Superconducting Magnetic Energy Storage

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SUPERCAPACITORS: ON THE PULSE OF A REVOLUTION

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Outline

• Superconductors

• SMES technology
  
  Concepts
  
  Power conditioning system
  
  State of the art

• Applications

• SMES activities at the University of Bologna
Superconductors

Resistance disappears at low temperature. “Superconducting” state is entered.

Superconductivity only occurs below the critical surface in the J-B-T space

\[ J < J_c(B,T) \]

- Superconducting properties \((J_c, B_c, T_c)\) of pure elements are too week.
- Practical superconductors are made of compounds or alloys
(Some) known superconducting materials

<table>
<thead>
<tr>
<th>Metals</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>9.25 K</td>
</tr>
<tr>
<td>Tc</td>
<td>7.80 K</td>
</tr>
<tr>
<td>V</td>
<td>5.40 K</td>
</tr>
<tr>
<td>NbTi</td>
<td>9.8 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intemetallics (A15)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb$_3$Ge</td>
<td>23.2 K</td>
</tr>
<tr>
<td>Nb$_3$Si</td>
<td>19 K</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.1 K</td>
</tr>
<tr>
<td>Nb$_3$Al</td>
<td>18 K</td>
</tr>
<tr>
<td>V$_3$Si</td>
<td>17.1 K</td>
</tr>
<tr>
<td>Ta$_3$Pb</td>
<td>17 K</td>
</tr>
<tr>
<td>V$_3$Ga</td>
<td>16.8 K</td>
</tr>
<tr>
<td>Nb$_3$Ga</td>
<td>14.5 K</td>
</tr>
</tbody>
</table>

- **“Unusual”**

<table>
<thead>
<tr>
<th>Material</th>
<th>Tc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs$<em>2$C$</em>{60}$</td>
<td>40 K</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>39 K</td>
</tr>
<tr>
<td>Ba$<em>{0.6}$K$</em>{0.4}$BiO$_3$</td>
<td>30 K</td>
</tr>
<tr>
<td>HoNi$_2$B$_2$C</td>
<td>7.5 K</td>
</tr>
<tr>
<td>GdMo$_6$Se$_8$</td>
<td>5.6 K</td>
</tr>
<tr>
<td>CoLa$_3$</td>
<td>4.28 K</td>
</tr>
</tbody>
</table>

- **Cuprates - Ln-Superconductors**

<table>
<thead>
<tr>
<th>Material</th>
<th>Tc</th>
</tr>
</thead>
<tbody>
<tr>
<td>GdBa$_2$Cu$_3$O$_7$</td>
<td>94 K</td>
</tr>
<tr>
<td>YBa$_2$Cu$_3$O$_7$-d</td>
<td>93 K</td>
</tr>
<tr>
<td>Y$_2$Ba$_4$Cu$<em>7$O$</em>{15}$</td>
<td>93 K</td>
</tr>
</tbody>
</table>

- **Cuprates - Bi-Superconductors**

<table>
<thead>
<tr>
<th>Material</th>
<th>Tc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi$<em>{1.6}$Pb$</em>{0.6}$Sr$_2$Ca$<em>2$Sb$</em>{0.1}$Cu$_3$O$_x$</td>
<td>115 K</td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$Ca$_2$Cu$<em>3$O$</em>{10}$</td>
<td>110 K</td>
</tr>
<tr>
<td>Bi$_2$Sr$_2$CaCu$_2$O$_9$</td>
<td>110 K</td>
</tr>
</tbody>
</table>

Fusion and accelerators, MRI, SMES

Cables, FCL, rotat. machines, SNES, MRI
Stability and AC Loss – Superconducting composites

Quench

• Localized transition to normal state can occur triggered by different causes (mechanical relaxation, non uniformity, .... ).

• A superconductor needs to operate in combination with a normal material which provides a bypass path to current and allows quick diffusion of heat.

Composite LTS wire

Composite HTS Tape

AC loss

• A superconductor is truly lossless only in DC condition.

• Electromagnetic loss occurs during transients or AC operation due to diffusion of magnetic field and induced currents in the normal conducting material.
SMES – Superconducting Magnetic Energy Storage

\[ E = \int_{\tau_\infty}^{\tau_{\text{coil}}} \frac{B^2}{2 \mu_0} \, d\tau \approx \int_{\tau_{\text{coil}}}^{\infty} \frac{B^2}{2 \mu_0} \, d\tau = \frac{1}{2} LI^2 \]
Advantages

• High deliverable power
• Infinite number of charge discharge cycles
• High efficiency of the charge and discharge phase (round trip)
• Fast response time from stand-by to full power
• No safety hazard

Critical aspects

• Low storage capacity
• Need for high auxiliary power (cooling)
• Idling losses
Cooling

Cooling methods

• Cryogen bath + vapor recondensation
  LHe@4.2 K, LH2@20 K, LNe@26 K, 2. LN2@63 K

• Conduction cooling
  “any” temperature

\[
COP_{\text{Carnot}} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{cold}}} \\
COP_{\text{Real}} = \frac{COP_{\text{Carnot}}}{0.1 - 0.3} \\
T_h = 300 \text{ K}
\]

<table>
<thead>
<tr>
<th>Tc</th>
<th>COP (ideal)</th>
<th>COP (real)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 K</td>
<td>70.43</td>
<td>200 - 7000</td>
</tr>
<tr>
<td>20 K</td>
<td>14.00</td>
<td>40 - 140</td>
</tr>
<tr>
<td>77 K</td>
<td>2.90</td>
<td>9 - 30</td>
</tr>
</tbody>
</table>

Total heat load

• Electromagnetic loss
• Heat invasion of supports
• Radiation
• Heat invasion and Joule loss of current leads

\[
\text{COP} = \frac{\text{Watt of input power}}{\text{Watt of heat removed}}
\]
PCS - Power Conditioning System

A controlled power is transferred from the DC bus to the grid by means of the inverter.

The voltage of the DC bus is kept constant by the SMES by means of the two quadrant chopper.
Idling Loss

If no power is delivered/absorbed the SMES current free-wheels in the chopper.

\[ P = 0 \]

Losses are produced during the idling phase.

\[ V_{on	ext{ }IGBT} = 0.5 - 1.5 \text{ V} \]
\[ V_{on	ext{ }DIODE} = 0.5 - 1 \text{ V} \]

\[ P_{IGBT} = I_{SMES} V_{on	ext{ }IGBT} \]
\[ P_{DIODE} = I_{SMES} V_{on	ext{ }DIODE} \]

\[ P_{idling} = 1 - 10 \text{ kW / kA} \]

- Time constants of RL circuit of typical SMES (1-5 MJ) during the standby phases are in the order of hundreds of seconds, at most.
• The whole energy of the SMES is lost in the power electronics within a few minutes

• Continuous recharge/compensation is needed
The use of a Thermal Actuated Superconducting Switch is

- Possible in principle
- Unfeasible in practice since it lowers the response time of the chopper
Efficiency of the SMES System

$P$, deliverable power
$\Delta t$, duration of delivery
$\Delta t_{\text{cycle}}$, duration of the cycle
$\Delta t_{\text{idle}}$, duration of idling phase
$\eta_s$, intrinsic efficiency of the storage device
$\eta_c$, efficiency of the converters
$P_{\text{aux}}$, power required for auxiliary services
$P_{\text{idle}}$, power loss (if any) during idling

$$\eta = \frac{P \Delta t}{\eta_s \eta_c + P_{\text{idle}} \Delta t_{\text{idle}} + P_{\text{aux}} \Delta t_{\text{cycle}}}$$

- SMES is unsuitable for long term storage
- SMES is well suited for continuous charge / discharge (but AC loss needs to be considered)
The state of the art of SMES technology
### The Kameyama SMES

10 MW – 1 s SMES system

<table>
<thead>
<tr>
<th>Parameters of 10 MVA SMES.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity and compensation time</td>
<td>10 MVA, 1-s</td>
</tr>
<tr>
<td>Rated input-and-output alternating voltage</td>
<td>3φ-6600 V, 60 Hz</td>
</tr>
<tr>
<td>Change over time</td>
<td>1/2 cycle + α</td>
</tr>
<tr>
<td>Coil configuration</td>
<td>4-pole coil arrangement</td>
</tr>
<tr>
<td>Rated current</td>
<td>1400 A</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>DC 6.6 kV</td>
</tr>
<tr>
<td>Withstanding voltage</td>
<td>DC 13 kV</td>
</tr>
<tr>
<td>Inductance</td>
<td>21.1 H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>20.7 MJ</td>
</tr>
<tr>
<td>Utilized energy</td>
<td>10.0 MJ</td>
</tr>
<tr>
<td>Maximum field</td>
<td>4.44 T</td>
</tr>
<tr>
<td>Coil dimension (A/B)</td>
<td></td>
</tr>
<tr>
<td>Inner radius</td>
<td>0.346 m/0.410 m</td>
</tr>
<tr>
<td>Outer radius</td>
<td>0.404 m/0.468 m</td>
</tr>
<tr>
<td>Height</td>
<td>0.194 m/0.495 m</td>
</tr>
<tr>
<td>Cooling method</td>
<td>LHe pool boiling</td>
</tr>
</tbody>
</table>

[Diagram showing time line and operation results for 5MVA and 10MVA SMES]
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- Superconductors
- SMES technology
  - Concepts
  - Power conditioning system
  - State of the art
- Applications
- SMES activities at the University of Bologna
SMES based power intensive systems

- Cost of battery scales with power and is roughly independent on the energy
- Cost of SMES scales with energy and is roughly independent on the power

Possible applications
- Pulsed loads (e.g. high energy physics, fusion, ...) 
- Increase transient peak capacity of Battery based energy storage
- ....
- Frequency regulation

If large power is required for a limited time SMES can represent a cost effective storage technology
1. Hybrid SMES - Battery systems

SMES can be conveniently used in combination with battery due to the complementary characteristics

- Battery provides long term base power – hence energy
- SMES provides peak power and fast cycling
Advantages:

- Reduced power rating of batteries
- Reduced wear and tear of batteries (no minor cycling)
- Reduced energy rating of SMES

Cost effective solution
2. Protection of sensitive equipment

1 MW – 5 s SMES system
Auxiliary network services provided by PCS of SMES

- Harmonic compensation
- Power factor correction
3. Power modulation by SMES

- No battery can be used for this application due to the prohibitive number of cycles
- Advantages brought by SMES can be significant also for moderate size systems
4. Hybrid SMES - Liquid Hydrogen (or liquid Air) system

- Liquid Hydrogen is used as energy intensive storage
- Free cooling power is available for SMES due to the presence of LH2 at 20 K
- SMES is used as power intensive storage
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<table>
<thead>
<tr>
<th>Total stored Energy</th>
<th>200 kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid</td>
<td></td>
</tr>
<tr>
<td>Inner</td>
<td>Outer</td>
</tr>
<tr>
<td>Inner radius</td>
<td>147 mm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>190.4 mm</td>
</tr>
<tr>
<td>Height</td>
<td>246.8 mm</td>
</tr>
<tr>
<td>Current density</td>
<td>120.7 A/mm²</td>
</tr>
<tr>
<td>Maximum magnetic flux density</td>
<td>4.42 T</td>
</tr>
</tbody>
</table>

- Diameter of the naked strand: 0.82 mm
- Diameter of the strand including insulation: 1.2 mm
- Number of Nb-Ti filaments: 6534
- Diameter of filaments: 6±0.1 µm
- Cu/SC ratio: 2
- Twist pitch: 15±1.5 mm
- RRR: >100

Critical current:
- at 4.2 K and 5 T: 429 A
- at 4.2 K and 6 T: 324 A
- at 4.2 K and 8 T: 214 A

Current Sharing Temperature at 150 A and 5 T: 5.65 K

Cold test in 2004 (and 2013 at ENEA)
2. Conduction cooled MgB$_2$ SMES demonstrator (2014 – 2016)

• 3 kJ MgB$_2$ Magnet
• 40 KW Mosfet Based PCS

Cold test in progress
Full test at 1-10 kW to come shortly
3. Conduction cooled MgB₂ SMES Prototype (2017 – 2020)

**MISE - Italian Ministry of Economic Development**
Competitive call: research project for electric power grid

**Project funded**

**Budget: 2.7 M€**
**Duration: 2017-2020**

**300 kJ – 100 kW prototype**
**Full system**
Conclusion

• SMES is an established power intensive storage technology.

• Improvements on SMES technology can be obtained by means of new generations superconductors compatible with cryogen free cooling.

• Cooling and idling losses needs to be carefully considered when evaluating the viability of SMES systems.

• SMES and Supercapacitors have very similar characteristics. Careful investigation needs to be done in order to choose the most suitable solution.
Thank you for your kind attention ...

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