Robinson Research Institute

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 [1]
  - Cost competitive, depending on circumstances [2]
  - 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

[1] Pardo et al, 2015, Supercond. Sci. Tech. 28, 114008
[2] Staines et al, 2015, EUCAS poster presentation

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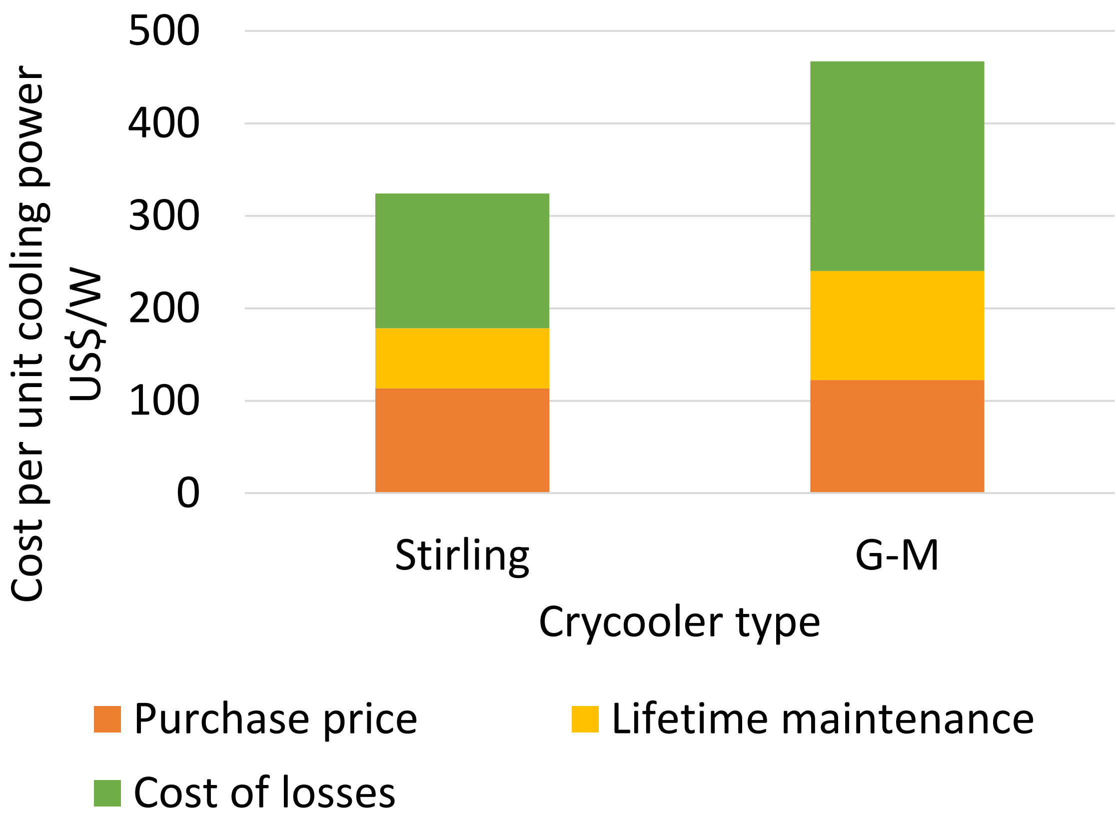
A cryocooler comparison (illustrative, not definitive)

	Gifford-McMahon	Stirling
	Cryomech AL600	Stirling Cryogenics SPC-4
Cooling power at 65 K (W)	470	2800
Cooling penalty (W/W)	26.5	16
Heat transfer	Conductive	Heat pipe / reliquefier
Load matching	Multiple units (6), can be cycled	Single unit meets base load
Back-up cooling	N+1 redundancy (extra unit)	Stored cryogen + pump
Overload cooling reserve	Stored cryogen + pump	Stored cryogen + pump

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

Turbo-Brayton: high efficiency; large capacity, variable - possibility for future

Cryocoolers – total cost of ownership (TCO)



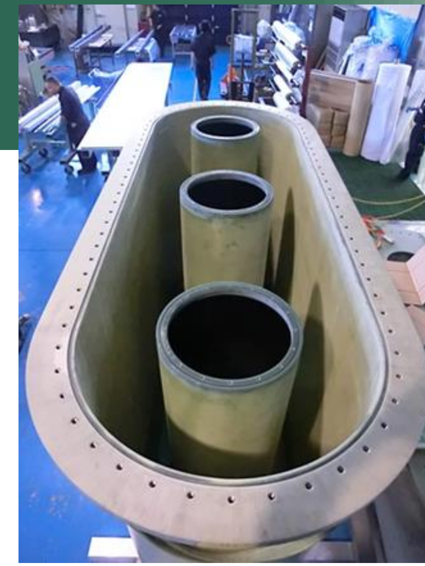
The figure of merit is the TCO per watt of cooling power, calculated here for:

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

Back-up system costs not included

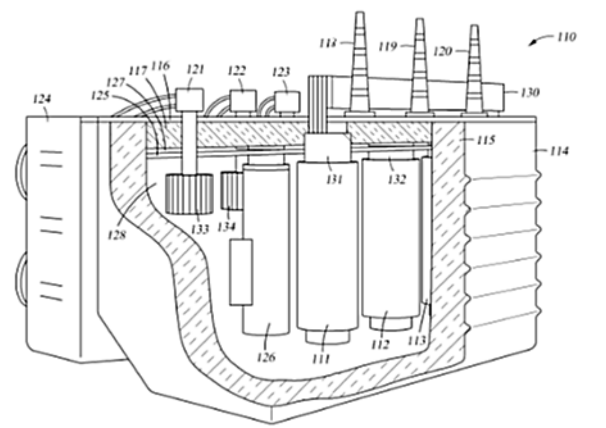
- Purchase price similar
- Maintenance costs add up
- Efficiency counts : lifetime cost of losses > purchase price (for 100% load factor)

Cryostats – hybrid concept



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

Hybrid cryostat concept:

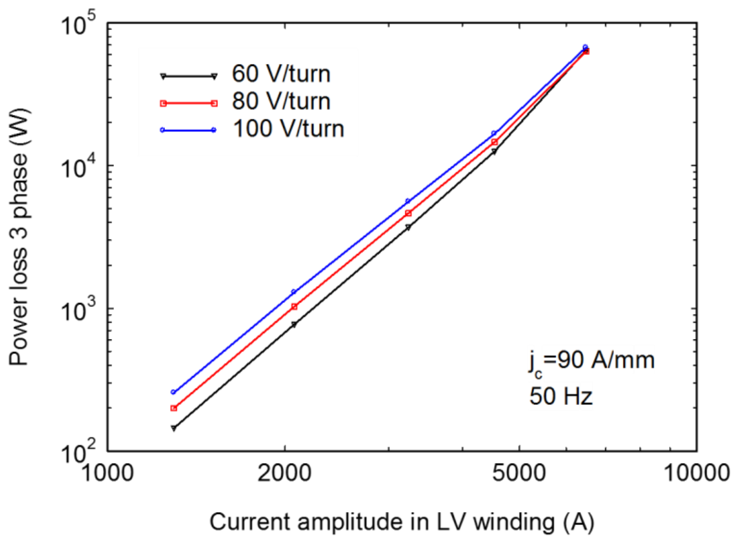


- Use vacuum insulation only around core penetrations
- Substitute foam around main tank 20 – 30 cm thick
- Estimated heat leak of foam tub ~300 W
- Lifetime energy cost ~$40K ($100K using TCO)
- Increased cost of vacuum cryostat is not justified by lifetime cost of losses

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

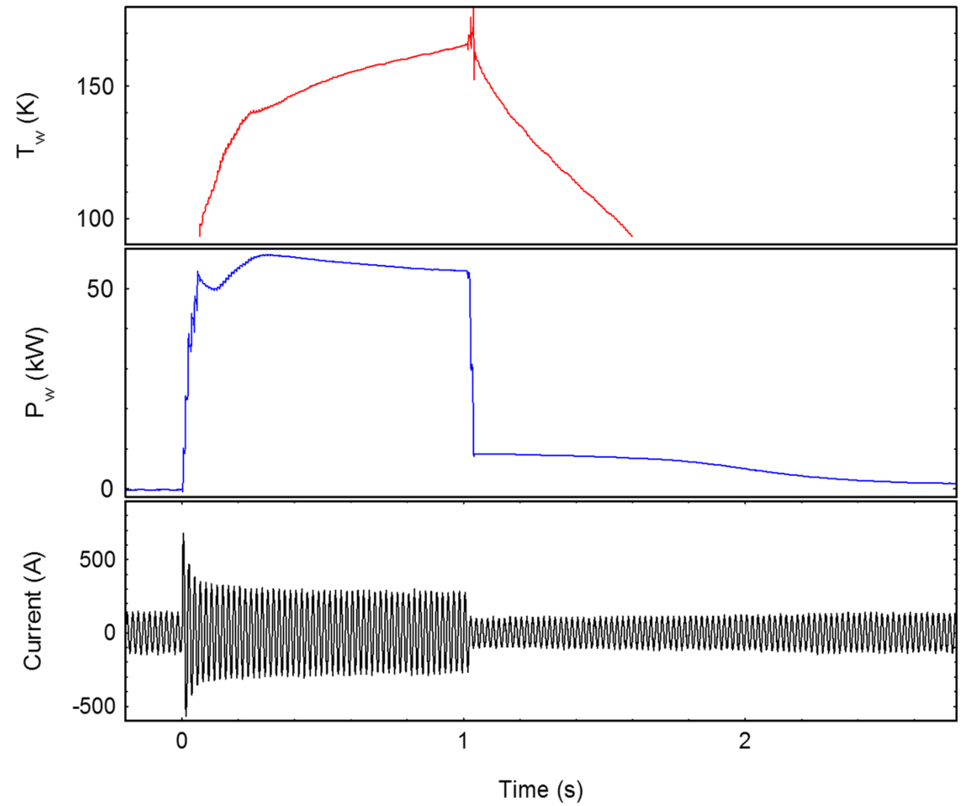


Calculated AC loss for 40 MVA design; loss increases as $I^{3.5}$

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 A/mm^2
- Compare with $J \sim$ 3 A/mm^2 for copper transformers
- Even with $J_e \sim$ 20 A/mm^2 HTS transformers can be much smaller and lighter than conventional



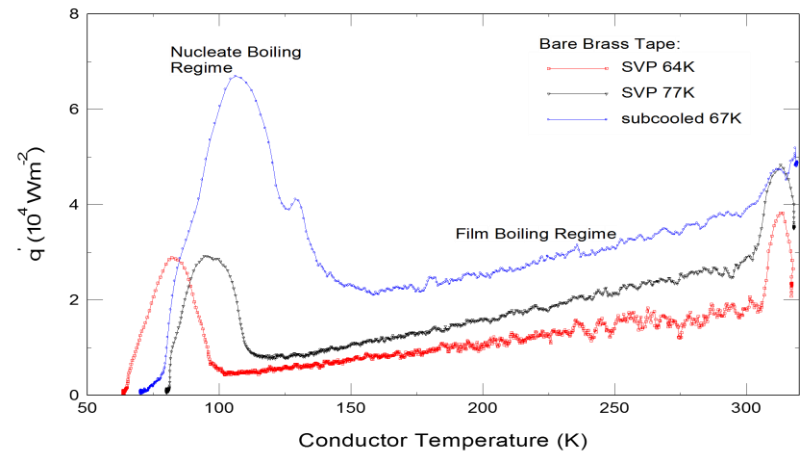
45 kVA FCL transformer winding, 0.4 mm thick wire: Heat transferred by boiling ≈ heat capacity

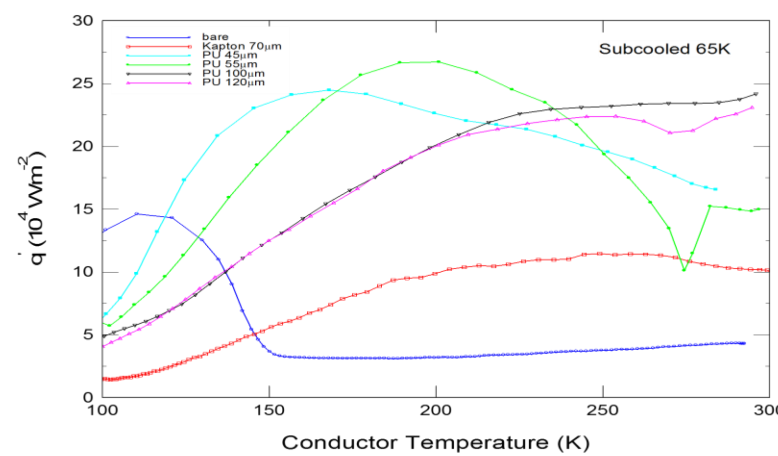
M. Yazdani-Asrami et al, EUCAS 2017

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 $\frac{d}{\kappa}$ extend the range of wire temperature for nucleate boiling by insulating the interface with the liquid nitrogen from the hot wire

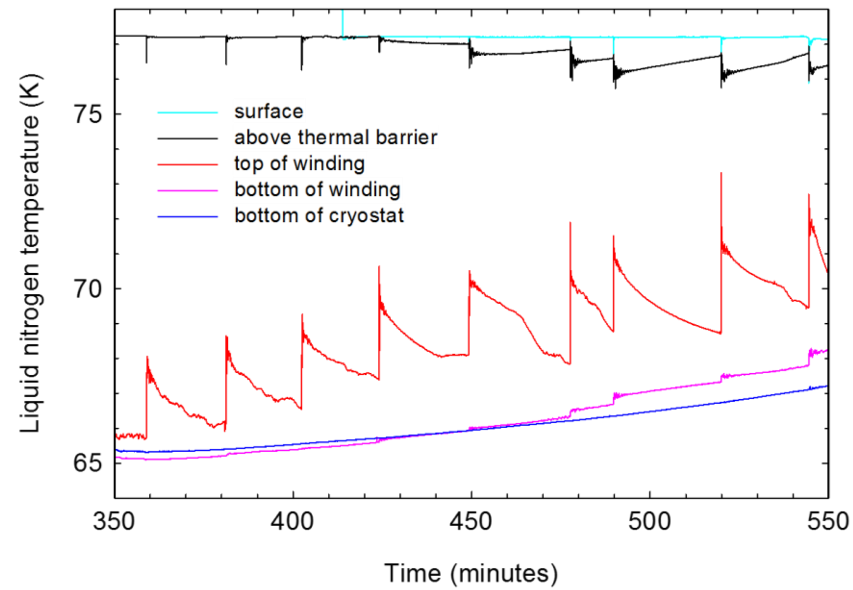




M. Yazdani-Asrami et al, Poster P-16, this meeting

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