Superconducting Power Filter for DC Electrical Grids

L. Quéval\textsuperscript{1,2}, B. Douine\textsuperscript{3}, I. Schwenker\textsuperscript{3}, D. Huchet\textsuperscript{1,2}, F. Trillaud\textsuperscript{4}, O. Despouys\textsuperscript{5}

\textsuperscript{1} Université Paris-Saclay, CentraleSupélec, CNRS, GeePs, Gif-sur-Yvette, France.
\textsuperscript{2} Sorbonne Université, CNRS, GeePs, Paris, France.
\textsuperscript{3} GREEN, Univ. de Lorraine, Nancy, France
\textsuperscript{4} Instituto de Ingeniería, National Autonomous University of Mexico (UNAM), Mexico
\textsuperscript{5} Réseau de Transport d’Electricité, Paris la Défense, France
Content

I. Stability of a DC grid with a constant power load

II. Stability of a DC grid with a constant power load and a superconducting power filter

III. Towards an experimental proof of concept

IV. Conclusion
I. Stability of a DC grid with a constant power load
Analytical stability limit

\[ P_s \leq \frac{RC}{L} V_e^2 \]

no ScFCL:
\[ P_{s,\text{max}} = 2.33 \text{ MW} \]

**Table 1: DC grid parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_e )</td>
<td>source voltage</td>
<td>5 kV</td>
</tr>
<tr>
<td>( R )</td>
<td>resistance</td>
<td>40 m( \Omega )</td>
</tr>
<tr>
<td>( L )</td>
<td>inductance</td>
<td>0.6 mH</td>
</tr>
<tr>
<td>( C )</td>
<td>capacitance</td>
<td>1.4 mF</td>
</tr>
</tbody>
</table>

Numerical stability

How to evaluate the stability?

- -> envelope of $v_{CPL}$

$P_s = 2.0 \text{ MW: stable}$

$P_s = 2.5 \text{ MW: unstable}$

$P_s = 3.0 \text{ MW: unstable}$

no ScPF:

$P_{s,max} = 2.33 \text{ MW}$
II. Stability of a DC grid with a constant power load and a superconducting power filter
DC grid with a constant power load (CPL) and a superconducting power filter (ScPF)

- **Superconducting Power Filter (ScPF)** = non-inductive SC coil + RLC
- It behaves as a current dependent resistance:

\[
P_S \leq \frac{[R + r_{\text{ScPF}}(i_{\text{ScPF}})]C}{L} V_e^2
\]
II. Stability of a DC grid with a CPL & a ScPF

1. ScPF lumped parameter thermo-electric model
Electric model

\[ E(j) = \frac{E_c}{J_c} \left| \frac{j}{J_c} \right|^{n-1} j \]

- Hypothesis
  - thermal effect neglected

Electric model

\[ v = E L_{sc} \]
\[ i = j A_{sc} \]
\[ I_c = J_c A_{sc} \]

Electric model

\[ E(j) = \frac{E_c}{I_c} \left| \frac{j}{J_c} \right|^{n-1} j \]
\[ v(i) = \frac{E_c L_{sc}}{I_c} \left| \frac{i}{I_c} \right|^{n-1} i \]

Hypothesis

Thermal effect neglected

\[ r_{sc}(i) \]

\[ \frac{v}{V_c} [\] \]

\[ \frac{i}{I_c} [\] 

Power law

ScPF for DC grids

2020-11-21

loic.queval@geeps.centralesupelec.fr
Electric model

\[ v = E L_{sc} \]
\[ i = j A_{sc} \]
\[ I_c(T) = \frac{J_c(T)}{j} A_{sc} \]

\[ E(j) = \frac{E_c}{J_c(T)} \left| \frac{j}{J_c(T)} \right|^{n(T)-1} j \]

\[ v(i) = \frac{E_c L_{sc}}{I_c(T)} \left| \frac{i}{I_c(T)} \right|^{n(T)-1} i \]

\[ r_{sc}(i, T) \]

\[ I_c(T) = I_c0 \left( \frac{92 \text{ K} - T}{92 \text{ K} - 77 \text{ K}} \right) \]

\[ n(T) = n_0 \frac{77 \text{ K}}{T} \]

Hypothesis
thermal effect included

power law @T
**Electric model**

\[
v(i) = \frac{E_c L_{sc}}{I_c(T)} \left( \frac{i}{I_c(T)} \right) [n(T) - 1]
\]

\[
I_c(T) = I_{c0} \left( \frac{92 \text{ K} - T}{92 \text{ K} - 77 \text{ K}} \right)
\]

\[
n(T) = n_0 \left( \frac{77 \text{ K}}{T} \right)
\]

**Thermal model**

\[
q \left[ \text{W/m}^2 \right] = 10^3 q_0 \Delta T \left[ \text{K} \right]
\]

II. Stability of a DC grid with a CPL & a ScPF

2. Simulation results
Numerical stability

Table 2: ScPF parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_c$</td>
<td>critical current criterion</td>
<td>$10^{-4}$ V/m</td>
</tr>
<tr>
<td>$I_{c0}$</td>
<td>tape critical current @77 K</td>
<td>300 A</td>
</tr>
<tr>
<td>$n_0$</td>
<td>power law exponent @77 K</td>
<td>21</td>
</tr>
<tr>
<td>$L_{sc}$</td>
<td>tape length</td>
<td>100 m</td>
</tr>
<tr>
<td>$n_t$</td>
<td>nb of tapes in parallel</td>
<td>2</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>shunt resistance</td>
<td>50 mΩ</td>
</tr>
</tbody>
</table>

no ScPF: $P_{s,max} = 2.33$ MW

$P_s = 2.0$ MW: stable  
$P_s = 2.5$ MW: stable  
$P_s = 3.0$ MW: stable
ScPF behavior

$P_s = 2.0$ MW: no losses

$P_s = 2.5$ MW: some losses

$P_s = 3.0$ MW: more losses
III. Towards an experimental proof of concept
III. Towards an experimental proof of concept

1. DC100 testbench at GeePs
Overview of DC100 testbench

\[ V_e \]

\[ i_{\text{ScPF}} \]

\[ v_{\text{ScPF}} \]

\[ R_1 \]

\[ L_1 \]

\[ i_{\text{CPL}} \]

\[ C_1 \]

\[ \frac{P_s}{v_{\text{CPL}}} \]

\[ v_{\text{CPL}} \]
Overview of DC100 testbench

How to make a real CPL?
Overview of DC100 testbench

\[ P_s = \frac{v_{load}^2}{R_{load}} \]

\( v_{load} \) is kept constant by controller \( \leftrightarrow \) \( P_s \) is kept constant (CPL)
DC100 testbench

![Diagram of DC testbench with components labeled]


Stable operation (no ScPF)

$P_s = 476$ W stable

Unstable operation (no ScPF)

\[ P_s = 1305 \text{ W} \]

unstable

III. Towards an experimental proof of concept

2. ScPF prototypes
Specifications

- Non-inductive coil
  \[ P_s \leq \frac{RC}{L} V_e^2 \]
- BSCCO or YBCO (77 K)
Prototype ScPF#1

- BSCCO
- $I_c = 63$ A
- $L_{sc} = 5.2$ m

Prototype ScPF#2

- ReBCO (Shanghai SC)
- $I_c < 90$ A
- $L_{sc} = 9$ m

Prototype ScPF#3a

- BSCCO (Sumitomo)
- $I_c = 175\, \text{A} \, \text{(datasheet 170 A)}$
- $L_{sc} = 5\, \text{m}$
Prototype ScPF#3c

- BSCCO (Sumitomo)
- $I_c = 154$ A (datasheet 170 A)
- $L_{sc} = 25$ m
Prototype ScPF#4a

- ReBCO (SuNAM)
- $I_c = 129$ A (datasheet: 199 A)
- $L_{sc} = 2$ m

Future works

• Winding and characterization of a ScPF made of 100 m of BSCCO
• Experimental proof-of-concept of the proposed function
IV. Conclusion
Conclusion

• A new application of HTS technology is introduced. The device referred to as "Superconducting power filter" (ScPF) aims at increasing the stability of DC grids by adding a current-dependent resistance to a classical RLC filter.

• In comparison with other stabilization techniques, a ScPF achieves a fully passive stabilization without decreasing the energy transferred to the load in nominal operation.

• To clarify its operation, a simple DC circuit with a controlled power load (CPL) and a ScPF was considered. Using an thermo-electric lumped-parameter model of the ScPF, the stability of the DC grid was assessed for a given test case.

• Efforts are underway to provide an experimental proof of concept.
References


Merci !