Supercapacitors for Transportation Applications

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Source: US Defence Logistics Agency
# Types of capacitor

<table>
<thead>
<tr>
<th>Traditional Capacitors</th>
<th>Supercapacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Have a dielectric between the electrodes</td>
<td>Have an electric double layer between electrolyte and each electrode (two capacitors in series)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No electrolyte</th>
<th>Electrolyte to contact/ heal thin dielectric on porous electrode</th>
<th>Has electrolyte to create double layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No dielectric</td>
</tr>
</tbody>
</table>

![Diagram showing types of capacitors: Pico Farads, Micro Farads, and Farads.](image)

More area and one hundredth of the thickness = up to 1000 times the capacitance.
A supercapacitor (EDLC) is a symmetrical device.

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.

\[ E = \frac{1}{2} CV^2 \]

\[ P = \frac{1}{4R} V^2 \]
Hybrid SCs versus EDLC

b. Electric Double Layer Capacitor

\[
\frac{1}{C_{EC}} = \frac{1}{C_1} + \frac{1}{C_2}
\]

(Activated Carbons as Electrodes)

c. Asymmetric Capacitor

\[
C_1 \ll C_2, \quad C_{EC} \approx C_1
\]

(Activated Carbons + Battery Type as Electrodes)
In any battery the internal resistance keeps increasing with the depth of discharge.
In a supercapacitor equivalent series resistance is relatively constant over the depth of discharge.
Given this situation, the maximum current and power deliverable by a SC is only limited by its voltage.
# Comparison of practical devices

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Manufacturer</th>
<th>Capacitance</th>
<th>Voltage Rating</th>
<th>ESR (mΩ)</th>
<th>Total Energy Storage Capability</th>
<th>Maximum possible output power (load resistance=ESR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercapacitor</td>
<td>LS Mtron</td>
<td>3000 F</td>
<td>2.7 V</td>
<td>0.36</td>
<td>10.9 kJ</td>
<td>6.07 kW</td>
</tr>
<tr>
<td>Electrolytic capacitor</td>
<td>Cornell-Dubilier</td>
<td>2200 μF</td>
<td>50 V</td>
<td>71</td>
<td>2.75 J</td>
<td>8.8 kW</td>
</tr>
<tr>
<td>Hybrid supercapacitor</td>
<td>Samwha Electric</td>
<td>7500 F</td>
<td>2.8 V</td>
<td>0.8</td>
<td>29.4 kJ</td>
<td>2.45 kW</td>
</tr>
<tr>
<td>Disposable energizer cell – C type</td>
<td>Energizer</td>
<td>8.35 Ah</td>
<td>1.5 V</td>
<td>324 mΩ</td>
<td>45.1 kJ</td>
<td>1.73 W</td>
</tr>
<tr>
<td>Li-ion cell</td>
<td>Panasonic</td>
<td>3.4 Ah</td>
<td>3.6 V</td>
<td>50 mΩ</td>
<td>11.52 kJ</td>
<td>64.8 W</td>
</tr>
</tbody>
</table>
An overall comparison – Key specifications based

<table>
<thead>
<tr>
<th></th>
<th>Power density max</th>
<th>Energy density max</th>
<th>Cycles</th>
<th>Low temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-ion battery</td>
<td>3 kW/kg</td>
<td>200 Wh/kg</td>
<td>500-1000</td>
<td>0°C to 60 °C</td>
</tr>
<tr>
<td>Supercapacitor</td>
<td>10 kW/kg</td>
<td>10 Wh/kg</td>
<td>1,000,000</td>
<td>-40°C to 80 °C</td>
</tr>
<tr>
<td>Hybrid supercapacitor</td>
<td>5 kW/kg</td>
<td>25 Wh/kg</td>
<td>&gt;10,000</td>
<td>-20°C to 60 °C</td>
</tr>
</tbody>
</table>
Depth of discharge and cycle life

![Graph showing depth of discharge and cycle life comparison between battery, supercapacitor (EDLC), and hybrid supercapacitor.]
Battery and Supercapacitor – Pros and Cons

**Supercap Pros**
- High Power → Low Cost/KW
- Fast charge acceptance
- High Cycle Life (1 million) → Low Cost/cycle
- >95% Charge Efficient and Charge Acceptance for life
- Wide temp operating range -40°C to 80°C
- Extends Battery Life
- DOD/SOC do not affect life

**Battery Pros**
- High Energy
- Low Cost / Whr
- Widely Available
- People know batteries

**Supercap Cons**
- High Cost per Whr (when not sized properly)
- DC/DC converter required
- Self discharge
- Low ultracap literacy rate
- Full value proposition requires crossing silos

**Battery Cons**
- Low Power
- High Cost / KW
- Close attention to DOD/SOC required
- Recycling/safety issues
- Poor low temp performance
- 70-80% Efficient
- Charge acceptance quickly falls based on battery age and DOD
Self-discharge of supercapacitors

- All types of supercapacitors have higher self discharge compared to Li-ion batteries.
- However, if you design a system for short-term use of pre-stored energy SCs are still ok.
- Hybrid types have better performance than symmetric devices.
Self Discharge

LIC Vs EDLC for Self Discharge

Ambient temperature: 25°C

Source: JSR Micro
In general, SCs have lower ESR than the electrolytic capacitors, but their DC voltage rating is very low.

<table>
<thead>
<tr>
<th>ENERGY STORAGE LIMIT</th>
<th>CAPACITOR TYPE</th>
<th>MANUFACTURER</th>
<th>CAPACITANCE (µF/F)</th>
<th>TERMINAL VOLTAGE (V)</th>
<th>SHORT CIRCUIT CURRENT (A)</th>
<th>ESR (m Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 1J</td>
<td>Electrolytic</td>
<td>RSS</td>
<td>2200 µF</td>
<td>16</td>
<td>104</td>
<td>153</td>
</tr>
<tr>
<td>1-5 J</td>
<td>Supercap</td>
<td>Maxwell</td>
<td>1 F</td>
<td>2.7</td>
<td>3.85</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cap-xx</td>
<td>2.4 F</td>
<td>2.3</td>
<td>115</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Electrolytic</td>
<td>Cornell Dubilier</td>
<td>2200 µF</td>
<td>50</td>
<td>704</td>
<td>71</td>
</tr>
<tr>
<td>5-50 J</td>
<td>Supercap</td>
<td>Maxwell</td>
<td>10 F</td>
<td>2.5</td>
<td>14</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cap-xx</td>
<td>1.2 F</td>
<td>4.5</td>
<td>112.5</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nesscap</td>
<td>10 F</td>
<td>2.3</td>
<td>33</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Electrolytic</td>
<td>Cornell Dubilier</td>
<td>82,000µF</td>
<td>16</td>
<td>1441</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VICOR</td>
<td>270 µF</td>
<td>200</td>
<td>325</td>
<td>614</td>
</tr>
<tr>
<td>Above 50 J</td>
<td>Supercap</td>
<td>Maxwell</td>
<td>350 F</td>
<td>2.7</td>
<td>840</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nesscap</td>
<td>120 F</td>
<td>2.3</td>
<td>144</td>
<td>16</td>
</tr>
</tbody>
</table>
### Nomenclature

<table>
<thead>
<tr>
<th>Traditional Capacitors</th>
<th>Supercapacitors (symmetrical – usually carbon on a metal electrode on either side)</th>
<th>Hybrid supercapacitors (one supercap electrode + one battery electrode)</th>
<th>Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical Double Layer Capacitors EDLC</td>
<td>Asymmetric Electrochemical Double Layer Capacitors AEDLC</td>
<td>When based on a lithium-ion battery – “lithium capacitor” or “Lithium-ion capacitor”</td>
<td></td>
</tr>
<tr>
<td>Ultracapacitors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>When based on a lead acid battery – trade name</td>
<td></td>
</tr>
</tbody>
</table>

**STORES MORE ENERGY Wh/kg or Wh/l**

**DELIVER MORE POWER W/kg or W/l**
Traditional Applications of Supercapacitors

• In general supercapacitors have much less energy density than batteries

• But their power delivery capability (Watts/kg) is quite high compared to batteries

• Large supercapacitors have very low ESR in the range of few mΩs to fractional mΩs

Common supercapacitor applications are in
• UPS systems
• Wind turbine systems
• Electric vehicles/ Fork lifts/ Hybrid buses
• Utility voltage stabilizer systems
• Photo voltaic systems
• Memory back up systems

• In many of these applications battery-supercapacitor hybrid systems are used
Which characteristics of ESS are useful in transportation?

- All transportation systems have several essential engineering components:
  - A prime mover
  - An energy storage system (ESS) to drive the prime mover
  - A transmission system
- When the systems become electrically driven we require:
  - An energy storage system
  - Electric wheel motors and the controller units
  - Charging system
- In EVs, HEVs and PHEVs energy storage systems can be in few common forms:
  - Battery packs
  - Battery –SC hybrids
  - Supercapacitors
  - Fuel cells
- Given the above, following primary specifications matter in [an electrical] energy storage system:
  - **Energy density** – dependent on the device technology
  - **Power density** - dependent on the open circuit voltage and the internal resistance
  - **Useful temperature range** - dependent on the device technology
  - **Cycle and calendar life** - dependent on the device technology
  - **Self discharge** - dependent on the device technology

In supercapacitors, power density is very high, and the operational temperature range is wider and cycle life is very much larger than batteries.
Three main market segments for supercapacitors

- **Consumer**
  - Burst Power
  - Battery Life Extension
  - Quick Charge

- **Industrial**
  - Burst Power
  - Regenerative Power
  - Back up Power

- **Transportation**
  - Burst Power
  - Regenerative Power

In addition there are many new and non traditional applications – i.e SCA Techniques
Supercapacitors in transportation systems

- In transportation systems, energy source should be as large as possible
- An internal combustion engine (ICE) and the fuel tank combination still wins - due to high energy density of fossil fuels
- In electric vehicle arena, electrical specifications of the ESS come into play
- Very high power density (result of lower ESR) of a SC bank, it helps in quick acceleration
- However, lower energy density means a lower driving range
- Batteries are having much lower cycle life than SCs
- Internal resistance of battery keeps increasing
  - With the age
  - With the depth of discharge
  - (Internal resistance increases internally dissipated heat in the ESS)
- In SCs, due to constant ESR, heat dissipation due to ESR does not matter
- Very long life cycle of SCs is a definite advantage.

- Only major disadvantage of SCs is the high manufacturing cost
SCs in Transportation - Three major application areas

- Hybrid –electric transit buses [In USA and China]
- Electric braking systems in passenger cars
- Stop-go hybrid vehicles

**Stop-Start Systems**

Engine shuts off when car stops (red light). SC provides braking power. AGM lead acid batteries broadly adopted. SC perform better in operational lifetime. Cost parity between AGM and SC will be reached soon. AGM 70% charge acceptance in 8 month (loxus, 2014).

**Energy Recovery**

SC perform better than lithium batteries. 80% energy can be recovered as opposed to 30% in batteries. Energy stored can be released when accelerating.

**Power Back-up**

Last resource for power in electronically-controlled back. Need for rapid discharge

22 x 100F ultracaps are used in the Toyota Prius II’s electronically controlled brake.

Production began 2007

**Power Buffering**

Fuel cells and battery degrade faster when exposed to frequent high power demands. Fuel cells efficient operation point is at constant power. 17% efficiency over a pure FC system. Addresses of PEMFC degradation (Imperial College 2013).

Source credit: ID TechEx
Automotive sector companies utilizing supercaps

<table>
<thead>
<tr>
<th>Company</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continental Automotive Systems</td>
<td>Maxwell-powered voltage stabilization system (VSS) will be a standard feature on 2016 Cadillac ATS and CTS sedans and ATS coupes, excluding the ATS-V, CTS-V and CT6 models.</td>
</tr>
<tr>
<td>PSA Peugeot Citroën</td>
<td>Peugeot 308 and other diesel platforms use supercapacitors in stop start systems.</td>
</tr>
<tr>
<td>Bosch</td>
<td>Supercaps have become the cheapest high power energy storage technology for power discharges below 13 seconds and below 250°C, that means all sports cars and cold weather countries.</td>
</tr>
<tr>
<td>Toyota BMW</td>
<td>Toyota’s TS040 winner racing car integrates supercapacitor technology. BMW-Toyota sports car partnership may integrate the technology in the future.</td>
</tr>
<tr>
<td>Automobili Lamborghini S.p.A.</td>
<td>Incorporated support a stop-start idle-elimination system in all Lamborghini’s Aventador cars.</td>
</tr>
<tr>
<td>Honda</td>
<td>Honda developed a supercapacitor system to buffer high power in their FCX fuel cell car platform.</td>
</tr>
<tr>
<td>Mazda</td>
<td>Mazda uses supercapacitors in their i-Eloop energy recovery system.</td>
</tr>
</tbody>
</table>

Source credit: ID TechEx
Transportation Applications

Truck starters which allow replacing several lead acids and operating down to $-40^\circ C$

Start stop systems in micro hybrid cars – ie Citroen / Continental

Energy recovery in hybrid cars – 80% recoverable by SC compared to 30% by batteries
Transportation Applications – contd..

Power at the point of demand

Electronic Controlled Brake

22 x 100F ultracaps are used in the Toyota Prius II’s electronically controlled brake. Production began in 2007.

Source: loxus

Sportscars use supercaps

Made to run without an onboard starter for reasons of saving mass. Instead a supercapacitor system will be used.

“The combined mass reduction from removing the starter and using the supercapacitor system has roughly the same impact on the car performance as the switch to the significantly more powerful race engine!”

Benoît Dupont
Renault-Sport’s circuit Technical Manager

Bombardier light rail and others use supercapacitor energy harvesting recovering up to 35% of electricity on braking of trains and trams. This used to be done with lithium-ion batteries.

Tolerates faster charging. Fit and forget. Space/cost not a problem.

Source: loxus
Hybrid energy systems

Hybrid Bus - USA

Hybrid Electric Bus Drive Trains
Several 100 buses in operation
- ISE Research, CA – leader in advance energy systems
- Diesel-electric
- Gasoline-electric

Source: Maxwell Technologies

CSR China – Hybrid Electric Bus

Aka: TEG (Times Electric Group)

48V modules per bus
- 10 series for Series-Parallel Hybrid
- 15 series for Series Hybrid

2009: 300 buses ~ 3800 modules
2010: 500 buses ~ 6,000 modules
2011: 750 buses ~ 9,000 modules

Source: Maxwell Technologies

Supercapacitors assist fast charging in ABB’s TOSA bus charging system in Geneva

Any hybrid bus is capable of running on the electrical energy stored aboard in supercaps or batteries, for a range going from about 400m (supercaps) to 2km (batteries), but in a degraded mode (limited acceleration, influence on lifetime for batteries...).

For example, the HESS 24m vehicle can ride up to 500m on supercaps

Source: Maxwell Technologies
Fork lifts to Aircrafts

Forklifts

- Increase usable time per battery charge by 33%
- Increase battery life by 2x – 4x

Not replacing

Supercapacitors applications in Aerospace

Promising applications include:
- Autonomous Wireless Sensors Networks (on-ground tests and flight)
- High power radar
- Energy reserve for calculator
- Simplification of the pyrotechnics chain
- High power actuators for the control of attitude
- Activation of electromechanical conduits
- Robot supply for exploration missions

As well as using supercapacitors to compensate the battery for power and energy applications (hybridization)

Energy Harvesting and Storage for Structural Health Monitoring
(predictive maintenance is a major challenge)

Source: Airbus Defence & Space
Supercapacitors in the future - Structural Energy Storage

The latest nanomaterials made of extremely thin and strong carbon fibre replace the car’s steel body panels and can be used in the car’s roof, doors, bonnet and floor. These panels also double up as the car’s battery.

The car’s weight can be reduced by 15 percent. There is potential for cutting weight still further.

The material can be recharged by 1) harnessing the energy generated when the car brakes 2) plugging into the mains electricity grid.

Expected range is 130 km when the doors, roof and bonnet are replaced.

The body panels are discharged as the car’s electric motor is used.
Thank you…..

Question Time…