DeepWind. From idea to 5 MW concept

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Contents

• DeepWind Concept
• 5 MW design
• Optimization process results
• Conclusion

  – Controller part: grid compliance
DeepWind
Contents

• DeepWind Concept
• Baseline 5 MW design
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The Concept

- No pitch, no yaw system
- Floating and rotating tube as a spar buoy
- C.O.G. very low – counter weight at bottom of tube
- Safety system

- Light weight rotor with pulltruded blades, prevailing loads from aerodynamics
- Long slender and rotating underwater tube with little friction
- Torque absorption system
- Mooring system

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Concept- Generator configurations

• The Generator is at the bottom end of the tube; several configurations are possible to convert the energy
• Robust integrated bearing technology
• Three selected to be investigated first:
  1. Generator fixed on the torque arms, shaft rotating with the tower
  2. Generator inside the structure and rotating with the tower. Shaft fixed to the torque arms
  3. Generator fixed on the sea bed and tower. The tower is fixed on the bottom (not floating).
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1st BaseLine 5 MW Design Floater

- Design space limitations

Hywind site:
~5000 tons mass
~35/60 sec natural periods in yaw/surge
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BaseLine 5 MW Design Blades

- Blade length 200 m
- Blade chord 5 m constant over length
- Blades pulltruded, sectionized GRP
- NACA 0018 and NACA 0025 profiles
DeepWind 5 MW Design Rotor

Geometry

- Rotor radius \((R_0)\) [m] 60.5
- \(H/(2R_0)\) [-] 1.18
- Solidity \((\sigma = Nc/R_0)\) [-] 0.165
- Swept Area \((S_{ref})\) [m²] 11996

![Graph showing the geometry and performance metrics of the DeepWind 5 MW rotor compared to the EOLE 4 MW (1.5, 25) reference.](image-url)
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Load cases

- Deterministic flow with Power law wind shear
- Airy waves
- Sea current 0-0.7 m/s

<table>
<thead>
<tr>
<th></th>
<th>$H_s$ [m]</th>
<th>$T_s$ [s]</th>
<th>Current [m/s]</th>
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<td>Sea state 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Sea state 1</td>
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<td>16</td>
<td>0.35 for $V_0 &lt; 14$ m/s, 0.7 for $V_0 &gt; 14$ m/s</td>
</tr>
</tbody>
</table>

- Water depth 200 m
- Site along Norwegian coast
- Met-ocean data, hindcast©DHI and WF
DeepWind Contents

• DeepWind Concept
• Baseline 5 MW design outline
• Results from Optimization process
• Conclusion
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BaseLine 5 MW Design Performance

Performance

<table>
<thead>
<tr>
<th></th>
<th>[kW]</th>
<th>[rpm]</th>
<th>[m/s]</th>
<th>[m/s]</th>
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<td>5.73*</td>
<td>14</td>
<td>5</td>
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<tr>
<td>Rated rotational speed</td>
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<td>Rated wind speed</td>
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<tr>
<td>Cut in wind speed</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cut out wind speed</td>
<td></td>
<td></td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>
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Floater performance at Sea states: 0.35 - 0.7 m/s Current

- Pitch
- Roll
  - Magnus forces change with current
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Constant blade chord with different profile thickness

- Blade weight from ~ 157 Ton to ~ 45 Ton per blade
- 5000 µm/m limit: complex strain distribution but in control
- Less bending moments and tension during operation
- Potential for less costly pulltruded blades
DeepWind Generator

Legend:
1) Permanent magnet
2) Stator tooth
3) Stator back iron
4) Winding coil
5) Rotor back iron

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value [mm]</th>
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<td>Outside Diameter</td>
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<tr>
<td>Inside diameter</td>
<td>5346</td>
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<tr>
<td>Length O/A</td>
<td>2648</td>
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</table>

Sample segment of the generator produced by the Design Tool.

3D sketch of the active parts of the 6 MW DeepWind Generator.

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Magnetic Bearing

• A controlled magnetic bearing was chosen for study in a test rig
• necessary to control the forces generated by the bearing (relationship between the magnetic force and the distance is in unstable equilibrium
• DSP based control system is proposed, using appropriate sensors and a controlled power supply for each direction unstable equilibrium
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Baseline 5 MW Electrical system

General diagram of the power transfer system.
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Special control challenges with Deepwind

- All active turbine control via generator torque (no pitch control)
- Large 2p variations in aerodynamic torque
- Stator is not fixed,

generator speed = rotor – stator

2p damping with notch filter and PI controller
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Fault ride-through capability

- Crucial for grid code compliance
- Illustrates interesting coupling between controls, turbine and mooring dynamics

**ALT 1: De-loading system**
Absorb excess energy in rotation of the turbine by reducing generator torque

**ALT 2: DC chopper system**
Dump excess energy via switched resistor in DC link
500 ms voltage dip in the grid, propagated to converter terminals

Resulting DC link voltage increase needs to be limited, to avoid damage and allow ride-through
- Chopper: OK
- De-loading: Not working very well

Generator torque unaffected with chopper system, drastically reduced with de-loading system
DeepWind  
Turbine response to grid fault

**Chopper system:**  
Turbine completely unaffected by the fault

**De-loading system:**  
Generator torque rapidly reduced  
→ Rotor (turbine) and stator (mooring system) acceleration in opposite directions  
→ Severe stress on mooring system  
→ Shaft vibrations in turbine

*The de-loading scheme does not work with DeepWind's non-fixed stator*

But interesting illustration of the coupling between turbine/generator/mooring/controls

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Conclusion

- Demonstration of an optimized rotor design
  - Stall controlled wind turbine
  - Pultruded sectionized GRF blades 2 profile sections
  - 2 Blades with ~95 T total weight, ~3½x less weight than 1st baseline 5MW design
  - Less bending moments and tension during operation
  - Potential for less costly pulltruded blades in terms of power capture
- Use of moderate thick airfoils of laminar flow family with smaller CD₀ good Cp and favourable rigidity
- Suite available for designing deep sea underwater, new radial flux synchronous generator module
- Utilizing magnetic bearings for generator module as option
- Generator and Controller implemented in global model
- Floater optimized for most dominant variables
- Grid compliance
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Video from Ocean lab testing
Thank You
Questions?

Thanks to the DeepWind consortium:
DTU(DK), AAU(DK), TUDELFT(NL), TUTRENTO(I), DHI(DK), SINTEF(N), MARINTEK(N), MARIN(NL), NREL(USA), STATOIL(N), VESTAS(DK) and NENUPHAR(F).

And
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