Advantages and Challenges of Superconducting Wind Turbine Generators

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Publication date: 2012

Citation (APA):
Advantages and Challenges of Superconducting Wind Turbine Generators

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2\textsuperscript{nd} International Conference E/E Systems for Wind Turbines
21\textsuperscript{st} – 23\textsuperscript{rd} May 2012, Bremen, Germany

DTU Electrical Engineering
Department of Electrical Engineering
Overview

• Background of superconductivity and its relevance for wind turbine generators

• Advantages of superconducting generators for wind turbines

• Challenges of superconducting generators for wind turbines

• Commercial activities
BACKGROUND
Technical University of Denmark (DTU)

- Based in Copenhagen, the Capital of Denmark
- 8200 students – 530 faculty – 1040 researchers
- Ranked 4th in Europe in the field of engineering by THE based on citations per journal paper from 2000-2010

(http://www.timeshighereducation.co.uk/story.asp?storyCode=414302&sectioncode=26)
Development of wind turbines

\[
\text{CoE} = \frac{\text{Annualised CAPEX and OPEX}}{\text{Annual energy production}}
\]
Current trend

- Elimination of Gearbox
- Permanent Magnet Generators

Conventional Turbine Generator

Copper Wound-Coil with Gearbox > 500 Tons

10 MW

Next Generation - No Gearbox

Permanent Magnet > 320 Tons

> 320 Tons
# 5MW and beyond

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Transmission</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens Wind Power</td>
<td>Direct drive</td>
<td>PMSG 6.0MW</td>
</tr>
<tr>
<td>Vestas</td>
<td>Medium speed</td>
<td>PMSG 7.0MW</td>
</tr>
<tr>
<td>Enercon</td>
<td>Direct drive</td>
<td>EESG 7.5MW</td>
</tr>
<tr>
<td>Alstom</td>
<td>Direct drive</td>
<td>PMSG 6.0MW</td>
</tr>
<tr>
<td>REPower</td>
<td>High speed</td>
<td>DFIG 6.2MW</td>
</tr>
<tr>
<td>Areva</td>
<td>Low speed</td>
<td>PMSG 5.0MW</td>
</tr>
</tbody>
</table>

# 10MW and beyond – proposals/investigations

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Transmission</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Superconductor</td>
<td>Direct drive</td>
<td>HTS 10MW</td>
</tr>
<tr>
<td>General Electric</td>
<td>Direct drive</td>
<td>LTS 10-15MW</td>
</tr>
<tr>
<td>Advanced Magnet Lab</td>
<td>Direct drive</td>
<td>MgB₂ 10MW</td>
</tr>
</tbody>
</table>
Schematic of a Superconducting Machine

- The superconductor must be kept at cryogenic temperatures

- The armature winding is usually proposed to be copper at ambient temperature

\[ P = \omega \times T \]

\[ T \propto A \times B \times V \]

- \( P \): power
- \( T \): torque
- \( \omega \): rotational speed
- \( A \): electric loading
- \( B \): magnetic loading
- \( V \): volume
High Temperature Superconductors

- The superconducting state is limited by
  - Critical flux density $B_c$
  - Critical current density $J_c$
  - Critical temperature $T_c$

- Superconducting materials can be characterised by IV curves

$$E[V / m] = E_0 \left( \frac{J}{J_c(B,T)} \right)^{n(B,T)}$$

- $E_0$ is the electric field at the critical current (1μV/cm)
Overview of superconductors

<table>
<thead>
<tr>
<th>Type</th>
<th>Price €/m</th>
<th>$J_e$ A/mm²</th>
<th>Flux density [T]</th>
<th>Temp. [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>0.4</td>
<td>$10^3$</td>
<td>5</td>
<td>4.2</td>
</tr>
<tr>
<td>Nb₃Sn</td>
<td>3</td>
<td>1-4$\times$10³</td>
<td>5</td>
<td>4.2</td>
</tr>
<tr>
<td>MgB₂</td>
<td>4</td>
<td>$10^2$</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Bi-2223</td>
<td>20</td>
<td>390</td>
<td>3 tape</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>3 tape</td>
<td>50</td>
</tr>
<tr>
<td>YBCO</td>
<td>30</td>
<td>98 (480)</td>
<td>3 tape</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49 (190)</td>
<td>3 tape</td>
<td>50</td>
</tr>
</tbody>
</table>
ADVANTAGES
Generator Power

\[ P = \omega_m T = \omega_m \sqrt{2AB_gV \cos(p\psi)} \]

\[ A \approx 70,000 \text{A/m} \text{ limited by stator cooling} \]
\[ \omega \approx 1.05 \text{rad/s} \text{ limited by the power rating of the WT} \]
(around 10rpm at 10MW)

PM Generator \( B_g = 0.9 \text{T} \)  
HTS Generator \( B_g = 2.5 \text{T} \)

\[ P = 10 \text{MW} \Rightarrow V_{PM} = 115 \text{m}^3 \]
\[ P = 10 \text{MW} \Rightarrow V_{HTS} = 42 \text{m}^3 \]

With an axial stack length of 2.0m, this would result in an airgap diameter of:

\( D_g = 8.6 \text{m} \)
\( D_g = 5.2 \text{m} \)
**PM in wind turbines**

- A 6MW direct drive wind turbine is estimated to use 5 tons of permanent magnets

- This is the same as 2500 Toyota Prius

- Should we be worried?
Summary

• Very high torque density

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

• Very limited dependence on rare earth materials

<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid</td>
<td>50kgR/MW</td>
<td>20gR/MW</td>
</tr>
<tr>
<td>Direct drive</td>
<td>250kgR/MW</td>
<td>100gR/MW</td>
</tr>
</tbody>
</table>

\[ m_R = 0.27m_{R-B-Fe} \]

• Higher efficiency than an equivalent direct drive PM generator

\[ P_{Cu} = I_{Cu}^2 R_{Cu} = J_{Cu}^2 A_{Cu}^2 \frac{l_{Cu}}{A_{Cu} \sigma_{Cu}} = \frac{J_{Cu}^2 V_{Cu}}{\sigma_{Cu}} \]
CHALLENGES
Cooling system

- The superconductors need to be cold:
  - <5K for LTS
  - <20K for MgB$_2$
  - 30-50K for HTS

- Insulation requires large effective airgap
  - Large fault currents and torques

- Torque transfer

- Reliability has yet to be proven and requires years of operating experience

- Production capacity of HTS and MgB$_2$ are currently not adequate for large-scale commercialisation – this should change if the need is present
Size and weight

- Size and weight do not necessarily scale linearly
  \[ P = \omega \times T, \quad T \propto A \times B \times V \]

- Iron coreback is required to shield the magnetic field from ambient

- Not as cheap to increase the number of poles

Mass, HTS length and price as a function of pole number
Cost of HTS and PM in a 10MW wind turbine

• If 400km of 4mm HTS tape is assumed for a 10MW wind turbine generator

• With a current carrying capacity of 80A and a price of €50/kAm, this gives €4/m

• The cost of the HTS tape for a 10MW would therefore be €1.6 million

• In addition the cryostat, cryocooler etc. will have to be added

• PM price today? €50/kg

• If 10 tons of PM is required for a 10MW wind turbine

• The cost of the PM for a 10MW would be k€500
Future cost of HTS must/will come down

• It is not unlikely that the price of HTS tape will come down to €15/kAm

• This would result in €480,000 for a 10MW wind turbine

• This would be competitive with PM technology

• But it is clear that the usage of HTS tape must be minimised!
COMMERCIAL ACTIVITIES
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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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

Reproduced with permission from GE
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

\[ P = \omega \times T \]
\[ T \propto A \times B \times V \]
Patent Development

- Web of Knowledge search with keywords: “Supercond*” and “machin*”
Discussion and conclusion

• Superconducting generators might be the answer to large wind turbines
  – Smaller generator
  – Less RE demand by a three orders of magnitude

• A collaborative effort is needed including:
  – Wire manufacturers
  – Wind turbine manufacturers
  – Wind turbine operators

• Large-scale demonstrators are needed
  – To test the performance in a wind turbine
  – To test the reliability
Continue research at universities

- Building small scale prototypes
- Learning from these and extrapolating to large scale
Results for a simple prototype

![Image of a simple prototype](image.png)

- **Simulation of perpendicular flux as a function of current**
- **Measured critical current of the HTS tape**

![Graph showing simulation and measurements](graph.png)

- **Voltage across HTS tape vs. Current in HTS tape**
- **Torque vs. Rotor angle**
THANK YOU!
QUESTIONS?