Supercapacitor Assisted Techniques

For power converters and protection systems

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Presentation outline

• Introduction to supercapacitors (SC) and long time constant circuits

• SCs as lossless droppers --- for very low frequency converters [SCALDO technique]

• SC based circuits to absorb high voltage transients - [ SCASA technique]

• SC modules as rapid energy delivery systems – [ SCATMA technique]

• SCs for DC microgrid systems – minimization of batteries in renewable systems [ SCALLED/ SCAWG techniques]

• SCs for high performance inverters in renewable systems [ SCAHDI/ SCASMI]

• Generalized SCALoM theory

• Future possibilities

• Conclusion
Normal capacitors and their limits

Physical Comparison of Supercapacitors (SC) and Electrolytic Capacitors

Typically, in SCs we get approximately one million times bigger capacitance, but at the penalty of very low DC voltage rating
Ragone plot

Source US Defence Logistics Agency
Commercially available supercapacitor types

- There are few basic types
  - Symmetrical double layer capacitors
  - Hybrid types with one battery type electrode
  - Capa-batteries
  - Lithium SCs

- Early versions were symmetrical double layer capacitors [3.7Wh energy capability example]

Then hybrid devices with one electrode similar to Li-ion batteries were commercialized [8.2Wh energy capability example]

More recently capacitor-batteries were introduced [40 Wh energy capability example]

Lithium supercapacitors [Source: Vinatech]
## Comparison of supercapacitor types and rechargeable batteries

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symmetrical SCs</th>
<th>Hybrid SC</th>
<th>Supercapacitors</th>
<th>Lead–Acid</th>
<th>Li-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy density (Wh/kg)</strong></td>
<td>5-8</td>
<td>10-14</td>
<td>50-120</td>
<td>50-125</td>
<td>250-670</td>
</tr>
<tr>
<td><strong>Power Density (W/kg)</strong></td>
<td>8000</td>
<td>2500-4000</td>
<td>1600-3200</td>
<td>25-100</td>
<td>375-1750</td>
</tr>
<tr>
<td><strong>Cycle life</strong></td>
<td>1,000,000</td>
<td>40,000-50,000</td>
<td>15,000-20,000</td>
<td>500-2,000</td>
<td>1000-1200</td>
</tr>
<tr>
<td><strong>Rated voltage per cell (Volts)</strong></td>
<td>2.5-3.0</td>
<td>2.7-2.8</td>
<td>2.7</td>
<td>2</td>
<td>3-3.6</td>
</tr>
<tr>
<td><strong>Capacitance (F)</strong></td>
<td>1-5000</td>
<td>200-7500</td>
<td>1000-70,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Temperature range (°C)</strong></td>
<td>-40 to 60</td>
<td>-20 to 60</td>
<td>-20 to 50</td>
<td>0 to 40</td>
<td>0-60</td>
</tr>
</tbody>
</table>
Battery versus SC

- Capa-batteries gradually reach the energy density of lead-acid batteries.

Source: Samwha Electric

In a battery internal resistance increases with % discharge.

But a SC’s ESR remains relatively constant with % discharge.

Comparison of internal resistance: Battery versus SC.
Non traditional applications of supercapacitors

Supercapacitor Assisted (SCA) Techniques
Supercapacitor as a lossless voltage dropper – for high efficiency linear DC-DC converters

- Linear DC-DC converters have the pros of
  - High quality noise free output
  - High output current slew rate capability
  - Lower cost
- Their only major issue is the lower efficiency
- Efficiency is based on the series losses in the power transistor
- Approximate efficiency, \( \eta \approx \frac{V_{\text{out}}}{V_{\text{in}}} \)

- If we insert a resistor losses in transistor reduces, but efficiency remains the same
- But if we use (an ideal) capacitor voltage drop across capacitor will be lossless
- Voltage change across capacitor will be given by, \( \Delta V_C = \frac{I_L \Delta t}{C} \)
- If the capacitor is small it will charge and block the circuit quickly
- If a SC is used, it will take along time to block and if ESR is small, it will be a lossless dropper.

Efficiency of a 12-5 V case \( \approx 42\% \)
Efficiency of a 5-3.3 V case \( \approx 66\% \)
Implementation of the Supercapacitor Assisted Low Dropout (SCALDO) regulator technique

An LDO is a linear regulator, where input to output voltage difference is low, to keep the efficiency high.

Now let us insert a SC pre-charged to Vc in the series path …

LDO’s efficiency will be $\frac{V_{\text{reg}}}{V_{\text{in}}}$, but input voltage now is $V_{\text{in}} + V_{C}$

When load current, $I_L$ is drawn through the SC its voltage keeps increasing while $V_{\text{in}}$ keeps dropping

Given the size of the capacitor it will be a slow process, and when $V_{\text{in}}$ drops to minimum, we can connect the capacitor to LDO directly, and disconnect the input supply (as per lower Figure)

When $V_{C}$ goes below $V_{\text{in}} \text{min}$ the circuit will return to series configuration (as per upper figure)

The above approach allows us to develop a high-efficiency 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

Ref: (2014) Kankanamge, K., Kularatna, N., Improving the end-to-end efficiency of DC-DC converters based on a supercapacitor assisted low dropout regulators (SCALDO) technique, IEEE Transactions on Industrial Electronics, Vol 61, Iss 1, January 2014, pp 223-230
A summary on SCALDO technique

- SCALDO is a high efficiency linear DC-DC converter
- It provides the hall marks of a linear converter, while eliminating the low efficiency of a straight linear converter
- No RFI/EMI filters needed since energy recirculation happens at fractional Hz frequency
- By over-sizing the SC DC-UPS capability can be added to the converter
- It can be extended to many applications
  - Split rail high efficiency linear converters
  - High current DC power supplies
  - 48 V Google new architecture power supplies
  - AC input based high efficiency isolated power supplies
  - Renewable energy DC-DC converters
- It is not a variation of switched capacitor converters

Supercapacitor based techniques for transient surge absorbers

SC Assisted Surge Absorber (SCASA) Technique
Advantage of a long time constant SC circuit in absorbing surge

- All transients have time durations of microsecond order timings, with kilo-volt order peak voltages
- An R-C circuit, subjected to a **step DC voltage of 1000 V**, generates an exponentially growing DC voltage and exponentially decaying loop current.
- If \( R=1 \ \Omega \) and \( C = 1 \ \mu F \), \( \tau=1 \ \mu s \) and capacitor could reach maximum voltage after approx 5 \( \mu s \) [In Figure \( T_{step} >> 5 \ \mu s \)]
- Max energy stored in capacitor = \( 0.5*1*10^{-6}*(1000)^2 =0.5 \ \text{J} \) Energy dissipated in resistance of the loop is also 0.5 J.
- Capacitor should be able to withstand 1000 V
- However, if we **replace the normal cap with a SC of 1 F** (and DC voltage rating of 2.5 V) time constant jumps to 1 sec.
- Now if the duration of the step pulse is only say 10 \( \mu s \),
  - Capacitor develops a voltage of much smaller value (about 0.1 mV only)
  - Resistor will dissipate approx. \( (1000^2*10*10^{-6} \approx 10 \ \text{J}) \)
- SC has a energy storage capability of \( 0.5*1*(2.5)^2 =3.12 \ \text{J} \)
- What capacitor accumulates is only \( [0.5*1*(0.1*10^{-3})^2 \approx 0.05 \ \mu \text{J}] \)

All what this tells us is the SC creates a case to dissipate all energy in the 10 \( \mu s \), 1000 V DC pulse in the loop resistance!
This leads us to think of using a SC based resistive loop to absorb the surge energy, where SC acts as a switch to turn the loop current on
Surge Capability Testing of Supercapacitor Families Using a Lightning Surge Simulator

Nihal Kularatna, Senior Member, IEEE, Jayathu Fernando, Amit Pandey, and Sisira James, Student Member, IEEE

Supercapacitor circuits have very long time constants

Fig. 2. SC equivalent circuits. (a) Classical equivalent circuit. (b) Ladder circuit.

Fig. 3. Few examples of wave shapes defined in surge test standards. (a) Open-circuit voltage waveform. (b) Short-circuit current waveform. (c) Ring wave.
Can we directly replace the MOV/ BBD in a common surge protector by a SC?

- **The answer is no** due to two primary reasons?
  1. If we try to place it between live and neutral, the SC will fail due to its low voltage rating!
  2. Even if we build a very large cap with adequate voltage rating, its AC impedance \((1/2\pi * 50 * C)\) will be almost a short circuit!

We had to invent\(^1,^2\) a completely new circuit topology to overcome these issues!

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**SCASA circuit** – SC is placed in the sub-circuit MOV [NLD in figure] is shifted to end of primary coil of the coupled inductor (based on a powdered alloy)
A commercial product based on SCASA

[Courtesy of Thor Technologies, Australia]

- A commercial product was developed in collaboration with Thor Technologies, Australia
- This has lesser components compared to a traditional surge protector
- It satisfies UL 1449 3rd Ed test specification without component deterioration, when repeated surges are applied

In SCASA\textsuperscript{1}, number of components are less and the transient related voltage at the protected load is less than the clamping voltage at the MOV

Figure 5.19: Performance comparison of SCASA with two commercial surge protectors

Ability of supercapacitors to deliver rapid power bursts

Supercapacitor Assisted Temperature Modification Apparatus (SCATMA): A SC based solution to hot water delay issue
Supercapacitor Assisted Temperature Modification Apparatus (SCATMA)

A SC based solution to hot water delay issue

- Supercapacitors have relatively lower ESR values, compared to battery packs.
- ESR does not vary much with the % discharge.
- Larger the size of the SC ESR is smaller.
- Maximum power capability of voltage source is given by, \( V^2 / 4R_{\text{int}} \)

- A 3000 F, 3.0 V rated (single cell) SC from Samwha has a DC ESR of 0.23 mΩ.
- This capacitor could deliver a maximum power of 9.8 kW when fully charged!
- Short circuit current starts at 13,000 amps!
- If you build a series array of ten of them it can theoretically deliver a maximum power of 98 kW!
- However total energy in a single cell will be 3.75 Wh

These simple calculations lead to case of rapid water heater!
Instant water heating : SCATMA

Well-known problem at water faucets

- In our home environments central water heater is at a distant location from individual faucets
- 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 less than 2.5 kW
- If flowing water is to be heated fast, a 10 to 20 kW heater element is required just before the faucet
- Building heaters and tanks to do this is complex and costly
- Safety/ regulatory issues if 230, 50 Hz mains is to be wired close to faucet [You need a voltage source lower than 70 V AC/ DC to be safe]

Energy and power requirements for rapid water heating

<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>

SCATMA
Implementation

- A SC bank of 50 to 150 Wh with very low ESR was developed.
- It operates from a DC source less than 50 V to be safe next to a water faucet.
- A water fallow rate sensor and a microprocessor based control units with high current MOSFET switches were added.

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.
Supercapacitors for DC Microgrid (DCMG) applications

- DCMGs are a rapidly growing new concept for better utilization of renewable energy.
- This is driven by the fact that most electrical products internally operate from DC voltage rails.
- Use of battery packs with a maximum power point tracking (MPPT) charger/controller is very common in traditional solar powered systems coupled to the AC grid supply.
- With SC modules could be build with hybrid or capacitor type SC cells, we gradually see the possibility of using SCM in place of battery packs.
- One major issue faced in replacing a battery bank with a SCM is the MPPT implementation.
- All MPPT techniques, try to match the internal resistance of a solar panel to the input resistance of the (battery+load) and the controller.
- A SCM for energy storage means a capacitive load ….
- Matching impedances is a theoretical issue!

Another SC assisted (SCA) technique set can solve this issue.
Is there a common theoretical concepts behind all these SCA techniques?

Answer is a **BIG YES**... a unique extension to our text book R-C circuit theory

- It is based on two simple concepts
  - In the simple RC circuit replace the capacitor with a supercapacitor... [Extend time constant]
  - Add a useful resistive load, a heater, DC-DC converter, inverter or any power electronic building block (PEBB) [To consume losses in resistor of RC circuit]

Then by modifying the power source by a *factor m* and keeping the capacitor pre-charged with *factor k* (as in Figure 3(c)), you achieve SCA- Loss management theory
SCALoM Theory

- All what we achieve is the reduction of losses in parasitic components of the RC circuit
- And, extending the circuit time constant by several orders due to supercapacitor for low speed operation for less dynamic losses

SC assisted LED lighting for DC microgrid and renewable energy systems

**SCALED Technique\(^1\)**

- LED lighting is internally operating with a DC supply
- DC products are more attractive for DCMG systems
- SC banks could replace battery banks, for environmentally friendly systems
- MPPT systems for battery banks will not work with SC banks (Impedance matching not possible)
- SCALED systems were developed to rescue this theoretical issue
- In SCALoM concept, we use a DC operable LED lamp load as the PEBB

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\(^1\) D. Jayananda ; N. Kularatna ; D.A. Steyn-Ross. Supercapacitor-assisted LED (SCALED) technique for renewable energy systems: a very low frequency design approach with short-term DC-UPS capability eliminating battery banks, IET Renewable Power Generation, Vol. 14 Iss. 9, pp. 1559-1570
SCALED System was tested in NZ at Auckland Port

- SCALED concept can be extended to DC whitegoods and air conditioners etc.
- This research is in progress now
- Details of the SCALED is published in IEEE/ IET

Currently we are extending this SCALED technique into SCA-white goods (SCAWG) technique to power DC operable white goods
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 SCM and a useful resistor (inverter) to circumvent losses
This technique can also be used to extend the input range of inverters useful in renewable energy systems

### Summary of SCA Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Start</th>
<th>Current Status</th>
<th>Commercial outcomes</th>
<th>Clients</th>
<th>Collaborations</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| SC assisted low dropout regulator (SCALDO)              | 2008  | • Two Completed PhDs  
• Two ongoing PhDs at UOW  
• One ongoing PhD at AUT          | US patent granted                            |                                              | Southampton University, UK / Ampere Labs, France | First silicon IC is expected                   |
| SC Assisted Surge absorber (SCASA)                      | 2011  | • One PhD completed  
• Two ongoing PhDs at UOW       | Several patents granted                     |                                              | Thor Tech, Perth, Aus                            |                                              |
| SC assisted Temperature Modification Apparatus (SCATMA)  | 2012  | • One PhD completed                                                      | Patent granted                                |                                              | Rinnai NZ Ltd                                   |                                              |
| SC assisted LED (SCALED)                                | 2016  | • One PhD ongoing                                                          |                                              | Ports of Auckland Ltd                           | POAL demo container at the public entry area    |                                              |
| SC Assisted high density inverter (SCAHDI)              | 2015  | • One PhD ongoing at AUT                                                  |                                              |                                              | Inspired by the Google Little Box Challenge     |                                              |
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
  • Building high efficiency very low frequency DC-DC converters
  • Developing 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 ice burg… Creative circuit designers can make us of commercial EDLCs in many more applications and much more versatile than in simple energy storage systems….
Thank you…

5th May 2020