Superconducting lightweight generator for large offshore wind turbine

Iker Marino
Iker.marino@tecnalia.com

ZIEHL IV, Bonn
12th March 2014
Who we are

Our mission: To transform knowledge into GDP, improving people’s quality of life by generating business opportunities for companies.

TECNALIA is the first Applied Research Centre in Spain and one of the most important in Europe with around 1,500 staff, 110 million Euro turnover and over 4,000 clients.
CONTENT

• Offshore wind
• Superconducting generators
• Comparative study
• 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>

Cumulative Business volume-Offshore Wind

<table>
<thead>
<tr>
<th></th>
<th>-2020</th>
<th>2020-2030</th>
<th>2030-2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>180.000 M€</td>
<td>565.000 M€</td>
<td>1,34 B€</td>
</tr>
<tr>
<td>World</td>
<td>450.000 M€</td>
<td>1,412 B€</td>
<td>3,35 B€</td>
</tr>
</tbody>
</table>

Source: EWEA and IEA

Cost per installed MW: 4,5 M€/MW (2020); 3,5 M€/MW (2030); 2,5 M€/MW (2040)

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 capital and operation expenses”

<table>
<thead>
<tr>
<th>DRIVER</th>
<th>3 MW turbines</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>Balance of plant</td>
<td>2.55</td>
<td>2.10</td>
<td>-18%</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.
Cost reduction pathways

Exhibit 3.30 Potential and anticipated FID 2020 LCOE impact* of top 12 innovations for 6MW-Class Turbine, Site B

- Introduction of holistic design of the tower with the foundation
- Improvements in blade aerodynamics
- Introduction of continuously variable transmission drive trains
- Introduction of direct-drive drive trains
- Introduction of multi-variable optimisation of array layouts
- Introduction of mid-speed drive trains
- Introduction of buoyant concrete gravity base foundations
- Introduction of DC power take-off (incl impact of DC array cables)
- Improvements in jacket manufacturing
- Introduction of direct-drive superconducting drive trains
- Introduction of float out and sink installation of turbine and support...
- Increase in turbine power rating

*Note: Reduction in LCOE compared with a 4MW-Class Turbine, FID 2011. Only considers relevant innovations.

Source: Technology work stream report

Maximum technical potential impact on LCOE

Confidential information, unauthorized use or diffusion of this information is legally prohibited
CONTENT

• Offshore wind

• Superconducting generator
  ➢ Superconducting low speed machines
  ➢ MgB$_2$ cryogen free generator

• Comparative study

• Conclusion
Superconductors for low speed rotating machines

Specific Power \( \left( \frac{\text{kW}}{\text{m}^3} \right) \):  

\[
P \propto B \cdot A \cdot \omega
\]

\( \omega \) (rad/s): rotating speed

\( B \) (T): Air-gap Magnetic flux

\( A \) (A/m): Linear current density (depends on stator winding)

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

High B requires to eliminate stator teeth \( \rightarrow \) air-gap winding is required but more space is available \( \rightarrow \) more copper coils can be introduced \( \rightarrow \) 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>MgB$_2$</td>
<td>20 K</td>
<td>1.8 T</td>
<td>100 A/mm²</td>
<td>22,5 €/kAm</td>
<td>14</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>
</tbody>
</table>

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

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

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

Patented by TECNALIA (PTC/ES2009/070639)
Challenges

**MgB\textsubscript{2} 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 Generator

- Scaling based on the reduction of number of poles (4 warm iron poles)
- Identical coils and modular cryostat size
- Same field excitation
- Same cooling and torque transmission systems
- Same airgap shear stress (112 kPa),
- ~ 0.5 MW, ~120 rpm and ~40 kNm.
Development Plan

2011
- Generator Design
- Patent granted
- Applied SC facilities
- European FP7 funding

2013
- MgB2 coil development
- Cryostat and cooling system design and validation

2015
- Demonstrator construction and validation
- Industrial Studies

2017
- Business Plan

2020
- Industrial Development

**SUPRAPOWER:** 5.4 M€ project 4 years project. Tecnalia leads a consortium constituted by Columbus, KIT, Oerlikon, ELU, University of Southampton, D2M and Acciona
Why MgB$_2$? It is an industrial solution with already competitive cost performance ratio.

| 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                     |

Decreasing Cost performance:
• Decreasing cost
• Enhancement of the SC performance

Data and picture courtesy of [Columbus Superconductors](https://www.columbus-superconductors.com)
MgB2 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.

- Dummy coils have been developed to validated the design, cooling concept and manufacturing process.
- Thermal and quench simulations validation.
Rotating modular cryogen free cooling system

• Designed for facilitating offshore installations and maintenance operations
• The concept consists on a 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
• Cryogen-free conduction cooling in rotor.
  ➢ Commercial GM cryocooler (robust, reliable and low maintenance)
  ➢ Simpler cryostat compared to liquid based solutions.
• Technical details:
  ➢ Cold heads rotate jointly with SC coils
  ➢ Rotary joint is required to connect the He compressor to the cold head
Generator integration

• Direct drive generator mechanical integration must be considered. Supporting structure is part of the generator.

• Mechanical air gap must absorb misalignments at large diameters.

• Minimization of the distance between wind turbine axis and nacelle yaw bearing plane to avoid stresses over it.

• A structure of arms will support the generator rotor to the wind turbine and transmit mechanical torque.

• Similar structure to attach the stator to the nacelle goose neck.

• Components of large diameter have been designed in several segments (typically 6 or 12)
CONTENT
• Offshore wind
• Superconducting generators
• Comparative study
• Conclusion
# Comparison Superconducting vs Permanent Magnet

Comparison of volumes, weights, efficiencies and costs of generators including structural parts

<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated Power</strong></td>
<td>10 MW</td>
<td></td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>8.1 rpm</td>
<td></td>
</tr>
<tr>
<td><strong>Turbine diameter</strong></td>
<td>211 m</td>
<td></td>
</tr>
<tr>
<td><strong>Wind speed (cut out)</strong></td>
<td>25 m/s</td>
<td></td>
</tr>
<tr>
<td><strong>Rated blade tip speed</strong></td>
<td>90 m/s</td>
<td></td>
</tr>
<tr>
<td><strong>Power Factor</strong></td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td><strong>Grid connection</strong></td>
<td>Full converter</td>
<td></td>
</tr>
</tbody>
</table>
30% less weight than a PM generator

Total weight of SC solution is 26-30% lighter than PMs.

Simplify commissioning and O&M works. Reduce other turbine elements cost.

Cost in the range of Permanent Magnets generator at the current cost of NdFeB magnets (December 2013)

MgB$_2$ is slightly over 11% of generator costs

Rare earth is over 12% of the costs.
Higher Efficiency than a PM generator

Additional 0.25-0.5% efficiency could be expected
CONTENT

- Offshore wind
- Superconducting generators
- Comparative study
- 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.
- Easier installation and so reduction of vessels and crane costs and reduction of mechanical requirements for 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 rare earths
- MgB2 is commercially available and very cost competitive material
Thanks for your interest

Iker Marino
Project Manager
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