High power supercapacitors enable new pulse, bridge and main power applications

Overview

The ultimate energy storage device should have high energy density that can be released rapidly. High energy batteries have been developed as single use or rechargeable systems but typically require minutes to hours to discharge, not seconds. For high power, standard capacitors are capable of discharging rapidly but have low energy density.

First generation supercapacitors also referred to as ultracapacitors and Electrochemical Double Layer Capacitors (EDLC), have relatively high energy density but also very high ESR (equivalent series resistance) and are therefore only used in very low power memory backup applications.

New Eaton supercapacitors have been developed incorporating both the high energy density of batteries (100 times the energy of electrolytic capacitors) and the high power of capacitors (10 to 100 times the power of batteries) as shown in Figure 1.

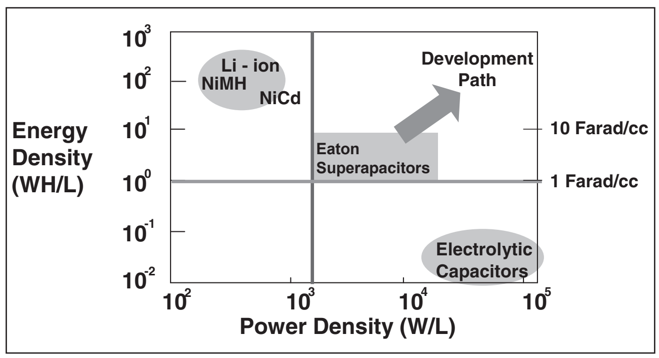

Figure 1. Power density vs. energy density

Imagine the possible uses of a high energy, high power energy storage device, sometimes referred to as "A solution looking for a problem". Many engineers have and these new supercapacitors are finding their way into a wide range of new applications. In many instances, the supercapacitor is the enabling technology for these new applications.

High power supercapacitors are designed similar to electrolytic capacitors however supercapacitors use high surface area carbon for accumulation of charge as opposed to the low surface area foils in electrolytic capacitors. An electric double layer is formed at the interface of the solid carbon electrode and liquid electrolyte. Eaton's supercapacitors use aerogel carbon as the active material, while the rest of the industry typically uses activated carbon. Aerogel carbon is known for its high level of purity, high usable surface area and high electrical conductivity. Key features for aerogel supercapacitors include:

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- Extremely low ESR for high power and low loss during operation
- High energy density for long run-time
- Ultra low leakage current (can hold a charge for several weeks)
- Wide operating temperature range
- Can be cycled hundreds of thousands of times with very fast charge and discharge rates, as opposed to only hundreds of cycles for batteries.

Eaton supercapacitors have reasonably high energy density compared with rechargeable batteries. In some applications, batteries have far more energy than is required, take too long to charge, do not like to be held fully charged or shallow discharged (NiCd memory effect) on a continuous basis without periodic maintenance, or do not cycle long enough. In applications such as electronic toys, UPS sys-tems or solar charged lighting, supercapacitors have replaced batteries as a better alternative.

Eaton supercapacitor designs include 2.5 V radial leaded cylindrical and 5 V leaded rectangular devices. Large cylindrical and prismatic designs up to 2500 F are also available.

These supercapacitors have characteristics that make them ideal for applications in electronic circuits, portable devices and systems powered by batteries, fuel cells or dc power supplies. The supercapacitors can be used in applications ranging from low tech (toys) to medium tech (electronic control systems, valves and solenoids) to high tech (microprocessor- controlled devices).

Eaton supercapacitors provide:

- Pulse power characterized by short, high current pulses delivered to a load, allowing the use of a smaller power supply or battery
- Hold-up or bridge power to a device or equipment for seconds, minutes or days when the main power or battery fails or when the battery is swapped out
- Main power or battery replacement

Pulse power

A growing number of applications today require short bursts of power, including phones, wireless modems, radio transceivers, motors, valves and solenoids. An engineer now has two battery design options: (1) use a larger battery (or power supply) capable of the high pulse current or (2) use a smaller battery (or power supply) with higher energy density (at the expense of lower power density) configured in parallel with a high power supercapacitor.

The second option is known as a battery-supercapacitor hybrid configuration and results in a high energy / high power device with smaller size, lower weight and lower cost than the first option of a larger battery or power supply.

Pulse power calculations

Pulse power applications are characterized by a relatively low value of continuous current with brief, high current requirements. Applications have pulses that range from less than 1 msec to as high as a few seconds, and the pulse current can be orders of magnitude higher than the continu-ous or background current. The duty cycle of the pulses is usually low, typically less than 20%.

A worst-case design analysis assumes that the supercapacitor is the sole supplier of current during the pulse. In this case the total drop in working voltage in the circuit consists of two components: (1) instantaneous voltage drop due to the internal resistance of the supercapacitor, and (2) capacitive drop during the discharge pulse. This relationship is:

$V_{drop} = I_{load} (R + t/C)$
V_{drop} = Change in voltage (V)
I_{load} = Load current (A)
R = Internal resistance (Ohms)
t = Time (sec)
C = Capacitance (Farads)

For a small voltage drop, this equation shows that the supercapacitor must have low R and high C. For many pulse power applications where t is small, the value of R is more important than the value of C. For example a lower ESR 1.5 F supercapacitor has an estimated internal resistance of 0.060 Ω. For a 0.001 sec pulse, t/C is less than 0.001 Ω. Even for a 0.010 sec pulse, it is only 0.007 Ω. Clearly, the value of R (0.060 Ω) dominates the outcome of V_{drop} in Equation (1) for short pulse power applications. Where t is large, 3 seconds for example, t/C = 2 Ω and now C dominates the outcome of V_{drop} in Equation (1).

Ultra thin (down to 1 mm), low ESR supercapacitors have been developed for GSM / GPRS applications, including wireless PCMCIA modems. Type II PCMCIA cards have only 5 mm inside clearance, but with a two-sided 1 mm circuit board, the supercapacitor height restriction can be as low as 2 mm. New thin supercapacitors using flexible packaging have been developed with very low ESR. The PCMCIA specification allows less than 1 A of current to flow from the notebook battery to the PC card but GSM / GPRS transmis-sions requires up to 2 A. GSM transmits for approximately 0.6 milliseconds every 4.6 milliseconds then runs at lower currents for receive and standby modes in the remaining 4 milliseconds. The supercapacitor is charged by the excess or available battery current in 4 milliseconds between the 0.6 millisecond discharges.

The GPRS protocol allows higher transmission rates with double to quadruple transmit times of GSM. Although low ESR is the primary design criteria to minimize the voltage drop from the supplied voltage (3.3 V) to the minimum volt-age required for the power amplifier (3 V), supercapacitors have significantly more capacitance than other capacitor technologies allowing the extended pulse lengths of GPRS.

An example of an application requiring more capacitance to minimize voltage drop during a pulse discharge is digital cameras. Low ESR supercapacitors enable alkaline batteries to last longer in digital cameras. The challenge is to run longer on fewer, low power alkaline batteries. The high power requirement of the zoom motor causes alkaline batteries to fail before they have released all of their stored energy. Due to the relatively long (several seconds) discharge pulse requirement for the zoom motor, larger capacitance (6 to 10 F) supercapacitors have been found to extend the useful life of the alkaline batteries.

Figure 2 compares 2 AA alkaline batteries (top) to 2 AA alkaline batteries connected in parallel to a single 6 F supercapacitor (bottom), without additional circuitry. To simulate the zoom motor in a digital camera, each system was discharged at 4 Watts for 3 seconds every 3 minutes.

This sequence resulted in 55 zoom cycles every 10,000 seconds. The voltage drop was larger for the battery (left) compared to the hybrid (right). The battery-supercapacitor hybrid ran approximately three times longer than the battery alone.

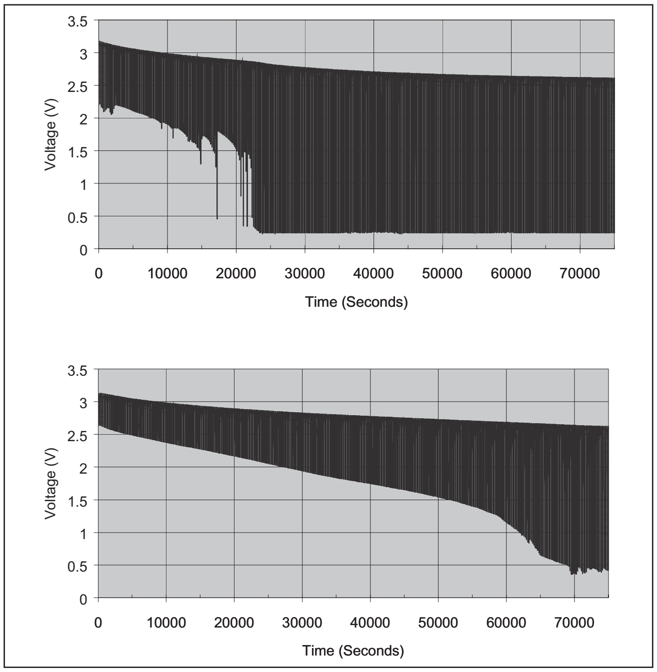

Figure 2. 2 AA alkaline batteries (top) to 2 AA alkaline batteries connected in parallel to a single 6F super-capacitor (bottom)

Hold-up or bridge power

Hold-up power applications are characterized by a short, high current or "bridge power" pulse followed by a longer, low current drain. Standard memory backup type supercapacitors are capable of the low current drain but unable to handle the short, high current pulse due to their high ESR. During the pulse, the system voltage will drop below the lower voltage allowed by the device's electronics and the system will shut down. For these applications, new low ESR supercapacitors are capable of handling the high current pulse to minimize the voltage drop.

Bridge power examples include solid-state hard drives and portable data terminals. In the solid-state hard drive, all memory is stored in DRAM. When main power is lost, the information in the DRAM must be transferred to non-volatile memory. This requires a high discharge current for a num-ber of seconds after which the device requires a very low current to maintain the system.

Portable data terminals use supercapacitors to "bridge" between swapping of batteries when the device is in operation and not simply in sleep mode. Batteries can also fall out or become temporarily disconnected if the device is dropped. To prevent loss of data, supercapacitors are designed to provide continuous power to the portable data terminal until it is able to safely power down or the battery is swapped or reconnected.

Main power

The energy density for today's supercapacitors has grown substantially and is now only 3 to 10 times lower than some rechargeable batteries (i.e. lead-acid), but with the added benefits of nearly infinite cycle life, very short recharge times and very high power density. Supercapacitors can be charged directly from alkaline batteries, solar panels or other DC power sources. As a result some portable and remote applications are now using supercapacitors in place of rechargeable batteries.

The toy cars and airplanes that claim "Charge in under 10 seconds" all use supercapacitors as the main power source and alkaline batteries to charge them. The fast charge is particularly important for children as their attention spans are not long enough to wait for batteries to charge.

Solar charging is particularly important in remote applications. With 365 charge/discharge cycles per year, rechargeable batteries require frequent replacement. These applications include remote monitoring systems, transmitters, lighting and traffic signs. New portable applications currently under development include flashlights, remote controls and radios all charged using solar power.

Another main power application that is ideal for supercapacitors is local area or restaurant pagers. These pagers run for up to two hours while the patron is waiting for a table. After being returned to the host/hostess, the pager only requires a 10 second charge for the next customer. Nickel cadmium batteries perform poorly in these shallow depth-of-discharge applications due to their "memory" effect (loss of capacity due to continuous shallow discharges). As a result, constant battery replacement is no longer an issue or added cost when supercapacitors designed to last the life of the product are used for main power.

Design considerations

Energy and capacitance calculations

To determine your supercapacitor requirements, four key parameters are required:

- Working voltage, V_{wv}, in Volts
- Minimum voltage, V_{min}, in Volts
- Average discharge current, I_{load}, in Amps
  (if necessary convert power, P, in Watts, to current, I_{load}, where $I_{load} = P/V_{avg}$)
- Discharge time, t, in seconds

One can estimate the value of a supercapacitor needed for most applications (Note 1). This calculation equates the energy needed during the discharge period to the energy decrease in the supercapacitor, from

V_{wv} to V_{min}.

Energy needed for discharge:

$$1/2\ I_{load}(V_{wv} + V_{min})\ t \quad \text{(Joules)}$$

Energy decrease in supercapacitor:

$$1/2\ C(V_{wv}^2 - V_{min}^2) \quad \text{(Joules)}$$

Therefore, the minimum capacitance value that guarantees hold-up to V_{min} is:

$$C = \frac{I_{load}(V_{wv} + V_{min})t}{(V_{wv}^2 - V_{min}^2)} \quad \text{in Farads}$$

Voltage balancing

When the working voltage of the circuit exceeds the maximum operating voltage rating of a single supercapacitor, a series configuration is required. Often, the series arrangement requires balancing to ensure equal voltage sharing. Either passive or active balancing can be used to maintain similar voltages among supercapacitors where the leakage currents may be slightly different.

Passive balancing uses equal value resistors in parallel with the supercapacitors. Using high value resistors, small currents are allowed to flow between the supercapacitors to maintain similar voltages. Resistors with high values result in lower leakage currents on the order of microamperes, an important design consideration for hybrid battery-supercapacitor solutions. Lower value resistors lead to higher leakage currents but faster voltage equilibration of mismatched components, and can be used where the main power is delivered by a continuous source of power (power supply or fuel cell).

Active balancing uses a microprocessor to measure voltage differences and open gates allowing equilibration to occur quickly but only when needed. Active balancing does not add significant current leakage in the final configuration, but comes at a higher price than passive balancing. High relia-bility applications, with higher voltages (> 5 V), typically use active balancing.

Summary

High power, high energy supercapacitors offer solutions for applications by providing pulse, hold-up, or main power.

Note 1: A supercapacitor calculator program is available online at https://tools.eatonelectronics.com/ and can be used to predict required energy, capacitance and ESR for any application.

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