Calculation of temperature profiles and pressure drop in concentric three-phase HTS power cables

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AmpaCity Project - Germany

Technical specification
- 1 km distance between substations
- 10 kV system voltage
- 2.3 kA operating current (40 MVA)

System in continuous operation since March 10th, 2014

Luftbild: "Darstellung aus HK Luftbilder / Karten Lizenz Nr. 197 / 2012 mit Genehmigung vom Amt für Geoinformation, Vermessung und Kataster der Stadt Essen vom 13.02.2012"

Source: Nexans Deutschland GmbH
Cable design

Annular circular duct (LN$_2$ return)

PPLP dielectric

Inner tube (LN$_2$ supply)

Cryostat

Screen

Phase 3

Phase 2

Phase 1
Electrical design

- Transmission power 40 MVA at an electric potential of 10 kV

- BISCCO Tapes (Bi 2223)
  - $I_C(T = 78 \text{ K}) = 163 \text{ A}$
  - Power dissipation @ 78 K
    - Phase 1 (22 tapes) = 2.5 W/m
    - Phase 2 (26 tapes) = 1.5 W/m
    - Phase 3 (30 tapes) = 1.0 W/m

$$P_{AC}(T) = P_{AC,tape}(T) \cdot N_{\text{tape}} \cdot f_N$$

Elliptic Norris Equation

Thermal design – Radial heat conduction

- Steady state heat equation in cylindrical coordinates

\[
\frac{d^2 T}{dr^2} + \frac{1}{r} \cdot \frac{dT}{dr} + \frac{P_{AC}(T)}{\lambda \cdot A} = 0
\]

- 8 Differential equations
- 16 Boundary Conditions
  - a) Convection BC → \( T_{fld}(z) \)
  - b) Interface BC
Thermal design – Fluid flow energy balance

Annular circular duct

Inner tube

Heat radiation

Heat conduction + Heat generation

Infinesimal small tube element

Phase 3
Phase 2
Phase 1

$T_{\text{fl}, z}$

$T_{\text{fl}, z+dz}$

$r$

$dz$
## Model verification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AmpaCity - Project</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature (K)</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>Outlet temperature (K)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Mass flow (kg/s)</td>
<td>0.425</td>
<td>0.425</td>
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<tr>
<td>Inlet pressure (bar)</td>
<td>8.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Heat radiation (W/m)</td>
<td>1.7</td>
<td>1.7</td>
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<tr>
<td>Nominal current (A)</td>
<td>200</td>
<td>200</td>
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<tr>
<td>Outlet pressure (bar)</td>
<td>6.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Cable length (m)</td>
<td>1000</td>
<td>1010</td>
</tr>
</tbody>
</table>
Model verification – Axial temperature profile

Global maximum temperature at $z = 623\,\text{m}$

- LN$_2$ return flow
- LN$_2$ supply flow
- Reversal point

Cable length $L = 1010\,\text{m}$
Model verification – Radial temperature profile

![Diagram showing radial temperature profile](image_url)

- Temperature (K)
- Pressure (bar)
- Mass flow (kg/s)
- Heat radiation (W/m)
- Nominal current (A)
- Cable length (m)

### Model Parameters
- **Inlet temperature (K):** 68
- **Outlet temperature (K):** 70
- **Mass flow (kg/s):** 0.425
- **Inlet pressure (bar):** 8.4
- **Heat radiation (W/m):** 1.7
- **Nominal current (A):** 200
- **Outlet pressure (bar):** 6.4
- **Cable length (m):** 1000

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**Radial Temperature Profile**

- Phase 1
- Phase 2
- Phase 3

**Temperature at z = 623 m**

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Eugen Shabagin - Calculation of temperature profiles and pressure drop in concentric three-phase HTS power cables

Institute for Technical Physics (ITEP)
Cable operating range

- Longer cable and a higher nominal current are possible by increasing the mass flow of the coolant

<table>
<thead>
<tr>
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<th>Model</th>
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<tbody>
<tr>
<td>Nominal current</td>
<td>2150 A</td>
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<tr>
<td>Mass flow</td>
<td>0.85 kg/s</td>
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<td>Cable length</td>
<td>1700 m</td>
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<td>Pressure drop</td>
<td>10.6 bar</td>
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<td>Additional cooling unit</td>
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<tr>
<td>Cable length</td>
<td>3330 m</td>
</tr>
</tbody>
</table>
Mixed refrigerant cooling

(a) Temperature profile for LN₂ return and supply, cable length $L \approx 3330\ m$

(b) Temperature profile for mixture return and supply, cable length $L \approx 5310\ m$

Heat transfer unit
Outlook

- Calculation of transient temperature profiles during a short circuit current in superconducting cables

Thank you for your attention