Recent Developments on Supercapacitors and their Applications

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What is a supercapacitor

- Supercapacitor is almost one million times larger in capacitance compared to an electrolytic capacitor.
- Its energy storage capacity is one to three orders of magnitude larger than an electrolytic.
- With a much lower ESR, it can provide very high power outputs for short periods of time (high power density).

Comparison of supercapacitor and normal capacitor sizes and maximum energy storage.
SCs with constant and very low ESR can deliver much higher power into a load than an electrochemical battery, where ESR keeps increasing with the discharge.
### SCs versus electrolytics - Comparison of Specifications

#### TABLE 2. COMPARISON OF TYPICAL ELECTROLYTIC CAPACITORS AND SUPERCAPACITORS FOR THEIR ESR VALUES AND OTHER USEFUL SPECIFICATIONS

<table>
<thead>
<tr>
<th>ENERGY STORAGE LIMIT</th>
<th>CAPACITOR TYPE</th>
<th>MANUFACTURER</th>
<th>PARAMETERS</th>
<th></th>
<th></th>
<th></th>
<th>ESR (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CAPACITANCE (µF/F)</td>
<td>TERMINAL VOLTAGE (V)</td>
<td>SHORT CIRCUIT CURRENT (A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 1J</td>
<td>Electrolytic</td>
<td>RSS</td>
<td>2200 µF</td>
<td>16</td>
<td>104</td>
<td></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></td>
<td></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></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></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></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></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></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></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></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></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></td>
<td>16</td>
</tr>
</tbody>
</table>

In general, SCs have lower ESR than the electrolytic capacitors, but their DC voltage rating is very low.
**SC is an electric double layer device**

- Inside a SC two capacitors are formed in series

\[ E = \frac{1}{2} CV^2 \quad \quad P = \frac{1}{4R} V^2 \]
**From Traditional Caps to Batteries – With SCs in the middle**

<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>When based on a lead acid battery – trade name</td>
<td></td>
</tr>
</tbody>
</table>

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

**DELIVERS MORE POWER W/kg or W/l**
Supercapacitors versus Hybrid Supercapacitors

b. Electric Double Layer Capacitor

c. Asymmetric Capacitor

\( \frac{1}{C_{EC}} = \frac{1}{C_1} + \frac{1}{C_2} \)

(Activated Carbons as Electrodes)

(Activated Carbons + Battery Type as Electrodes)
Internal material and cost structure of (EDLC )

Strategy: Masses ratio of each parts in a 54V standard module (based on benchmark analysis)

Electrolyte + activated carbon 31.3%
Cell can 17.4%
Additional parts (electronics, mechanical and insulating parts) 39.6%
Separator 0.3%
Al collector + polymers + conductive additive 11.4%

Benchmark: 3000 Farad supercapacitor

Source: IDTechEx, Maxwell Technologies
## Electrolytes

<table>
<thead>
<tr>
<th></th>
<th>Organic Electrolyte</th>
<th>KOH/H$_2$SO$_4$ Aqueous Electrolyte</th>
<th>Aprotic Ionic Liquids (AILs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltage</td>
<td>2.7-2.8 V</td>
<td>0.8-1.0 V</td>
<td>~3.0 V</td>
</tr>
<tr>
<td>Conductivity</td>
<td>~ 0.02 S/cm</td>
<td>~ 1 S/cm</td>
<td>~ 0.005 S/cm</td>
</tr>
<tr>
<td>Maximum Capacitance</td>
<td>150-200 F/g</td>
<td>250-300 F/g</td>
<td>100-120 F/g</td>
</tr>
</tbody>
</table>
| Technological, economical and safety aspects | • Manipulation in inert atmosphere  
• Expensive  
• Environment Unfriendly | • Easy manipulation  
• Not Expensive  
• Environment Friendly | • Performing at high temperature (40-60 °C) but decreasing stability  
• Expensive  
• Environment friendly |

Source: IDTechEx
Electrolytes used by the manufacturers – recent trends

Source: IDTechEx

The percentage represents the number of companies using each type of electrolyte.

Aqueous, 19%

ACN, 44%

PC, 37%
Research trends and commercialisation

- In SCs higher performance is achieved by
  - Increasing electrode surface area
  - Using better electrolytes
- To have larger surface area active research on new materials such as
  - Graphene
  - Graphene oxide
  - Carbon nano-tubes (CNT)

Graphene potential in SC is not fully developed yet but is good enough. Developments on SC manufacturing integration of graphene in progress.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Surface Area (m²/g)</th>
<th>Conductivity (S/cm)</th>
<th>Specific Capacity (F/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene Theoretical</td>
<td>2675 [1]</td>
<td>Higher than 600,000</td>
<td>550 [3]</td>
</tr>
<tr>
<td>Copper</td>
<td>NA</td>
<td>600000 [6]</td>
<td>NA</td>
</tr>
<tr>
<td>Aluminum</td>
<td>NA</td>
<td>350000 [7]</td>
<td>NA</td>
</tr>
</tbody>
</table>

Eq. 1: \[ E = \frac{1}{2} CV^2 \]
Eq. 2: \[ P = \frac{1}{4R} V^2 \]

*Lab Results pack device*

Source: IDTechEx
Ragone plot

Source: US Defence Logistics Agency
## Comparison of practical devices

<table>
<thead>
<tr>
<th>Image</th>
<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><img src="image" alt="Supercapacitor" /></td>
<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><img src="image" alt="Electrolytic capacitor" /></td>
<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><img src="image" alt="Hybrid supercapacitor" /></td>
<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><img src="image" alt="Disposable energizer cell – C type" /></td>
<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><img src="image" alt="Li-ion cell" /></td>
<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 on different energy storage technologies:

<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><strong>Li-ion battery</strong></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><strong>Supercapacitor</strong></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><strong>Hybrid supercapacitor</strong></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>
Useful characteristics of SCs for analog and power electronic circuits

• They are approximately 20 to 100 times larger energy density than electrolytic capacitors

• Larger the SC, ESR is lower

• Typical ESR values are
  • 30 to 100 mΩ for 0.1 to 2F capacitors (such as the thin profile Cap-XX types)
  • 100 to 1000 mΩ for 1 to 100 F
  • 0.3 to 2 mΩ for 600 to 5000 F devices

Source: Cap-XX, Australia

Smaller ESR of SCs – Useful in short term high power delivery
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

A unique new way to look at supercaps- Treat them as one million times larger devices compared to electrolytic caps!!!
Non-traditional applications of supercapacitors

- When a SC is treated as a one million times larger capacitance with very low ESR multitude of new applications can be developed
- Few examples are
  - SC as lossless voltage dropper for high efficiency RFI/EMI free linear DC-DC converters – Patented SCALDO technique with built in DC-Ups capability
  - SC as a transient energy absorber for commercial surge protectors – Patented SCASA technique
  - Rapid water heating technique for domestic hot water supply – Patented SCATMA technique
  - SCALED technique for DC lighting in DC-Microgrid systems
  - SCAHDI technique for high performance solar inverters
- The above techniques are generally known as Supercapacitor Assisted (SCA) techniques developed at University of Waikato, New Zealand

In developing SCA techniques for commercially useful novel applications, research team has looked at a SC as very large capacitor with a negligible ESR – leading to multiple international patents and publications
**The SCALDO Technique**

- Load receives the low-noise and high-current slew rate capable DC output of a linear regulator
- End to end efficiency is improved by a factor of 2 to 3 [for a 12-5 V case efficiency is two times improved]
- Switching frequency is extremely low (Fractional Hz to few Hz)
- RFI/EMI issues are eliminated
- Output currents ranging from mA to over 100 A
- DC-UPS capability

The above approach allows to design a linear DC output converter with an energy re-circulation frequency, typically in the range of millihertz to fractional hertz
Practical implementation of the SCALDO technique

- SCALDO technique allows you to build very high efficiency linear regulators

In a typical SCALDO circuit such as this 12-5V converter we get an efficiency improvement factor of 2.
SCALDO variations
RS-SCALDO technique for high current converters

By splitting the LDO into two half size LDOs we can reduce the number of power switches.
Basis for linear VRM systems!

Another variation is the dual-output SCALDO [Do-SCALDO] for dual rail DC-DC converters.

Figure 1.1: (a) Basic SCALDO configuration with single LDO and 4 switches (b) Modified RS-SCALDO (Reduced switches) configuration with two identical LDOs and two switches
Surge protectors based on supercapacitors: SC Assisted Surge Absorber (SCASA) Technique
Despite their low DC voltage rating, supercapacitors are large time constant circuits

- A typical SC circuit has a time constant from milliseconds to seconds
- 1 F SC with an ESR of 100 mΩ will have a time constant of 100 ms
- Such a circuit will take about 0.5 seconds to charge the capacitor to DC source voltage
- However, if the source voltage lasts only 10-100 µs (as in a case of a lightning induced case) capacitor will not charge to a significant voltage

Can SCs absorb high voltage transients like lightning surges/inductive energy dumps induced on power rails?
Typical surge protector circuits and power line transients

Typical surge protectors use MOVs and BBDs to absorb surge energy. However, they are transient rated devices, and if repeated surges occur they tend to get destroyed.
SCASA Technique

SCASA Technique with a SC sub-circuit for better surge absorption

Practical implementation in a commercial design

Commercial product based on SCASA technique

SCASA advantage over well-known surge absorber techniques

<table>
<thead>
<tr>
<th>Component type</th>
<th>High end</th>
<th>Low end</th>
<th>SCASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOVs</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Inductors</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>X-type capacitors</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

In SCASA, number of components are less and the transient related voltage at the protected load is less than the clamping voltage at the MOV.
Supercapacitor Assisted Temperature Modification Apparatus (SCATMA) : A SC based solution to hot water delay issue
Well-known problem at water faucets

- In our home environments central water heater is at a distant location from individual faucets
- This makes cold water storage between the central heater and the faucet
- Result is delayed hot water at the faucet
- Delay can be anything from about 10 seconds to a minute depending on the length of the buried pipes
- This creates a huge waste of water, every day

Why it is not easy to solve the problem

- Maximum power we can draw from a wall socket is about 2.3 kW
- Water is not stationery and hence heating power deliverable into water should be at a value much larger than 2.5 kW maximum
- Building heaters and tanks to do this is complex and costly
- Safety/ regulatory issues

Instant water heating: SCATMA

<table>
<thead>
<tr>
<th>Flow Rate (L min⁻¹)</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rise (°C)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Total Energy (Wh)</td>
<td>46</td>
<td>70</td>
</tr>
<tr>
<td>Average Power (kW)</td>
<td>5.6</td>
<td>8.4</td>
</tr>
<tr>
<td>Average Current at 50 V (A)</td>
<td>112</td>
<td>168</td>
</tr>
</tbody>
</table>
Design Approach and Implementation

- Energy Storage System
  - Supercapacitors (SC) vs. Batteries
    - Neither media has both high energy density and power density
  - Superior cycling capability of SC- but with low power density
  - Constant lower ESR of SCs allow high currents at lower depth of discharge
  - SCs are environmentally friendly

In first prototypes, to lower the cost, a battery-SC hybrid solution had to be used. However with new hybrid SCs SC only solution is feasible.
Inserting a useful resistive load in the charging path to circumvent the loss

Simple RC circuit where resistive losses could waste energy up to a 50%

- The useful resistive load ($R_L$) can be:
  - Lighting load
  - Inverter
  - Any resistive load
- Losses in each resistive element:
  \[ E_{\text{loss}} = \frac{r_b + r_i + r_c}{r_b + r_i + r_c + R_L} \times E_{\text{loss}} \]
- The $R_L$ utilizes the wasted energy;

\[ E_{\text{loss}} = \frac{r_b + r_i + r_c}{(r_b + r_c + r_i) + R_L} \times 50\% \]

Inserting useful resistive load in the charging loop

This concept was used in the SCALDO technique, where $R_L$ was the loaded LDO

SC assisted high density inverter (SCHADI) technique

- A loaded inverter is used in the charging path of a SC bank in an inverter system
- The overall inverter is divided into several micro-inverters
- Outputs are series connected to get the required AC voltage
- SC banks keep powering half the micro-inverters
- Other half are directly powered through the charging loop

In SCAHDI also we use a SC and a useful resistor to circumvent losses
Conclusion

- When a capacitor becomes almost a million times larger it can be creatively used for very new circuit topologies and techniques
- These new techniques can help in
  - Reducing lost energy in power converters
  - Developing new surge protectors with low component count and better performance
  - Low voltage rapid energy transfer into flowing liquids
  - High density inverters
  - DC Microgrid applications for energy efficiency

What was presented is only the tip of the iceberg... Creative circuit designers can use EDLCs in much more versatile ways than in simple energy storage systems....
Thank you.....

Question Time...