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 : \text{R}_2\text{Fe}_{14}\text{B} magnets + Fe
    PM Direct Drive
    Pseudo Direct Drive
3G : Superconductor + Fe

\begin{align*}
\text{T}_c &= 1043 \text{ K} \\
\text{B}_r &\sim 0 \text{ Tesla}
\end{align*}

\begin{align*}
\text{T}_c &= 583 \text{ K} \\
\text{B}_r &\sim 1.4 \text{ Tesla}
\end{align*}

\begin{align*}
\text{T}_c &= 93 \text{ K} \\
\text{B}_{c2} &\sim 100 \text{ Tesla} \\
\text{J} &< 200 \text{ kA/mm}^2
\end{align*}

\begin{align*}
\text{T}_c &= 39 \text{ K} \\
\text{B}_{c2} &\sim 40 \text{ Tesla} \\
\text{J} &< 20 \text{ kA/mm}^2
\end{align*}
Superconductor Direct Drive

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

MgB\(_2\) RBCO
-234 \(-180^\circ\text{C}\)

INNWIND.EU

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

$\text{Fe: } \ 3 \text{ €/kg} \quad \text{MgB}_2: \ 4 \text{ €/m}$

$\text{Cu: } 15 \text{ €/kg} \quad \text{G10: } 15 \text{ €/kg}$

$L_{\text{MgB}_2} \sim 500 \text{ km}$

“Light weight & Expensive”

$10.6 \text{ MNm} @ 9.7 \text{ rpm}$

$D: 6.0 \text{ m} \quad L: 2.3 \text{ m}$

$m_{\text{active}} \sim 150 \text{ tons}$

$L_{\text{MgB}_2} \sim 20 \text{ km}$

“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

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

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

- Without cooling system cost.
- **Deliverable 3.3.2** - Converter designs based on new components and modular multilevel topologies.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</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>Converter</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>Total drive train</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

Kirby, Calverley, Stehouwer & Hendriks EWEA 2014
Integration into King-Pin nacelle

Geared rotation

Electrical power

Main rotor input

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

The graph shows the variation of efficiency with power in percent of rated power for two different rated powers, 10 MW and 20 MW. The efficiency remains relatively constant across the power range for both ratings, indicating good performance for both sizes.

*DTU Wind Energy, Technical University of Denmark*
Cost of Energy (CoE) @ 10 MW

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

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

**Type** | **Cost** \([\text{M€}]\) | **\(\Delta\)CoE** \([\%]\) |
--- | --- | --- |
PDD | 1.7 + 6% | -4 |
RBCO | 1.6 | +0 |
MgB\(_2\) | 2.3 + 44% | -1 |

*Preliminary

\[ C_R \approx 30 \text{ M€}, O \approx 35 \text{ M€} \]

LT = 25 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
  – Superior in term of efficiency and cost. \( \Delta \text{CoE} \sim -4\% \)
  – 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)
D. Karwatzki & A. Mertens, University of Hannover(D)
M. Parker & S. Finney, University of Strathclyde

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Project website: www.innwind.eu
Drive train mix in 2030?