Traction Brake Energy Regeneration By Supercapacitor Energy Storage System

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Panama Canal
Energizing the Panama Canal to take on double the traffic

Facebook
Energizing data center as forward-thinking as Facebook itself

Valero
Energizing a refinery to take arc flash danger out of the operation

Schaltanlagenbau Gormanns GmbH
Energizing a potato plant to make sorting 120 tons of potatoes a one-man job

Johann Cruijff ArenA
Energizing by stored energy saving 117,000 tons of CO2

TriRiver Health Partners
Energizing IT systems to power the transformation of healthcare

Beijing subway
Energizing a subway system to move even faster than the speed of a growing Beijing

PGE Salem Smart Power Center
Energizing a working smart grid for energy intelligence.

What matters to our customers, matters to us
30-40% - the traction energy potentially to be saved by regenerative braking

- AUX supplies during braking
- Powering other trains on the same section
- Energy return to the AC grid by reversible substations
- Inject in Energy Storage Systems (ESS)

15-25% - the traction energy cost efficiently could be saved
ESS CHALLENGE

- High power (MWs) to absorb in short time (30-60s)
- Braking power and energy differs from train to train – depending on the train’s powertrain and weight
- Unpredictable charge and discharge sequence – multiple trains in the same section interfere with each other

There is an OPTIMAL ESS DESIGN for all sections which maximize the return-on-investment
Key Elements Of The ESS

HV AC grid

TPS

Rectifier

600V-3kV DC

Switchgear

Bidirectional Converter

Energy Storage Unit
## High Power Density Energy Storage Technologies

<table>
<thead>
<tr>
<th>Key Characteristic</th>
<th>Units</th>
<th>Supercapacitor</th>
<th>Li-ion Batteries</th>
<th>Flywheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage per base unit</td>
<td>V</td>
<td>2.5-3</td>
<td>3.6-4.2</td>
<td>400-500</td>
</tr>
<tr>
<td>Cold Operating Temp</td>
<td>°C</td>
<td>-40</td>
<td>-20</td>
<td>-10</td>
</tr>
<tr>
<td>Hot Temperature</td>
<td>°C</td>
<td>+70 (85)</td>
<td>+45</td>
<td>+40</td>
</tr>
<tr>
<td>Cycle Life</td>
<td></td>
<td>&gt;1,000,000</td>
<td>10,000</td>
<td>unk</td>
</tr>
<tr>
<td>Calendar Life</td>
<td>Years</td>
<td>5-20</td>
<td>3-10</td>
<td>20</td>
</tr>
<tr>
<td>Energy Density</td>
<td>Wh/L</td>
<td>1 – 10</td>
<td>250-650</td>
<td>0.6 – 1.2 incl converter</td>
</tr>
<tr>
<td>Power Density</td>
<td>W/L</td>
<td>1000 – 10,000</td>
<td>850 - 3000</td>
<td>98 - 275</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>&gt;98</td>
<td>80 - 90</td>
<td>98</td>
</tr>
<tr>
<td>Charge Rate</td>
<td>C/x</td>
<td>&gt;1,500</td>
<td>&lt;40</td>
<td>~4</td>
</tr>
<tr>
<td>Discharge Time</td>
<td>Sec or Minutes</td>
<td>Hours</td>
<td>Seconds</td>
<td></td>
</tr>
<tr>
<td>Cost per kWh</td>
<td>$</td>
<td>10,000-15,000</td>
<td>100-500</td>
<td>2,000-5,000</td>
</tr>
<tr>
<td>Cost per kW</td>
<td>$</td>
<td>0.1-0.2</td>
<td>100-500 (1C)</td>
<td>300-500 (many factors)</td>
</tr>
</tbody>
</table>
Train Braking Energy Regeneration Example

- Inputs taken into consideration for the sizing:
  - V catenary train brake = 800-900VDC
  - I regenerative brake = 1000A / ~ 800kW considering efficiencies, but can be more available
  - T regen = 30s - considering only 20+Km/h
  - V boost during train acceleration = 750VDC
  - Frequency of regenerative cycle is 1 per 5 minutes => ~ 100,000 cycles per year
## Which One Is The Ideal ESU Technology?

<table>
<thead>
<tr>
<th>ESU Technology</th>
<th>Required Capacity</th>
<th>Total Volume</th>
<th>Total Weight</th>
<th>Expected ESU Cost</th>
<th>Estimated Lifetime</th>
<th>Roundtrip Efficiency</th>
<th>Regenerated energy during lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercap (Eaton XLM)</td>
<td>35F @ 1500V =&gt; 6.7kWh</td>
<td>~3m3</td>
<td>~3 Tons</td>
<td>$200k</td>
<td>12yrs, 1M+ cycles – continues to operate with lower capacity year by year</td>
<td>96%</td>
<td>5.7 GWh</td>
</tr>
<tr>
<td>Li-Ion (LMO)</td>
<td>192kWh @ 800V (1C considered)</td>
<td>~2m3</td>
<td>~2.7 Tons</td>
<td>$50k</td>
<td>3yrs, 300k cycles – EOL condition</td>
<td>90%</td>
<td>1.62 GWh</td>
</tr>
</tbody>
</table>

*: ESU cost only, no converter and switchgear considered

For the energy regeneration cost per return is similar for supercapacitor and Li-Ion technology
Advantageous Use Cases Supercap and LiIon Batteries

**SUPERCAP**

- More cost effective if the regeneration frequency is higher than 1 in 5 minutes due to the infinite cycle life.
- Better for **outside installations** as highly efficient in cold and hot temperatures as well (-40/+65°C).
- Better in case stored energy is used for **substation power boost** due to better overall efficiency.
- Better where maintenance and replaceability is difficult due to **maintenance free** and long life being.

**Li-Ion BATTERY**

- More cost effective if the regeneration frequency is lower than 1 in 5 minutes.
- Better in case the stored energy is to be used to **power the train station** energy needs during peak consumption by the accumulated energy.
- Better if the stored energy is planned to be used to **power the catenary for longer periods** (up to 30min) in case of failure in external power supply and move trains around in this down period.
Supercapacitor – Battery Hybrids

- In rapidly fluctuating regeneration cycles a supercap-battery hybrid solution is beneficial
- Supercaps are handling the high rise current portions both for charge and discharge
- Benefits of a hybrid solution:
  - Longer battery life ~2x
  - Less thermal stress on the battery
  - Efficiency improvement ~5%

Eaton Developed A Simulation Program To Evaluate Battery-Supercap Hybrids For Different Drive and Recovery Cycles/Profiles
The Ultimate Solution

HV AC grid

TPS

Rectifier

600V-3kV DC

DC = DC

Eaton Supercap

DC = DC

Eaton xStorage

DC = AC

Train Station