Superconducting Rotating Machines

Qiang Li

Head of Advanced Energy Materials Group
Topology and advantages of SC Machines

- High magnetic field in the air gap (1.5 – 2 Tesla) and no iron core in SC rotor
  - Low synchronous reactance,
  - Robust during the transient faults.
  - Superior damping
  - Improved reactive power (VAR) for both over- and underexcited operating conditions.
  - Compact and lighter

- Virtually no harmonics in the terminal voltage.

- Potentially longer rotor life due to the elimination of thermal load cycling for field winding current changes.

- Higher efficiency, even under partial load conditions, with potential for significant operating cost savings.

- Structure-related vibrations and noise are lower than conventional machines

Scaling relationship for ship propulsion motors - low speed, high torque

P ~ D^5 – SC Motors

P ~ D^3 – Conventional motors

Size Comparison of Large Wind Turbines

Main Stream Geared | Conventional Direct Drive | Optimized HTS Direct Drive (AMSC)

5 MW

4.5 MW

10 MW

LTS SC Machines

Mid 1960s
- Multifilamentary NbTi
- Development of nuclear power

LTS SC machine R&D (1970s-1990s)
- Westinghouse
  - 5MV utility generator
  - 5/10-MVA SC generator for the US Air Force
- GE built 20 MV generators
  - Two-pole 60 Hz
  - Four-pole high frequency

Super GM (Japan)-built generator—70-MW two-pole 60-Hz machine. Three SC rotors tested in a common stator. (12 years project started in 1988)

Siemens/KWU
SC Rotor model ready for cooldown

Alstom prototype rotor - a 1200-MW

**LTS SC Machines**

- Difficulty of transporting liquid helium to the rotor with inlet and outlet temperatures within a band of 4–6K.
- Small thermal margin of LTS windings, which were prone to quench with slightest local rise in temperature.
- Reliability concerns relating to liquid helium refrigerators.

**HTS SC Machines**

- Only ambient-temperature helium is transferred to the rotor
- Cryocooler cold heads are located on the rotor for cooling the HTS windings.
- Windings operating at 30–40K have large thermal margin.
- Cryostat (thermal barrier on the rotor) design is much simpler
- Available off-the-shelf cryocoolers are reliable and mean time between failure (MTBF) is estimated to be >9 years.
HTS SC Machines

Neon-operated commercial GM cryocooler (thermosiphon) in the foreground of a Bi-HTS race-track coil for a 400 kW synchronous motor (in blue) (Siemens).

Completed cold mass of rotor (SC coils and filler pieces) on pole former before bandaging and application of superinsulation.

Closed-cycle rotor cooling system, GM cryocooler inserted from top, motor shaft on the left.
HTS Wire Development

1) SuperPower-Inc., Schenectady, NY – 2G (ReBCO) coated conductor
2) AMSC, Devens, MA – 2G (ReBCO) coated conductor
3) SuNAM, Korea – 2G (ReBCO) coated conductor
4) Sumitomo Electric Industries (SEI), Japan – 1G (DI-BSCCO-2223) wire
5) Hypertech Research, Columbus, OH – MgB₂ wire.

Table 5.6.2 Summary of HTS wire characteristic data in 2013.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Super power</th>
<th>AMSC</th>
<th>SuNAM</th>
<th>DI-BSCCO-2223</th>
<th>MgB₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>ReBCO</td>
<td>ReBCO</td>
<td>ReBCO</td>
<td>BSCCO-2223</td>
<td>MgB₂</td>
</tr>
<tr>
<td>Critical current, $I_c$ (A)</td>
<td>480</td>
<td>500</td>
<td>390</td>
<td>200</td>
<td>2000</td>
</tr>
<tr>
<td>Temperature at quoted $I_c$ (K)</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>20</td>
</tr>
<tr>
<td>Wire width (mm)</td>
<td>12.2</td>
<td>12.3</td>
<td>12.2</td>
<td>4.6</td>
<td>1</td>
</tr>
<tr>
<td>Wire thickness (mm)</td>
<td>0.1</td>
<td>0.32</td>
<td>0.20</td>
<td>0.26</td>
<td>1</td>
</tr>
<tr>
<td>Copper stabilizer thickness (mm)</td>
<td>0.045</td>
<td>0.1</td>
<td>0.09</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Critical tensile strength at 77K (MPa)</td>
<td>550</td>
<td>150 (RT)</td>
<td>700</td>
<td>130</td>
<td>—</td>
</tr>
<tr>
<td>Critical axial tensile strain at 77 K (%)</td>
<td>0.45</td>
<td>—</td>
<td>0.4</td>
<td>0.2</td>
<td>—</td>
</tr>
<tr>
<td>Critical bend diameter in tension at RT (mm)</td>
<td>11</td>
<td>100</td>
<td>30</td>
<td>70</td>
<td>—</td>
</tr>
<tr>
<td>Critical bend diameter in compression at RT (mm)</td>
<td>11</td>
<td>100</td>
<td>30</td>
<td>70</td>
<td>—</td>
</tr>
</tbody>
</table>

Operating Temperature

- ReBCO: 30–35K
- DI-BSCCO: 30K
- MgB₂: 20 K

Superconducting Wires for Direct-Drive Wind Generators

Qiang Li (PI) - Brookhaven National Lab

Project target: 1600 A/cm-w at 30 K, 1.5 T //c

BNL scientist Qiang Li discusses next-generation superconducting wires with US Energy Secretary Ernest Moniz at February 2014 ARPA-E Energy Innovation Summit

Superconducting Wires for Direct-Drive Wind Generators

Qiang Li (PI) - Brookhaven National Lab

At Brookhaven National Laboratory, we demonstrated a roll-to-roll irradiation process\(^1\) on an AMSC’s production length 2G wire (46 mm wide and over 80 meters long) that resulted in doubling the critical current in the 4 – 50 K operating regime targeted for rotating machine applications and high field magnet applications.\(^2\) The roll-to-roll irradiation was carried out with ion energies readily accessible with commercial electrostatic generators.

\(I_c\) enhancement at 30 and 77K (relative to an unirradiated control sample) of a stationary short sample and a moving tape after irradiation with 18 MeV Au to a dose of \(6 \times 10^{11} \text{ Au/cm}^2\)

References

1. Patent pending (BNL/AMSC)
2. To be presented at EUCAS 2015
HTS 2G wire price (current $150-250/KA-m)

Total cost of a 12 MW SCSG

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>20.5 $/kg</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>1.5 $/kg</td>
</tr>
<tr>
<td>Silicon steel plate</td>
<td>4.1 $/kg</td>
</tr>
<tr>
<td>HTS wire</td>
<td>5 $/m (100 A @ 77 K)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parts</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator coil</td>
<td>985 k$</td>
</tr>
<tr>
<td>Stator body</td>
<td>206 k$</td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>18 k$</td>
</tr>
<tr>
<td>Rotor body</td>
<td>16 k$</td>
</tr>
<tr>
<td>HTS wire</td>
<td>1,873 k$</td>
</tr>
<tr>
<td>Structure</td>
<td>306 k$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Active parts</th>
<th>Weight</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator coil</td>
<td>48 ton</td>
<td>Copper</td>
</tr>
<tr>
<td>Stator body</td>
<td>50 ton</td>
<td>Silicon steel plate</td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>12 ton</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Rotor body</td>
<td>11 ton</td>
<td>Stainless steel</td>
</tr>
</tbody>
</table>

Total length of HTS wire: 375 km

Total cost of the 12 MW SCSG
=3,403,709 $, ~4M$
~15% of total system price

Ref. Design of direct-driven permanent-magnet generator for wind turbines, Anders Grauers
Ref. SuperPower (4mm HTS wire)
Challenges for HTS motors

Applications

- **slow speed (<20 r/min)**
  wind generators, ship propulsion motors
- **(100–250 r/min)**
  Industrial motors, generators
- **(1200–3600 r/min)**
  synchronous condensers, high-speed generators
- **(15000-r/min)**
  direct coupling to gas turbines.

- Rotor winding and cooling
  (3D winding, pancake coils?)
  (MgB$_2$ wire is better)
- Coolant transfer to rotor (solved)
- Stator winding consideration
- User acceptance
- HTS wire cost, in field performance
Superconducting Motors

Q. Li – Brookhaven National Lab
ARPA-E Advanced Motor Drive Commercialization, March 15, 2012, Orland, FL

Superconducting Motor for Ship propulsion

HTS motor: Small & Light, Cooled by liquid Nitrogen, High efficiency, Low CO₂ Emission

World’s Largest L Nitrogen cooled HTS Motor with High Torque Density: 1.8x10⁴ Nm/m³

HTS Electric Vehicle

To validate the potentials and challenges of DI-BSCCO, the Electric vehicles drove by HTS Motor were developed.

- Max Speed 85 km/h
- Max Torque 120 Nm
- Max Power 31 kW

Precondition
- Route bus
- 600 thousands
- 50,000km/y

Expected Energy Loss Reduction >10%

Figures and Photos - Courtesy of Dr. K. Sato, Sumitomo Electric Industries, Japan,