Cooling systems for HTS transformers: impact of cost, overload, and fault current performance expectations

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Outline

• Specification: what are the expectations?
• Cryocoolers: a comparison
• Cryostats
• Providing for overload capability
• Coping with fault currents
Commercial HTS transformers: specification

- **Target rating 40 MVA**
  - AC loss modelling available
  - Cost competitive, depending on circumstances
  - Feasible next step

- **Cost ~ US$ 1 M**
  - Warm iron → composite cryostat
  - Operating temperature 65 – 67 K (AC loss drops 10% K⁻¹)
  - Thermal budget 2.5 - 3 kW
  - Closed cryogenic system → cryocooler

- Security of service in case of cryosystem outages – maintenance, breakdown
- Fault current tolerant – fault withstand time, recovery under load

- Overload capability – desirable
- Fault current limiting – desirable

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1 Pardo et al, 2015, Supercond. Sci. Tech. 28, 114008
2 Staines et al, 2015, EUCAS poster presentation
# A cryocooler comparison (illustrative, not definitive)

<table>
<thead>
<tr>
<th></th>
<th>Gifford-McMahon</th>
<th>Stirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling power at 65 K (W)</td>
<td>470</td>
<td>2800</td>
</tr>
<tr>
<td>Cooling penalty (W/W)</td>
<td>26.5</td>
<td>16</td>
</tr>
<tr>
<td>Heat transfer</td>
<td>Conductive</td>
<td>Heat pipe / reliquefier</td>
</tr>
<tr>
<td>Load matching</td>
<td>Multiple units (6), can be cycled</td>
<td>Single unit meets base load</td>
</tr>
<tr>
<td>Back-up cooling</td>
<td>N+1 redundancy (extra unit)</td>
<td>Stored cryogen + pump</td>
</tr>
<tr>
<td>Overload cooling reserve</td>
<td>Stored cryogen + pump</td>
<td>Stored cryogen + pump</td>
</tr>
</tbody>
</table>

GM: lower efficiency  
Stirling: best with fixed load, pumped cooling required for back-up  

Turbo-Brayton: high efficiency; large capacity, variable - possibility for future
The figure of merit is the TCO per watt of cooling power, calculated here for:

- Operating temperature 65 K
- Lifetime energy cost 8.5 US$/W
- 100% load factor

Back-up system costs not included

- Purchase price similar
- Maintenance costs add up
- Efficiency counts: lifetime cost of losses > purchase price (for 100% load factor)
Cryostats – hybrid concept

- Single cryostat for 3 phases desirable
- All vacuum composite construction challenging, expensive
- Cost ~$1M

Hybrid cryostat concept:

- Use vacuum insulation only around core penetrations
- Substitute foam around main tank 20 – 30 cm thick
- Estimated heat leak of foam tub ~300 W
- Lifetime energy cost ~$40K ($100K using TCO)
- Increased cost of vacuum cryostat is not justified by lifetime cost of losses

*Single phase demonstrator underway*
Overload capability

- Overload capability without loss of lifetime a selling point for HTS?
- IEC 60354 overload limits: 150% cyclic, 180% short-time
- But AC loss scales as $I^{3.5}$: double the current, ten times the loss
- Overload for substantial time requires large cooling power reserve
- Not economically practical to have large reserve cryocooler capacity

Solutions:
- LN storage and pump for reserve capacity (also most cost-effective back-up for cryocooler outage)
- Provide only for applications where overload not required, e.g. generator step up transformer

Calculated AC loss for 40 MVA design; loss increases as $I^{3.5}$

Pardo et al, 2015, Supercond. Sci. Tech. 28, 114008
Fault tolerance: fault withstand time

- IEC 60076-5 fault withstand time 2 s
- Network operators require time for protection systems to operate
- Adiabatic heating of the windings during fault - the only reliable design assumption
- Increased withstand time requires more thermal mass
- 1 mm wire thickness with 4 mm wire carrying 100 A: $J_e = 25 \text{ A/mm}^2$
- Compare with $J \sim 3 \text{ A/mm}^2$ for copper transformers
- Even with $J_e \sim 20 \text{ A/mm}^2$ HTS transformers can be much smaller and lighter than conventional

45 kVA FCL transformer winding, 0.4 mm thick wire: Heat transferred by boiling $\approx$ heat capacity

M. Yazdani-Asrami et al, EUCAS 2017
Fault tolerance: maximizing the recovery current

- HTS transformer needs to be able to recover after a fault while carrying rated current
- Increasing the heat transfer when cooling from around 300 K:
  1. Subcooled operation increases heat transfer in film and nucleate boiling regimes because the vapour phase condenses in the liquid
  2. Coatings with tailored thermal resistance $\frac{d}{k}$ extend the range of wire temperature for nucleate boiling by insulating the interface with the liquid nitrogen from the hot wire

M. Yazdani-Asrami et al, Poster P-16, this meeting
Fault tolerance: nitrogen boil-off

- HTS transformer should ideally survive a fault without cryogen boil-off
- Subcooled operation ensures gas venting limited by condensation in subcooled liquid: bulk of vapour is condensed and heat taken up by liquid heat capacity
- 45 kVA demonstration: only 1-2% of fault dissipation results in boil-off, temperature rise ~2 K in ~1/3rd of subcooled space
- Gas venting should not be a problem given sufficient cryogen capacity: ~ 1 kg/kJ fault energy

45 kVA FCL transformer winding: 2 K temperature rise of nitrogen at winding top at each short circuit, but surface liquid hardly affected

M. Yazdani-Asrami et al, EUCAS 2017
Summary

• Cost: cryosystem must be designed for TCO competitiveness with conventional transformers

• Cryocoolers:
  • Capital cost is a fraction of TCO
  • Multiple units – high lifetime maintenance $/kW

• Cryostats: opportunity for foam insulation

• Overload: large extra cooling load demands pumped liquid nitrogen back-up system

• Fault currents: subcooled LN and solid insulation aid recovery after fault is isolated