Cooling topology options for HTS rotating electric machinery

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**Motivation**

- High-temperature-superconductors are being developed for use in rotating electric machinery
- Rotors for low speed, medium power (5~10 MW) wind turbines
- Fully-superconducting high-speed machines for airpower & shipboard generation and propulsion
- Challenging cryosystem design for high-speed, fully-superconducting machines
- High AC losses in stator
- Rotor cooling typically requires high-speed cryogen transfer coupling

**Objective**

- Examine unconventional cryostat configurations to reduce cryosystem demands
- Emphasize cooling options for high ac loss stator windings

**Common cryostat configuration**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Pro</th>
<th>Con</th>
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<tbody>
<tr>
<td>Active 20 K cooling of MgB₂ stator, convection cooling of 50~60 K ReBCO rotor</td>
<td>√ Elimination of high-speed rotor cryocoupling</td>
<td>× Need to control cryostat residual gas pressure – balancing windage vs. heat transfer</td>
</tr>
<tr>
<td>Torque transfer through magnetic coupling and non-conducting cryostat boundary</td>
<td>√ No hermetic shaft seals</td>
<td>× Large size, complex configuration, large cantilever for rated torque</td>
</tr>
<tr>
<td>Magnetic bearings inside cryostat</td>
<td>√ Large reduction in rotating friction heat load</td>
<td>× The load (motor weight and torque) gets transmitted through the cryostat. × Low radial stiffness may affect dynamic mechanical stability</td>
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**Residual gas cooling for ReBCO-based rotor**

- Assume 1 m long, 0.36 m diameter rotor
- Allow a rotor heat load of 130 W (~100 W/m²)
- Use ~1 mTorr H₂ or He gas pressure in cryostat for cooling where, conductivity, k, viscosity, υ, are pressure independent
- Actively cool stator to ~ 20 K
- Simulate operation at 7000 rpm, with 1 cm gap
- Roughly 35 K temperature difference stator to rotor
- 0.01 N-m torque and 10 W loss to windage
**Stator conductor and cooling design**

- Conductor based on fine-filament MgB$_2$ strand
  - ~10 μm filament diameter
  - ~10 mm twist pitch
  - ~10$^{-6}$ Ohm-m matrix resistivity
- Two-channel cable-in-conduit configuration
  - Inner cooling channel diameter accommodates conductor ac losses (hysteresis, coupling, transport current)
  - 15~20 m conductor length per stator winding
  - Strand diameter and number to fit annular cable space
- Helium gas cooling
  - 20 K, 20 atm gas supplied at conductor inlet
  - ½ atm pressure drop, 3 K temperature rise at outlet
- Estimated stator losses for 14 MW, 7 krpm, 6.6 kV design
  - 1.7 ~ 3 W/m conductor ac loss
  - 1.0 ~ 1.5 W in iron teeth
  - 25~30 kW in back iron

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**Separate cryostat - for rotor, and entire stator**

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<tr>
<td>Separation of teeth from back iron</td>
<td>✓ Removes large back iron loss from cryogenic environment</td>
<td>X Complicated cryostat design and stator assembly</td>
</tr>
<tr>
<td>Use of non-magnetic teeth between stator windings</td>
<td>✓ Removes iron tooth loss from cryogenic environment ✓ Provides robust mechanical support for stator windings</td>
<td>X Increases magnetic field amplitude (and hysteresis ac loss) on stator conductor</td>
</tr>
<tr>
<td>Use of conventional room temperature rotor bearings</td>
<td>✓ Proven technology</td>
<td>X Challenging design to minimize heat leak to rotor while maintaining high shaft stiffness for dynamic stability</td>
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Rotor cryostat design considerations

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<tbody>
<tr>
<td>Warm rotor iron</td>
<td>Faster cool down time</td>
<td>Space constraint; Large number of load cycles (7 Billion/yr) may limit lifetime of internal cryostat structural/thermal elements</td>
</tr>
<tr>
<td>Cryogenic transfer coupling</td>
<td>Increased cooling reliability compared to residual gas transfer</td>
<td>Challenging design at this rotational speed</td>
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Stator with individual coil cryostats

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<tr>
<td>Elimination of cold stator iron and cold stator teeth</td>
<td>Significant reduction in cryogenic heat load</td>
<td>Reduction in mechanical support for stator windings; Large number of load cycles (7 Billion/yr) may limit lifetime of internal cryostat structural/thermal elements</td>
</tr>
<tr>
<td>Introduction of cold bus between stator windings</td>
<td>Permits replacement of individual faulty coil</td>
<td>Complicated assembly and QA procedures</td>
</tr>
<tr>
<td>Introduction of adjacent phase winding in common slots</td>
<td>Simplifies assembly; Maximizes use of rotor field</td>
<td>Leads to significant magnetic field peaking; Cryostat design significantly limited by the space constraint between the teeth</td>
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Summary

- Significant challenges to the development of high-speed, HTS rotating electric machinery exist
- Relatively high conductor ac loss, compared to equivalent LTS conductors
- Cannot efficiency gain from higher temperature (20~50 K) gas cooling, offset by low coolant density
- Use of high-speed cryo-transfer coupling for rotor cooling remains challenging
- Additional cryostat topologies will be examined in effort to improve feasibility
- No significant break throughs yet
- Working to reduce magnetic field peaking for individual stator winding cryostat configurations