \qquad \text{(Wh/kg)},$$

thereby demonstrating the energy storage limitation of traditional capacitors.

Energy Storage Comparison

The table in the upper part of Fig. T8-3 displays typical values or ranges of values for each of five attributes commonly used to characterize the performance of energy storage devices. In addition to the energy density W', they include the power density P', the charge and discharge rates, and the number of charge/discharge cycles that the device can withstand before deteriorating in performance. For most energy storage devices, the discharge rate usually is shorter than the charge rate, but for the purpose of the present discussion we will treat them as equal. As a first-order approximation, the discharge rate is related to P' and W' by

$$T = \frac{W'}{P'} \, .$$

We note from the information given in Fig. T8-3 that supercapacitors are capable of storing 100 to 1000 times more energy than a traditional capacitor, but 10 times less than a battery, and they can discharge their stored energy in a matter of seconds, compared with hours for a battery. Moreover, the supercapacitor's cycle life is on the order of 1 million, compared with only 1000 for a rechargeable battery. Because of these features, the supercapacitor has greatly expanded the scope and use of capacitors in electronic circuits and systems.

Future Developments

The upper right-hand corner of Fig. T8-3 represents the ideal energy storage device with $W' \simeq 100$–1000 Wh/kg and $P' \simeq 10^3$–10^4 W/kg. The corresponding discharge rate is $T \simeq 10$–100 ms. Current research aims to extend the capabilities of batteries and supercapacitors in the direction of this prized domain of the energy-power space.

Energy Storage Devices

Feature	Traditional Capacitor	Supercapacitor	Battery
Energy density W' (Wh/kg)	$\sim 10^{-2}$	1 to 10	5 to 150
Power density P' (W/kg)	1,000 to 10,000	1,000 to 5,000	10 to 500
Charge and discharge rate T	10^{-3} sec	$\sim$ 1 sec to 1 min	$\sim$ 1 to 5 hrs
Cycle life N_c	∞	$\sim 10^6$	$\sim 10^3$

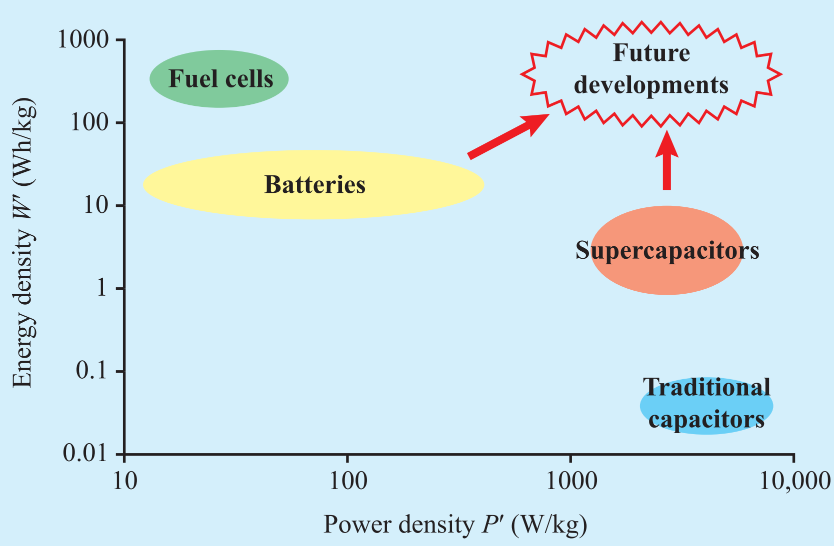

Figure TF8-3: Comparison of energy storage devices.