Superconducting Generator Technology for Large Offshore Wind Turbines

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Motivation

- Weight and volume reductions
- Practically rare earth metal independent

In the end, it is all about costs
Superconductors

- Materials that carry large DC current densities lossfree at low temperatures
- Exhibit losses under AC operation
- Widely used in MRI diagnostics equipment at hospitals
- Under evaluation for several large scale power applications
The concept

- Rotor field generated by superconducting coils at cryogenic temperatures

- Stator (armature) windings composed of copper conductors at room temperature
Volume and weight is magnetic field dependent

- \( P = \omega \tau \)
  - \( \omega \) is the angular frequency (given by maximum tip speed)
  - \( \tau \) is the torque

- \( \tau \propto B I V \)
  - \( B \) is the air gap magnetic field
  - \( I \) is the stator current (given by stator constraints)
  - \( V \) is the generator volume

The only variables to play with are the magnetic field strength and the volume
Volume and weight: Superconductor versus permanent magnets

- Permanent magnet air gap flux density ~ 1 T
- Superconductor air gap flux density ~ 2.5 T
- Superconductor generator volume 40% less than corresponding permanent magnet generator

Additionally, the superconductor field windings are light weighted.
Rare earth metal dependency: Superconductor versus permanent magnets

10 MW generator:

- Permanent magnet based: 6 ton RE PM
- Superconductor based: 10 kg RE in HTS

A permanent magnet based off-shore generator technology would double the world market for such magnets
The superconductor possibility –
Current trends in research

Choosing superconductor

• Choice of operating temperature, magnetic field strength, cost and availability

• Superconducting wires are under development – increasing performance, reducing costs

Several actors – several concepts
## Conductors

<table>
<thead>
<tr>
<th>Material type</th>
<th>Operating temperature</th>
<th>Magnetic field</th>
<th>Current density</th>
<th>Cost 2012</th>
<th>Cost 2020 (at large scale deployment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>4.2 K</td>
<td>5 T</td>
<td>1000 A/mm²</td>
<td>1 €/kAm</td>
<td>1 €/kAm</td>
</tr>
<tr>
<td>YBCO</td>
<td>40 K</td>
<td>3 T</td>
<td>200 A/mm²</td>
<td>300 €/kAm</td>
<td>30 €/kAm</td>
</tr>
<tr>
<td>MgB₂</td>
<td>20 K</td>
<td>3 T</td>
<td>200 A/mm²</td>
<td>10 €/kAm</td>
<td>3 €/kAm</td>
</tr>
<tr>
<td>Cu</td>
<td>50°C</td>
<td>&lt; 1 T</td>
<td>4 A/mm²</td>
<td>50 €/kAm</td>
<td>50 €/kAm</td>
</tr>
</tbody>
</table>

## Generator activities

<table>
<thead>
<tr>
<th>Material type</th>
<th>Transmission</th>
<th>Power rating</th>
<th>Industrial interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>Direct drive</td>
<td>10 MW</td>
<td>General Electric</td>
</tr>
<tr>
<td>YBCO</td>
<td>Direct drive</td>
<td>10-15 MW</td>
<td>AMSC</td>
</tr>
<tr>
<td>MgB₂</td>
<td>Direct drive</td>
<td>10 MW</td>
<td>Advanced Magnet Lab European consortia – Suprapower, InnWind.EU</td>
</tr>
</tbody>
</table>
General Electric (GE) 10-15MW

- LTS – Superconducting field winding
- Extensive experience from the MRI sector
- Rotating armature

- Challenge
  - Complicated cooling system and higher cooling power

- Advantage
  - Proven technology from MRI
  - Cheaper superconductor

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American Superconductor (AMSC)  
SeaTitan 10MW

- HTS – Superconducting field winding  
- Copper armature winding  
- Generator diameter: 4.5–5 meters  
- Weight: 150-180 tonnes (55-66Nm/kg)  
- Efficiency at rated load: 96%

- Challenge  
  - HTS price and availability

- Advantage  
  - Relatively simple cooling system with off-the-shelf solutions  
  - Cooling power

Highest torque HTS machine intended for ship propulsion:
- 36.5MW @ 120rpm  
- 2.9MNm @ 75 tons  
- 39Nm/kg

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Advanced Magnet Lab (AML)
10MW fully superconducting

- MgB$_2$ – Fully superconducting generator
- Superconducting field winding
- Superconducting armature winding

- Challenge
  - Complicated cooling system and higher cooling power
  - Improvement in MgB$_2$ wire is needed
  - AC losses

- Advantage
  - Cheap superconductor
  - Fully superconducting
  - More torque dense

\[ P = \omega \times T \quad , \quad T \propto A \times B \times V \]

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Aiming at integrated wind turbine concepts with:

- Light weight rotor
- Low-weight, direct drive generator
- Standard mass-produced tower and substructure

- Design of 10-20 MW concepts
- Hardware demonstrators of critical components

A joint European effort with more than 25 partners
MgB$_2$ superconducting rotor coils

- MgB$_2$ superconductors from multiple producers

- Scaled race-track coils

Evaluating key components
INNWIND.EU

MgB₂ superconducting rotor coils

• Testing at full-scale thermal and electromagnetic conditions
• 15-20 K, 3-4 T, 200 A/mm²

Taking advantage of existing magnet technology
Summary

• Superconducting generators may reduce volume and weight

• Material development intensive

• Basic design concept under evaluation

• Reliability to be proven

• Cost is both the prime concern and the prime driver