Baseline Design of a Hurricane-Resilient Wind Turbine

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Abstract
Under U.S. Department of Energy-sponsored research Funding Opportunity Announcement 415, the National Renewable Energy Laboratory (NREL) led a team of research groups to produce a complete design of a large wind turbine system to be deployable in the Western Gulf of Mexico region. As such, the turbine and its support structure would be subject to hurricane loading conditions. Among the goals of this research was the exploration of advanced and innovative configurations that would help decrease the design’s levelized cost of energy (LCOE), and the expansion of the basic International Electrotechnical Commission’s (IEC) [1] design load cases (DLCs) to include hurricane environmental conditions. The wind turbine chosen was a three-bladed, downwind, direct-drive, 10-MW rated machine. The rotor blade was optimized based on an IEC load suite analysis. The drivetrain and nacelle components were scaled up from a smaller sized turbine using industry best practices. The tunnel steel tower was sized starting from ultimate loads at tower top derived from the rotor optimization analysis. The substructure used is a new battered and raked jacket structure. The complete system has also been modeled within an aero-servo-hydro-elastic tool, and future papers will discuss results of the dynamic response analysis for select DLCs. Although resource limitations prevented multiple design iterations, the results are valuable for predicting the LCOE of large offshore wind turbines deployed in subtropical U.S. waters, as well as for demonstrating the impact of design innovations on LCOE.

Rotor Design
Wetzel Engineering Inc performed a design optimization that considered the following:
• Downwind rotor to try and relax stiffness requirements and lighten the blades
• Airfoil: WEHI-FB (maximum chord, inboard) and DU-NACA (outboard) 64%–21% t/c
• LCOE and maximum root-bending moment as main drivers
• IEC DLCs including EOG, ECD, and hurricane survival cases
• Carbon-reinforced spar cap and thick airfoils
• Analysis of approximately 4 million blade configurations
• Blade length, platform, and tip-speed as design variables

The final design was constrained by:
• Maximum tip-deflection of 15% (no tower clearance issues)
• Composite layers’ utilization <1
• Modal requirements (resonance avoidance rotor forcing 1P, 3P, ...)
• Including structural and manufacturability constraints (e.g. weldability and max yaw bearing)

Nacelle Design

Nacelle and blade loads

- Hub, drivetrain, and generator designed by Siemens Wind Power based on simple scaling laws and current line of products
- NREL derived additional aeroelastic properties needed for FAST simulations
- Basic torque and pitch controller devised by NREL

Main Environmental and Structural Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design hub height (m)</td>
<td>135/20.7 (clears 1,000-yr wave crest – [2])</td>
</tr>
<tr>
<td>Wind speed (1-hr mean, 10 m MSL) [m/s]</td>
<td>30.7</td>
</tr>
<tr>
<td>Max wave height and period: H_{m0} [m] / T [s]</td>
<td>10.1/11.3</td>
</tr>
<tr>
<td>Surge [m/Current [m/s]</td>
<td>1.1/5.2</td>
</tr>
<tr>
<td>Wake robustness 500-yr RP Event</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Penetration Range [m]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wake robustness 10-yr RP Event</td>
<td>2.4/2.4</td>
</tr>
</tbody>
</table>

Optimized Tower
The tower mass was minimized while:
• Maximizing ULS utilization (GL and Eurocode standards [4-5]) under prescribed turbine loads (from rotor analysis)
• Targeting a prescribed system (soft, stiff) first natural frequency
• Including structural and manufacturability constraints (e.g. weldability and max yaw bearing)

Optimized Support Structure
The substructure was optimized by:
• Verifying members against code checks (ISO898) under prescribed turbine, tower, and hydrodynamic loads
• Targeting first eigenfrequency (0.14–0.17 Hz)
• Ensuring designated deck height
• Ensuring proper pile penetration
• Minimizing overall steel mass.

Main Design Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>BLA (nacelle-mass assembly)</td>
<td>865</td>
</tr>
<tr>
<td>LCOE-min (turbine)</td>
<td>5.78</td>
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<tr>
<td>LCOE-min (substructure)</td>
<td>4.382</td>
</tr>
<tr>
<td>Design wind speed [m/s]</td>
<td>23.0</td>
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<tr>
<td>Substructure equivalent wind/wave survival constant (k-factor)</td>
<td>1.35/2</td>
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<tr>
<td>Substructure equivalent rotational survival constant (k-factor)</td>
<td>1.75</td>
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<tr>
<td>Target first eigenfrequency [Hz]</td>
<td>0.14</td>
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</table>

Conclusions and Future Work
This paper introduced the results of a conceptual design study focusing on a baseline, hurricane-resilient, offshore wind turbine. More details will be provided in future technical reports and papers including LCOE optimization.

API RP2 MET (interim bulletin) [3] was used to extend the IEC DLCs to hurricane events
• Several innovations were selected (e.g., downwind system and innovative substructure)

This final design is a good candidate for future wind turbine configurations. The additional loading that is added by this model is 15% of the nacelle CM. This is an increase in the tower mass compared to a tower without hurricane loads. The additional load on the tower was calculated by the LDO program. This is an important factor in the overall design and optimization of the equipment.

References