Lightweight 10MW MgB$_2$ superconducting generator

Ainhoa Pujana
ainhoa.pujana@tecnalia.com

BMEW 2015
Bilbao, 20 April 2015
CONTENT

• Offshore wind market
• Superconducting generators
• Integration in wind turbine
• Development plan
• Conclusion
Offshore Wind Market

Offshore Wind cumulative market

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>40 GW</td>
<td>150 GW</td>
<td>460 GW</td>
</tr>
<tr>
<td>World</td>
<td>100 GW</td>
<td>375 GW</td>
<td>1150 GW</td>
</tr>
</tbody>
</table>

Huge business volume expected for the upcoming years. But severe cost reductions are demanded to reach these predictions.

Market demands “more powerful and reliable wind turbines to reduce offshore wind farm CAPEX and OPEX”
Offshore Wind Market

LCOE comparison between 2 x 3MW and 1 x 6MW turbine

<table>
<thead>
<tr>
<th>DRIVER</th>
<th>3 MW turbine</th>
<th>6 MW turbine</th>
<th>IMPROVEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX [EUR m/MW]</td>
<td>1.35</td>
<td>1.55</td>
<td>+15%</td>
</tr>
<tr>
<td></td>
<td>2.55</td>
<td>2.10</td>
<td>-18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-6%</td>
</tr>
<tr>
<td>Capacity factor [%]</td>
<td>43</td>
<td>48</td>
<td>+12%</td>
</tr>
<tr>
<td>O&amp;M costs [EUR '000/MW/year]</td>
<td>140</td>
<td>120</td>
<td>-14%</td>
</tr>
<tr>
<td>LCoE [EUR c/kwh]</td>
<td>13.4</td>
<td>11.1</td>
<td>-17%</td>
</tr>
</tbody>
</table>

But...8/10 MW barrier the current wind generators are difficult to scale up to 10 MW and beyond. Huge generator size and weight drive up the cost of structure, foundations and installation operations.

Superconductivity is the only technology able to achieve a radical reduction of the generator mass

Over 100 times more current than copper wire of the same dimensions

CONTENT

• Offshore wind

• Superconducting generators
  - Superconducting low speed machines
  - 10 MW class MgB$_2$ superconducting generator
  - Challenges

• Integration in wind turbine
• Development plan
• Conclusion
Superconductors for low speed rotating machines

Specific Power ($kW/m^3$): \( \frac{P}{V} \propto B \cdot A \cdot \omega \)

- \( \omega \) (rad/s): rotating speed
- \( B \) (T): Air-gap Magnetic field
- \( A \) (A/m): Linear current density (depends on stator winding)

B↑

Superconductors have the ability to produce higher magnetic fields (B) than conventional PM generator

A↑

High B requires to eliminate stator teeth → air-gap winding is required but more space is available → more copper coils can be introduced → Higher A can be achieved

Higher Power rate, lighter and more compact generators
Superconducting generators for wind turbines

- There are several superconducting generator concepts, as those proposed by GE, AMSC, RISO-DTU or AML.
- In general they show relevant challenges as:
  - LTS generators require complex and very low efficiency cooling systems.
  - HTS generators use expensive materials (1G and 2G HTS), with uncertain cost reduction perspectives.
  - Cryogenic fluids based cooling system are too complex and have low reliability for offshore locations.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Operating T</th>
<th>Peak field</th>
<th>Critical Current Density</th>
<th>2013 Cost performance</th>
<th>COP(*) at Operating T</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>4.2 K</td>
<td>5 T</td>
<td>750 A/mm²</td>
<td>5 €/kAm</td>
<td>70</td>
</tr>
<tr>
<td>YBCO</td>
<td>40 K</td>
<td>3 T</td>
<td>400 A/mm²</td>
<td>200 €/kAm</td>
<td>6.5</td>
</tr>
<tr>
<td>MgB₂</td>
<td>20 K</td>
<td>1.8 T</td>
<td>100 A/mm²</td>
<td>30 €/kAm</td>
<td>14</td>
</tr>
</tbody>
</table>

(**) Coefficient of performance-Carnot. It is used to characterise the cooling systems
10 MW class MgB$_2$ superconducting lightweight generator

It gives answer to the offshore sector demands while overcomes other superconducting generators challenges.

- Synchronous salient pole, direct drive
- 10 MW, 8.1 rpm, 11.8 MNm
- MgB$_2$ superconducting field coils
- Cryogen free cooling system (reduce maintenance requirements)
- Modular Cryostats
- 48 warm iron poles
- Air-gap armature winding
- 1.5 T of induction peak value
- Airgap shear stress of 112 kPa
- 10.1 m air-gap diameter,
- 0.74 m stack length

Patented by TECNALIA (PTC/ES2009/070639)
10 MW class MgB$_2$ SC lightweight generator

✓ Armature

• Magnetic core:
  • Material: stack of laminated conventional electric steel sheet (M350-50A)
  • Slotless configuration, to avoid saturation.
    • More room to allocate armature winding
    • Challenge in mechanical fix
  • Number of “slots”: 1440

• Winding:
  • Conventional copper coils
  • Eccentric armature winding, 1 layer.
  • No short pitch
  • Current density in armature coils (A/mm$^2$): 3
  • Specific linear load (A/m): 120,000
  • Mechanical fixing solution (patentability under study)
10 MW class MgB$_2$ SC lightweight generator

✓ Inductor

• Magnetic core:
  • Material: moulded low carbon Steel AISI 1008
  • Back yoke + salient poles
  • Solid pieces
  • Poles bolted to the back yoke
  • Number of poles: 48

• Winding:
  • MgB$_2$ superconducting field coils operating in cryogenic conditions inside modular cryostats (100A, 20K)
  • Located around pole, as conventional
  • Warm iron poles: Only the superconducting coils are cooled
10 MW class MgB$_2$ SC lightweight generator

✓ MgB$_2$ field coils

- Stack of several MgB$_2$ double pancakes racetrack coils, connected in series, placed between 2 thick copper plates for refrigeration of the assembly
- MgB$_2$ sandwich tape-like wire, it can be easily wounded in pancakes, but not in a continuous coil
- Quench detection and protection system

Design and validation of a real scale SC coil
10 MW class MgB$_2$ SC lightweight generator

✓ Why MgB$_2$ wire?

It is an industrial solution with already competitive cost performance ratio

<table>
<thead>
<tr>
<th>MgB$_2$</th>
</tr>
</thead>
</table>
| **Application range** | 15 K – 25 K with B up to 4 T
4.2 K – 12 K with B up to 10 T |
| **Cooling system** | GHe, Cryogen Free, LH$_2$ |
| **Shape** | round/square/flat |
| **Length in a batch** | 1.5 to 3 km |
| **Availability** | Immediate |
| **Customization** | Sheath materials, dimensions, number of SC filaments, stabilization |
| **Average price (2013)** | 3 to 4.5 €/m |

Data and picture courtesy of

Decreasing Cost performance:
• Decreasing cost
• Enhancement of the SC performance
10 MW class MgB$_2$ SC lightweight generator

✓ Rotating modular cryogen free cooling system
  • Designed for facilitating offshore installations and maintenance operations
  • One modular cryostat per pole and a thermal collector

• Warm iron poles configuration:
  ➢ Reduction of mass to be cooled
  ➢ Reduction of torque transmitted to superconducting coils
  ➢ Reduction of mechanical airgap (smaller cryostat)

• Cryogen-free conduction cooling system:
  ➢ Commercial GM cryocooler (robust, reliable and low maintenance)
  ➢ Simpler cryostat compared to liquid based solutions.
10 MW class MgB$_2$ SC lightweight generator

Cooling systems scheme

Rotating part
Cold heads rotate with the rotor

Crycoolers

He distribution system

Rotary joint is required to connect the He compressor to the cold head

Low-pressure He

High-pressure He

Low-pressure He

Stationary part
He compressors

Cryo compressors

Low pressure He buffer
Challenges

**MgB₂ wire**
- Discovered in 2001
- Limited experience in coil manufacturing

**cryogen-free cooling**
- Complex design of cryostat
- Low efficiency of cryocoolers

Technology development and validation through a Small Scale Machine

- Magnetic circuit with 2 warm iron poles
- Identical SC coils and modular cryostat size, with similar operating conditions
- Same value of field excitation
- Same cooling system
- Same airgap distance
CONTENT

• Offshore wind
• Superconducting generators

• Integration in wind turbine

• Development plan
• Conclusion
Integration in Wind Turbine

✓ Baseline data of wind turbine

<table>
<thead>
<tr>
<th><strong>Rated Power (MW)</strong></th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated blade rotation speed (rpm)</strong></td>
<td>8.1</td>
</tr>
<tr>
<td><strong>Wind speed (cut out) (m/s)</strong></td>
<td>25</td>
</tr>
<tr>
<td><strong>Rated blade tip speed (m/s)</strong></td>
<td>81</td>
</tr>
<tr>
<td><strong>Turbine diameter (m)</strong></td>
<td>190</td>
</tr>
<tr>
<td><strong>Transmission type</strong></td>
<td>Direct Drive</td>
</tr>
<tr>
<td><strong>Power Factor</strong></td>
<td>0.95</td>
</tr>
<tr>
<td><strong>Grid connection</strong></td>
<td>Full converter</td>
</tr>
</tbody>
</table>
Integration in Wind Turbine

- Reference PM machine also studied for comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PM REFERENCE</th>
<th>SC OPTIMIZED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power (MW)</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Rated speed (rpm)</td>
<td></td>
<td>8.1 (direct drive)</td>
</tr>
<tr>
<td>Generator type</td>
<td>Synchronous</td>
<td>Synchronous, salient poles</td>
</tr>
<tr>
<td>Excitation</td>
<td>Permanent magnet</td>
<td>SC MgB2 field coils</td>
</tr>
<tr>
<td>Voltage at rated speed (V)</td>
<td>1725</td>
<td>2280</td>
</tr>
<tr>
<td>Number of poles</td>
<td>360</td>
<td>48</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>24.30</td>
<td>3.24</td>
</tr>
<tr>
<td>Airgap diameter (mm)</td>
<td>11900</td>
<td>10100</td>
</tr>
<tr>
<td>Gross magnetic axial length (mm)</td>
<td>1795</td>
<td>744</td>
</tr>
<tr>
<td>Specific shear stress in the air gap (kPa)</td>
<td>34</td>
<td>112</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>1080</td>
<td>1440</td>
</tr>
<tr>
<td>Current density in stator coils (A/mm²)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Average magnetic induction in airgap (T)</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>
Integration in Wind Turbine

✓ Comparison in terms of efficiency

Efficiencies of a DD Generator rated 10 MW

Efficiency vs Fraction of power at generator terminals for PM and SC Generators.
Integration in Wind Turbine

✓ Comparison in terms of weight and size

![Weight Comparison Chart]

Under calculation, but > 40t of weight reduction expected in the rotor structural part

Additional 10% improvements are expected at short term driven by superconducting wire properties improvement and mechanical design optimization.
Integration in Wind Turbine

✓ Comparison in terms of costs

Cost in the range of Permanent Magnets generator at the actual cost of rare earth and MgB$_2$

Superconducting generator cost reduction potential:
- MgB$_2$ wire properties improvement
- Reduction of modular cryostat size
- Smaller end turns in air gap winding
- Industrialization process after technology validation
Integration in Wind Turbine

✓ Initial conceptual integration of SC generator, actually in review
CONTENT
• Offshore wind
• Superconducting generators
• Integration in wind turbine
• Development plan
• Conclusion
## Development Plan

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Generator Design</td>
</tr>
<tr>
<td>2013</td>
<td>Patent granted</td>
</tr>
<tr>
<td>2015</td>
<td>MgB$_2$ coil development</td>
</tr>
<tr>
<td>2017</td>
<td>Full scale generator design and integration</td>
</tr>
<tr>
<td>2017</td>
<td>Technology Validation</td>
</tr>
<tr>
<td>2020</td>
<td>Industrial Development</td>
</tr>
</tbody>
</table>

- **2011**: Generator Design
- **2013**: Patent granted
- **2015**: MgB$_2$ coil development
- **2017**: Full scale generator design and integration
- **2020**: Industrial Development

**European FP7 funding**

**Cryostat and cooling system design and validation**

**Full scale generator design and integration**

**Industrial Studies**

**Business Plan**

**Full scale generator design and integration**
SUPRAPOWER Outline

• FP7 cofounded research project: www.suprapower-fp7.eu
• Time scope: 2012 - 2016
• Total Budget: 5,4M€, EC funding: 3,9M€
• TECNALIA leads a consortium of 9 partners:

Coordinator:

Industrial Partners:

Research centres and Universities:

Confidential information, unauthorized use or diffusion of this information is legally prohibited
CONTENT
• Offshore wind
• Superconducting generators
• Integration in wind turbine
• Development plan
• Conclusion
Competitive advantages

**Reliable & Efficient**
- Direct drive (no gearbox)
- Cryogen free modular cooling system. Easy and Reduced maintenance.
- Over 95% efficiency (on-site).

**Weight reduction**
- 30% weight reduction with respect to a 10 MW Permanent Magnet generator.
- Weight and cost reduction of structural elements as the tower or foundations and floating platforms.

**Free of Rare-earths**
- PM generators are very dependent on rare earths materials while TECNALIA’s generator is free of rare earths (High price volatility 600% in 2011)

**Cost competitive**
- Cost competitive, in the range of the PM’s at current cost of rare earths
- MgB$_2$ is a very cost competitive commercially available wire
Thanks for your interest

Ainhoa Pujana
ENERGY AND ENVIRONMENT DIVISION / TECNALIA
M +34 664 116 953
ainhoa.pujana@tecnalia.com

Iker Marino
SUPRAPOWER project coordinator
ENERGY AND ENVIRONMENT DIVISION / TECNALIA
M +34 664 111 060
Iker.marino@tecnalia.com

TECNALIA
Parque Tecnológico de Bizkaia
c/Geldo, Edificio 700
E-48160 Derio - Bizkaia (Spain)
T 902 760 000 (Tecnalia)
T +34 946 430 850 (International calls)
www.tecnalia.com