New direct drive technologies of INNWIND.EU: Superconducting vs. Pseudo Direct Drive

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New direct drive technologies of INNWIND.EU:

Superconducting vs. Pseudo Direct Drive

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Wind Energy Denmark
Wednesday 26-27 October 2016

Battle of the wind generators workshop
26 October 14:00 – 15:15

The research leading to these results has received funding from the European Community’s Seventh Framework Programme under grant agreement No. 308974 (INNWIND.EU).
Motivation

Power $\propto BI D^2 l \omega$

1G: Copper + Iron

2G: R$_2$Fe$_{14}$B magnets + Fe
   - PM Direct Drive
   - Pseudo Direct Drive

3G: Superconductor + Fe

$T_c = 1043$ K
$B_r \sim 0$ Tesla

$T_c = 583$ K
$B_r \sim 1.4$ Tesla

$T_c = 93$ K
$B_{c2} \sim 100$ Tesla
$J < 200$ kA/mm$^2$

$T_c = 39$ K
$B_{c2} \sim 40$ Tesla
$J < 20$ kA/mm$^2$
Superconductor Direct Drive

SC: \( J \sim 100-330 \text{ A/mm}^2 \)
Cu: \( J \sim 2-3 \text{ A/mm}^2 \)

\( \begin{align*}
\text{MgB}_2 & \quad \text{RBCO} \\
-234 & \quad -180^\circ\text{C}
\end{align*} \)

INNWIND.EU

\( H_{\text{water}} = 50 \text{ m} \quad \text{Fix} \)
\( H_{\text{water}} > 50 \text{ m} \quad \text{Float} \)
\( D_{\text{rotor}} = 178 \text{ m @ 10 MW} \)
\( D_{\text{rotor}} = 252 \text{ m @ 20 MW} \)
Cost optimization

Fe: 3 €/kg  MgB$_2$: 4 €/m
Cu: 15 €/kg  G10: 15 €/kg

10.6 MNm @ 9.7 rpm
D: 6.0 m  L: 2.3 m
m$_{\text{active}}$ ~ 150 tons

L$_{\text{MgB}_2}$ ~ 500 km
“Light weight & Expensive”

L$_{\text{MgB}_2}$ ~ 20 km
“Cheap & Not too Heavy”
High temperature superconducting pole pair demo

"As high operation temperature as possible → HTC"

D: 7.0 m   L: 1.2 m

$m_{active} \sim 150$ tons
10 MW HTC SC direct drive

\[ L_{SC} = 5.3 \text{ km} \]

### Component Cost Table

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generator</strong></td>
<td>Stator iron</td>
<td>58188</td>
</tr>
<tr>
<td></td>
<td>Rotor iron</td>
<td>53735</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>117480</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>534896</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>764299*</td>
</tr>
<tr>
<td><strong>Converter</strong></td>
<td>Switches</td>
<td>160314</td>
</tr>
<tr>
<td></td>
<td>Generator filter</td>
<td>58084</td>
</tr>
<tr>
<td></td>
<td>DC Link</td>
<td>152000**</td>
</tr>
<tr>
<td></td>
<td>Grid filter</td>
<td>89000**</td>
</tr>
<tr>
<td></td>
<td>Cooling system</td>
<td>143000**</td>
</tr>
<tr>
<td></td>
<td>Mechanical support</td>
<td>184000**</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>786398</td>
</tr>
<tr>
<td><strong>Total drive train</strong></td>
<td>Total</td>
<td>1550697</td>
</tr>
</tbody>
</table>

* Without cooling system cost.
**Deliverable 3.3.2 - Converter designs based on new components and modular multilevel topologies.
Magnetic Pseudo Direct Drive (PDD)

PDD = Magnetic gear + Armature

- Compact
- No contact
- High efficiency
Integration into King-Pin nacelle

Geared rotation

Main rotor input

Electrical power

Kirby, Calverley, Stehouwer & Hendriks EWEA 2014
PDD optimized for 10 and 20 MW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>10MW</th>
<th>20MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airgap diameter</td>
<td>6.0m</td>
<td>8.5m</td>
</tr>
<tr>
<td>Active axial length</td>
<td>1.66m</td>
<td>2.35m</td>
</tr>
<tr>
<td>Permanent magnet mass</td>
<td>13.5tons</td>
<td>38.2tons</td>
</tr>
<tr>
<td>Copper mass</td>
<td>7tons</td>
<td>14tons</td>
</tr>
<tr>
<td>HS and PP rotor laminated steel mass</td>
<td>14tons</td>
<td>39.6tons</td>
</tr>
<tr>
<td>Stator laminated steel mass</td>
<td>15.5tons</td>
<td>45tons</td>
</tr>
<tr>
<td>Structural mass</td>
<td>100tons</td>
<td>383tons</td>
</tr>
<tr>
<td>Total mass</td>
<td>150tons</td>
<td>520tons</td>
</tr>
<tr>
<td>Cost of permanent magnets</td>
<td>58.1 k€/ton</td>
<td></td>
</tr>
<tr>
<td>Cost of copper material</td>
<td>4.59 k€/ton</td>
<td></td>
</tr>
<tr>
<td>Cost of laminated steel</td>
<td>1.61 k€/ton</td>
<td></td>
</tr>
<tr>
<td>Cost of structural material</td>
<td>0.32 k€/ton</td>
<td></td>
</tr>
<tr>
<td>Total material cost</td>
<td>896 k€</td>
<td>2542 k€</td>
</tr>
</tbody>
</table>

Variation of efficiency

Total material cost

- 10MW: 896 k€
- 20MW: 2542 k€
Cost of Energy (CoE) @ 10 MW

\[
\text{CoE} = \frac{C_D + C_R + O}{\text{AEP} \cdot \text{LT}}
\]

\[
\sim \frac{C_R + O}{\text{AEP} \cdot \text{LT}}
\]

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost* [M€]</th>
<th>ΔCoE [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDD</td>
<td>1.7 + 6 %</td>
<td>-4</td>
</tr>
<tr>
<td>RBCO</td>
<td>1.6</td>
<td>+0</td>
</tr>
<tr>
<td>MgB₂</td>
<td>2.3 + 44%</td>
<td>-1</td>
</tr>
</tbody>
</table>

*Preliminary

\( C_R \sim 30 \text{ M€}, O \sim 35 \text{ M€} \quad \text{LT} = 25 \text{ years} \)
Conclusion

• Innovative non-contact drive trains investigated

• Superconducting Direct Drive
  – RBCO: Race track coil demonstrated. $\Delta \text{CoE} \sim + 0 \%$
  – MgB$_2$: Race track coil under construction $\Delta \text{CoE} \sim -1 \%$
  – Both will have a hard time beating the PM direct drive
  – Both will remove dependency of Rare Earth Elements

• Magnetic Pseudo Direct Drive (PDD)
  – Demonstrated: $T = 5 \& 16$ kNm. Next step 200 kNm $\Delta \text{CoE} \sim -4 \%$
  – Superior in term of efficiency and cost.
  – Increased Rare Earth Elements dependency compared to permanent magnet direct drive
Contributions to work package Electro-Mechanical conversion of INNWIND.EU

D. Liu & Henk Polinder, Delft University of Technology (NL)
N. Magnuson, SINTEF (N)
A. Thomas & Z. Azar, Siemens Wind Power (DK / UK)
E. Stehouwer & B. Hendriks, DNV GL (NL)
A. Penzkofer & K. Atallah, University of Sheffield (UK)
Dragan, Meyers, Clark & Todd, Magnomatics (UK)
F. Deng & Z. Chen, Aalborg University (DK)
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Project website: www.innwind.eu
Drive train mix in 2030?