Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

Definition of a Baseline Rotor Design for a 25MW Floating Offshore Wind Turbine

To cite this article: Alejandra S. Escalera Mendoza *et al* 2024 *J. Phys.: Conf. Ser.* **2875** 012004

Definition of a Baseline Rotor Design for a 25MW Floating Offshore Wind Turbine

Alejandra S. Escalera Mendoza[1], D. Todd Griffith[1*], Carlos R. dos Santos[2], Serag-Eldin Abdelmoteleb[3], Erin E. Bachynski-Polić[3], and Luca Oggiano[2]

[1] Department of Mechanical Engineering, UTD Center for Wind Energy, University of Texas – Dallas, Richardson, TX, USA.
[2] Institute for Energy Technology, Kjeller, Norway.
[3] Department of Marine Technology, NTNU, Trondheim, Norway.

*E-mail: tgriffith@utdallas.edu

Abstract. Wind turbine sizes have grown rapidly in recent years with machine ratings of 15-16 MW available from multiple manufacturers for offshore wind turbines. While the industry advances large-scale turbine designs, offshore developers have initially focused on siting in shallow waters on bottom-fixed foundations; however, eyes are also on deep-water locations where floating systems are required. The present study presents the definition for an initial baseline rotor design at 25 MW scale, designed for a floating offshore system. The purpose of this paper is to document this 25 MW blade definition for use as a reference design for future floating wind technology development by industrial and academic researchers and developers. As this is an initial reference design, some opportunities (and plans) for further mass or cost reduction are also noted. In summary, the paper documents the initial baseline rotor design including aerodynamic and structural design of the rotor blades, along with key details about the control system and floating system designs for the floating 25 MW wind turbine system.

1. Introduction

As the offshore wind industry quickly moves to larger wind turbines and deep-water locations that exist near major population centers where floating system technologies are required, the research community needs larger reference models. For example, wind turbine reference models have been developed and made openly available at 10 to 15 MW scales [1,2], but the industry now eyes machines in the 20-25+ MW range. Such reference models are highly valuable to provide early guidance on technology performance and technology limits (or needs) while providing the entire community with common baseline reference designs aimed at evaluating both new turbine technology (e.g., new blade designs or control systems) along with new floating system designs (e.g., new hull and mooring configurations).

The present study presents the definition for an initial baseline rotor design at 25 MW scale for a floating offshore system (Figure 1). The team includes partners from IFE, NTNU, and UT-Dallas (University of Texas at Dallas, USA) where efforts have focused on the design of a floating 25 MW turbine (3-bladed upwind horizontal axis wind turbine) on a semi-submersible floating system [3], which we term as the IFE-UTD-NTNU 25 MW Floating Offshore Baseline. This paper includes details about the aerodynamic and structural design of the rotor blades, along with key details about the control system and floating system designs.

In summary, this paper presents insights on the following: (1) upscaling trends from 15 to 25 MW scale, (2) results from initial multidisciplinary integrated design of aerodynamics, structural, control system and floating system disciplines, and (3) a definition for an initial baseline 25MW rotor design for a floating wind turbine that meets a comprehensive set of design standards-based structural requirements and manufacturability constraints.

Figure 1. IFE-UTD-NTNU 25 MW Wind Turbine on Semi-submersible Floater

2. Floating 25 MW Wind Turbine Reference: Concept and System Design Methodology

The aim of this research is to address the need for research that pushes the boundaries of large wind turbine design. This is approached by applying a holistic approach in the design of large-scale horizontal axis wind turbine, selected to be at the 25MW scale, for a semi-submersible floating system type. To accomplish this holistic design, multiple disciplines are addressed in a system-level design approach as shown in Figure 2. This approach first considers concepts and then iterates on the detailed design of a particular concept for the various components of the design including the rotor (blade), substructure and tower (floating system), and the control system. In this approach, system design is performed by proceeding with the design from aerodynamic design to structural design, to controls and floating design, and the process is iterated until design goals are met. More details are provided in the next section where the detailed blade design process and design results are presented.

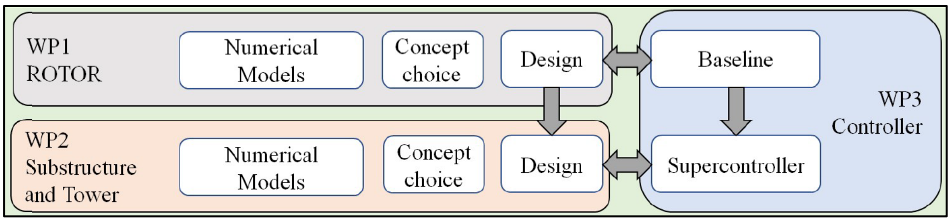

Figure 2. 25MW Floating Wind Turbine System-level Design Approach

3. Initial Baseline 25 MW Aero-structural Definition: Detailed Blade Design

As a starting point, the initial study examined existing public domain models, which were available at the 15 MW scale. Upscaling was examined to explore initial concept designs at the chosen 25 MW scale, which led to an initial aero-structural rotor design to support early control system and floating system design studies. Here the term aero-structural refers to the blade design having both an aerodynamic design and an associated structural design definition. For the interested reader, more information about the reference models at the 15 MW scale can be found for the complete IEA 15MW OpenFAST reference model in [2] and a detailed blade open-source structural model for the IEA 15MW documented in [4].

3.1 Aerodynamic Design

Following the initial upscaling work, the aerodynamic design for the 25 MW scale rotor was the next step in the rotor design, which produced the blade external geometry and an initial set of aerodynamic design loads used for structural design. Before moving forward with detailed structural design, the 25 MW aerodynamic design was evaluated for efficiency. This analysis showed that the 25 MW aerodynamic design had a maximum Cp of 0.50, which is aerodynamically efficient and deemed ready for further development in the structural design phase. More details about the aerodynamic design geometry and performance are shown in Figure 3. At the 25 MW scale, the blade length was designed to be 149.5 m, and with a hub radius of 4.5 m, the total rotor radius is 154 m.

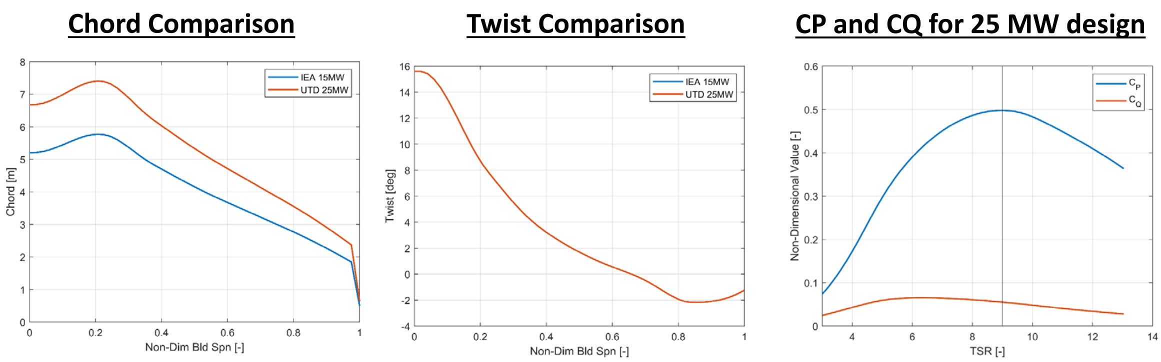

Figure 3. 25 MW: Aerodynamic Definition

3.2 Structural Design

After accepting the aerodynamic design, the next step was the detailed blade structural design where the composite layup was designed based on the baseline aerodynamic design loads to ensure the blade would meet structural requirements. The UT-Dallas design approach follows structural requirements of international design standards [5]. A typical design loop for the detailed blade design analysis is shown in Figure 4, where the structural requirements from the design standard are addressed related to strength, deflection, fatigue, buckling, and dynamic stability requirements. Further, the design loop illustrated in

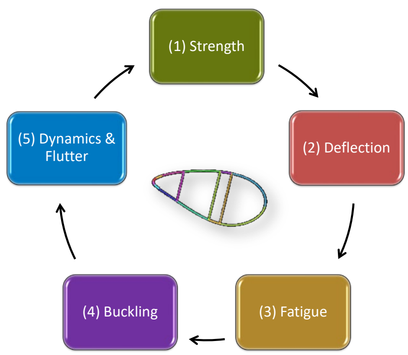

Figure 4. Design Loop for Detailed Blade Design Based on Structural Requirements of International Design Standards.

Figure 4 is also utilized to determine which design load cases (DLCs) as defined in the standards are the critical cases.

Once an iteration of 25 MW baseline aero-structural rotor design was completed, it was shared with the controls and floating system teams so that further control system design and floating system sizing could be performed. An example of the detailed geometry and structural

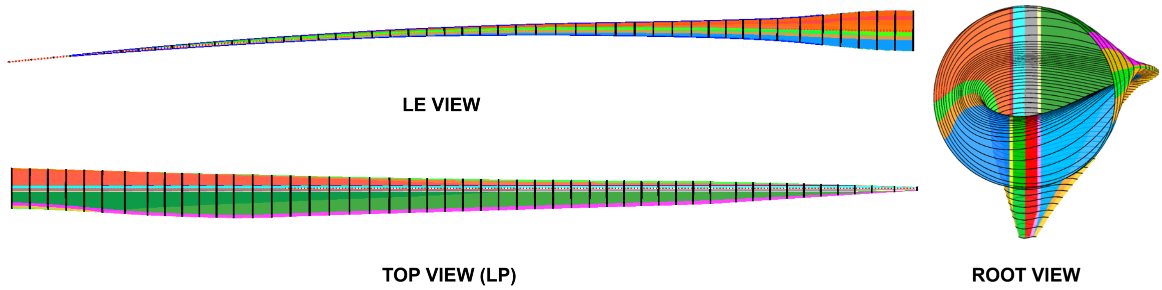

Figure 5. Initial (V1) Geometry for the Detailed Structural Definition

design is shown in Figure 5 for the initial iteration (V1) of the design.

3.3 Aero-Structural Rapid Screening (ASRS) Design Optimization Approach

Based on prior experience [6-8] with design of large blade structures, sequential aerodynamic and structural design steps can be quite time-consuming when performing detailed structural blade design. Therefore, the team began to utilize a recently developed aero-structural design approach called ASRS (Aero-Structural Rapid Screening) [9] for this 25 MW blade design. ASRS is an optimization-based design approach developed at UT-Dallas that allows fast and detailed evaluation of new blade design concepts (Figure 6). The goal in developing ASRS was to speed up the process to evaluate new blade design concepts, which may have a large design space (covering number of blades, aerodynamic definition, blade length, etc.), while including all the relevant disciplines (aerodynamics, structures, control, and cost) in the process. ASRS was

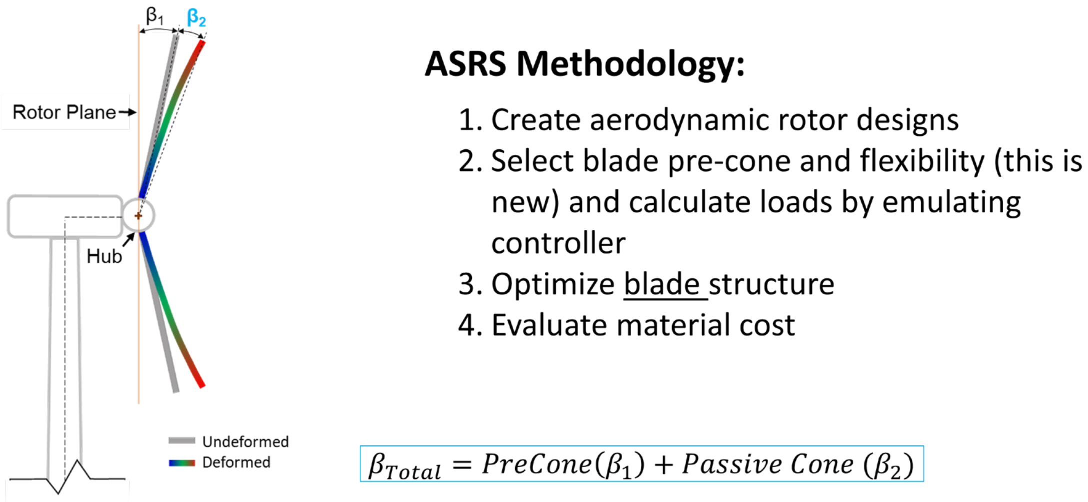

Figure 6. Aero-structural Rapid Screening (ASRS) Methodology for Blade Design

utilized here to speed up the design iterations for the blade design. For the interested reader, a detailed set of case studies in applying ASRS to examine the design space of downwind rotor design can be found in [9] along with details about the features of ASRS.

3.4 Floating Platforms Design

Two reference semi-submersible platforms were upscaled to support the 25 MW turbine. The reference platforms are the UMaine VolturnUS-S [10] which supports the IEA 15MW [2] on its central column, and the INO-WINDMOOR [11] which supports a 12 MW wind turbine on one of its peripheral columns. The upscaling process relied on 2D eigenvalue analysis of the platform rigid body motions and tower bending degrees of freedom. A design space exploration was performed to find the platform dimensions that would satisfy the following conditions: rigid body natural frequencies outside the wave excitation range; a stiff-stiff geometrically upscaled version of the floating IEA 15MW tower; and a 6 degrees static platform pitch angle under maximum thrust. This resulted in pitch natural frequencies of 0.024 Hz and 0.0235 Hz for the central and peripheral designs, respectively. The pitch natural frequencies were used to tune the controller described in the next section. More information on design of the platform can be found in [12]. The main influence of the rotor and controller designs on the floating platform design comes from the maximum thrust value. This is demonstrated in Figure 7 which shows the effect of thrust reduction on the steel mass of the platform and the turbines annual energy production (AEP) for the central tower design platform.

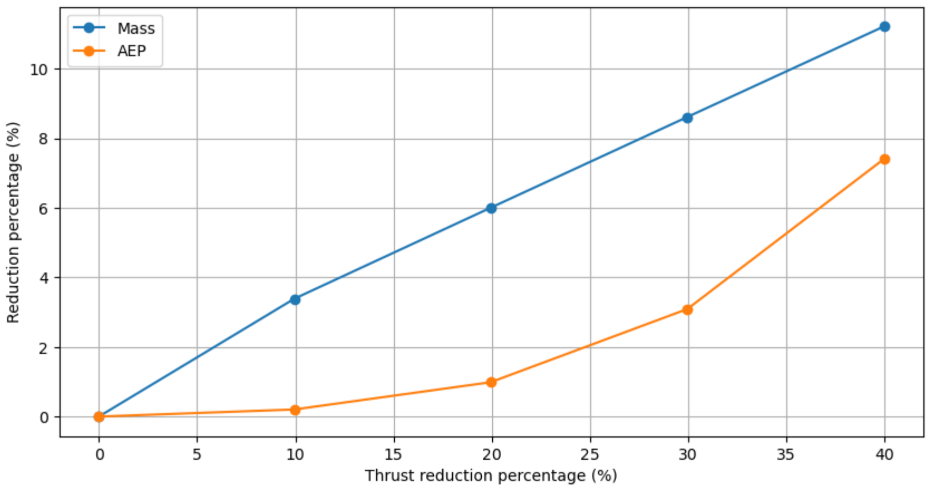

Figure 7. Effect of thrust reduction on platform steel mass and AEP for the upscaled 25 MW central tower design

3.5 Controller Design

The ROSCO controller version 2.3.0 [13] was selected as a baseline controller to be applied in this project. The controller was tuned through optimization to solve the trade-off between power output and platform stability, as discussed in previous works by the authors [14,15, and 16]. The resulting damping ratio for the controller was ζ_{pc}=0.59 and natural frequency ω_{pc} = 0.079 rad/s. Floating feedback has been applied to enhance system's stability. The performance of the baseline PI controller has been investigated considering the use or not of peak-shaving strategies. The thrust force as a function of the wind speed in steady-state regime is presented in Figure 8.

As discussed in previous articles [14,15], the trade-off between tracking the rated rotational speed while keeping platform stability leads to limit cycle oscillations in surge and pitch, which also affects the power output and the instantaneous rotational speed. These phenomena are shown in Figure 9. The use of peak-shaving strategies does not mitigate these limit cycle oscillations but reduces their amplitude, thereby reducing the fatigue load of structural components. An alternative to PI controllers has been

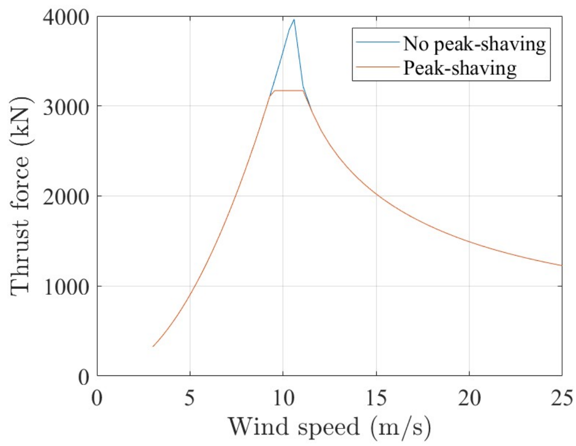

Figure 8. Thrust force as a function of the wind speed for the 25 MW wind turbine in steady-state regime.

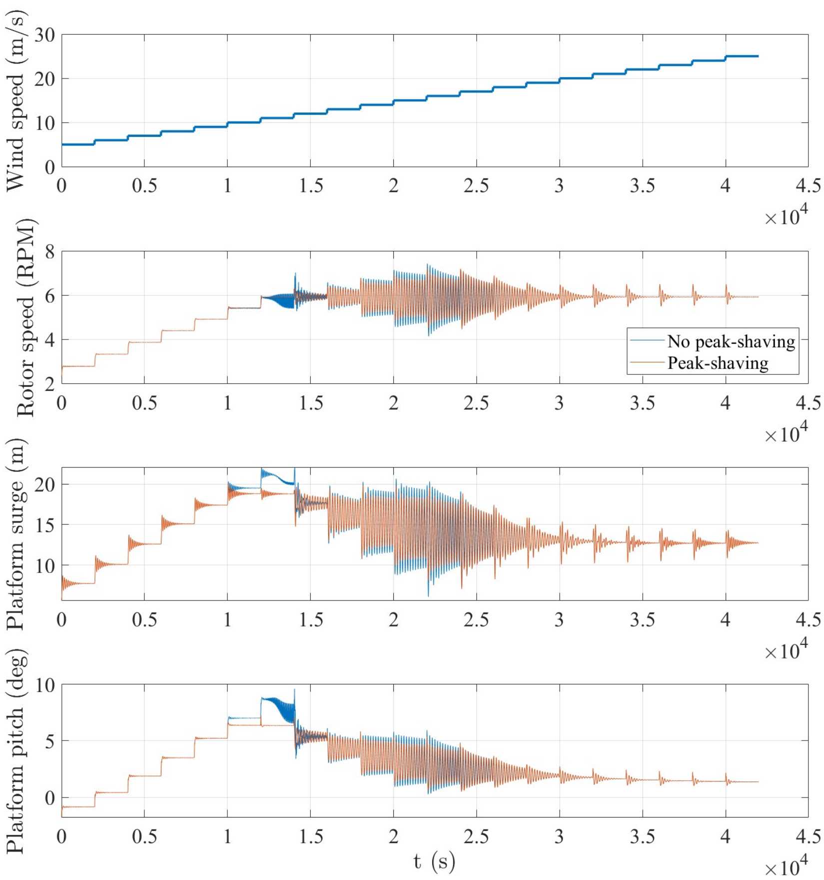

Figure 9. Step response of the floating turbine considering controllers with and without peak-shaving.

recently presented considering adaptive controllers [16]. This approach enables platform stability while keeping a good tracking of the power output and rotor speed.

4. Definition of the Baseline Blade Design: Key Results

In this section, the definition for the initial baseline blade design is provided along with an accounting of several design iterations leading to the baseline. Please note we refer to this as an initial baseline as additional work is ongoing to further optimize the baseline (although this baseline satisfies a comprehensive set of design standards-based structural requirements along with manufacturability constraints). Table 1 provides a detailed summary of the key design iterations from the early upscaled structural design (V1) to the initial baseline design V3. Intermediate design iterations for version V2 are also included to show the effects of the peak-shaving controls and the use of the ASRS (aero-structural rapid screening) optimization capability.

Starting with V1, the initially upscaled geometry and layup are analyzed. Although this design met many structural requirements, this early design iteration did not meet the blade deflection requirement (to avoid tower strike) and failed to meet panel buckling requirements. Therefore, subsequent iterations focused on addressing these issues by reinforcing the blade structure and core panels with additional materials. The V2 blade was examined for two cases, initially with a baseline control (with no peak-shaving) then with peak-shaving control, as noted in Table 1. In comparing V1 to V2 (no peak-shaving), the mass and cost of V2 (no peak-shaving) increased by 14% and 54%, respectively, due to the additional materials added to address deflection and buckling. The increased cost is largely due to greater use of carbon fiber in the spar cap.

Now we compare V2 for the cases of no peak-shaving versus with peak-shaving. Here the same V2 blade structural design was used in both cases, thus the blade mass and costs are the same for each case in Table 1. However, the resulting loads for the peak-shaving case (root bending moments) are shown to be reduced by about 7%, which leads to a reduction of the blade deflection (and increased excess design margin).

In the next step, ASRS optimization was applied to further reduce mass and cost for the V3 design, which we term as the “Initial Baseline”. This resulted in mass and cost reduction of 10% and 22% relative to V2 (with peak-shaving). As can be seen, for the 25 MW scale blade, peak-shaving controls and aero-structural optimization offer significant benefits to reduce design loads, reduce deflections, and reduce blade mass and cost.

The geometry for the V3 design is shown in Figure 10. Please note the revised tip geometry for V3 versus that of V1 (as shown in Figure 5). The tip was redesigned to have a smoother taper and rounded tip – this modification resulted in mass and cost increase, but provided a more feasible estimate of blade mass and cost based on detailed design of the geometry along with constraints on manufacturability while meeting all structural safety requirements on strength, deflection, buckling, fatigue and dynamic stability as defined in the design standard.

Again, V3 (the initial baseline) definition was developed using ASRS optimization with peak-shaving control. As with the case with other iterations, additional high-fidelity structural checks were done to verify that buckling and fatigue life requirements were met. In addition to this set of comprehensive structural analyses, manufacturing constraints were imposed in the layup designs to account for typical feasible layup schemes and ply-dropping. Again, this iterative process led to a baseline rotor design (V3) that leveraged recently developed aero-structural rapid screening (ASRS) tools along with a peak-shaving controller scheme.

Table 1. Blade Structural Design Results: Summary of the Key Iterations

		Early Stage Design	Meeting Structural Requirements	Introduce Peak-shaving	Initial Baseline (ASRS)	Future Design
Structural Iteration #		V1	V2	V2	V3	TBD
Controller		No Peak-shaving	No Peak-shaving	Peak-shaving	Peak-shaving	TBD
Blade Mass	Tons	143	163	163	146	TBD
Blade Material Cost	$M	1.39	2.15	2.15	1.68	--
1st Flap Frequency (0 RPM)	Hz	0.44	0.34	0.34	0.35	--
1st Edge Frequency (0 RPM)	Hz	0.52	0.43	0.43	0.49	--
Allowable RootMyb	kNm	5.76E+05	3.80E+05	3.80E+05	3.80E+05	--
Allowable RootMxb	kNm	5.74E+05	3.79E+05	3.79E+05	3.79E+05	--
Max. Root Myb (OpenFAST)	kNm	2.21E+05	2.59E+05	2.41E+05	2.44E+05	--
Max Root Mxb (OpenFAST)	kNm	6.88E+04	1.02E+05	1.01E+05	8.79E+04	--
Max. Tip Deflection (OpenFAST)	M	36 (exceeds allowable)	27.5 (2% margin)	22.2 (21% margin)	27.6 (22% margin)	--
DLC 1.2 AEP	GWhr	127.1	127.6	127.6	127.4	--

Note: For the AEP calculation, a Weibull distribution was used with scale factor of 11.2838 and shape factor of 2.0 resulting in a mean wind speed of 10m/s (IEC Class IB).

In the course of this work, loads analysis was performed for a wide range of design load cases (DLCs) to identify the maximum load DLCs in each iteration (from V1 through V3). As a result of this analysis, some critical DLCs having maximum loads or deflection were identified and include DLC 1.4 and DLC1.5 for deflection and DLC 6.1 for maximum root bending moment.

In summary, the V3 initial baseline blade design is a good structural design that satisfies a comprehensive set of design standards-based structural safety requirements and manufacturability constraints while taking advantage of peak-shaving control and initial structural optimization of the spar caps. In meeting the major structural and manufacturing

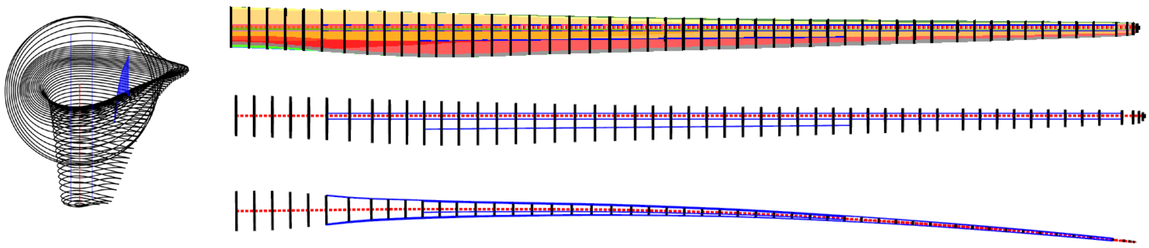

Figure 10. UTD 25 MW: Detailed Structural Definition for V3 with Revised Tip Geometry

constraints, the V3 blade has been comprehensively designed for structural requirements and manufacturability and is thus credible for 25MW simulations and cost studies, and for further research studies in blade design, control system development, or floating system design studies.

5. Conclusions and Future Work

This work presents the definition for a baseline 149.5 m blade design for a 25 MW floating offshore wind turbine. As documented, this initial baseline blade design (V3) is a good structural design that satisfies a comprehensive set of design standards-based structural safety requirements and manufacturability constraints while taking advantage of peak-shaving control and initial optimization of the spar caps. In meeting the comprehensive structural safety requirements and manufacturing constraints, the V3 blade is a credible design that the research community and industry can use in 25MW floating wind turbine simulations and cost studies, and for further research and design optimization studies in blade design, control system development, or floating system design studies.

Although this initial baseline is a credible design, the design is not fully optimized for weight or cost and can be improved through further optimization of additional blade structural elements including the root build-up and core materials. V3 was only ASRS-optimized in the spar cap, and ongoing work at UT-Dallas is examining potential to optimize at the 25 MW blade scale more systematically. As detailed, some excess design margins are present that can be explored further.

This research illustrates the value of peak-shaving controls for 25 MW scale rotors, where in this case peak-shaving was implemented resulting in reduction in blade loads and tip deflection. In addition, a new optimization capability called ASRS (aero-structural rapid screening) was utilized to reduce blade mass and cost. Through these design studies, critical design load cases at the 25 MW scale were also identified that lead to peak loads and peak deflections.

Acknowledgments

This work was supported by the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) under the Segmented Ultralight Morphing Rotor project [award number DE-AR0000667] and funding from the Research Council of Norway via subaward from the Institute for Energy Technology (IFE).

References

[1] Griffith, D.T. and Ashwill, T.D, "The Sandia 100-meter All-glass Baseline Wind Turbine Blade: SNL100-00," Sandia National Laboratories Technical Report, June 2011, SAND2011-3779.
[2] Gaertner E, Rinker J, Sethuraman L, Zahle F, Anderson B, Barter G E, Abbas N J, Meng F, Bortolotti P and Skrzypinski W, "IEA Wind Task 37: Definition of the IEA 15-megawatt offshore reference wind turbine," National Renewable Energy Lab.(NREL), 2020.
[3] Upscale, https://gcenode.no/project/upscale/, last accessed: July 11, 2024.
[4] Escalera Mendoza, A, Mishra, I., and Griffith, D.T., "An Open-Source NuMAD Model for the IEA 15 MW Blade with Baseline Structural Analysis," AIAA SCITECH 2023 Forum, 2093, DOI: https://doi.org/10.2514/6.2023-2093. View Video Presentation: https://doi.org/10.2514/6.2023-2093.vid
[5] IEC R.D.F., Part 1: Design requirements, IEC 61400-1 Wind Turbines (third ed.), International Electrotechnical Comission (IEC), Geneva, Switzerland (2005), pp. 34-36
[6] Yao, S., Chetan, M., and Griffith, D.T., "Structural Design and Optimization of a Series of 13.2MW Downwind Rotors," Wind Engineering, available online January 2021, https://doi.org/10.1177/0309524X20984164.
[7] Qin, C., Loth, E., Zalkind, D., Pao, L., Yao, S., Griffith, D.T., Selig, M., and Damiani, R., "Downwind coning concept rotor for a 25 MW offshore wind turbine," Renewable Energy, 2020, https://doi.org/10.1016/j.renene.2020.04.039.
[8] Yao, S., Chetan, M., Griffith, D.T., Escalera Mendoza, A.S., Selig, M., Martin, D., Kianbakht, S., Johnson, K., and Loth, E., "Aero-Structural Design and Optimization of 50 MW Wind Turbine with over 250-meter Blades," Wind Engineering, July 2021, https://doi.org/10.1177/0309524X211027355.
[9] Escalera Mendoza, A.S., Griffith, D.T., Jeong, M., Qin, C., Loth, E., Phadnis, M., Pao, L., and Selig, M., "Aero-Structural Rapid Screening of New Design Concepts for Offshore Wind Turbines," Renewable Energy, December 2023, DOI: https://doi.org/10.1016/j.renene.2023.119519.
[10] Allen C, Viselli A, Dagher H, Goupee A, Gaertner E, Abbas N, Hall M and Barter G 2020 Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine. National Renewable Energy Lab.(NREL), Golden, CO (United States)
[11] Silva de Souza C E, Engebretsen E, Bachynski E E, Eliassen L, Berthelsen P and Haslum H 2021 Definition of the INO WINDMOOR 12 MW base case floating wind turbine. SINTEF.
[12] Abdelmoteleb, S., Escalera Mendoza A., Renan dos Santos, C., Bachynski-Polic, E., Griffith D.T., and Oggiano, L. "Preliminary Sizing and Optimization of Semisubmersible Substructures for Future Generation Offshore Wind Turbines," DeepWind 2022 Conference, Trondheim, Norway, January 2022.
[13] Abbas, N. J., Zalkind, D. S., Pao, L., & Wright, A. (2022). A reference open-source controller for fixed and floating offshore wind turbines. Wind Energy Science, 7, 53-73.
[14] dos Santos, C. R., Abdelmoteleb, S.-E., Mendoza, A. S., & Bachynski-Polic, E. E. (2022). Control considerations for very large floating wind turbines. IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles. Kongens Lyngby, Denmark.
[15] dos Santos, C. R., Abdelmoteleb, S.-E., Mendoza, A. S., Bachynski-Polic, E. E., Griffith, D. T., & Oggiano, L. (2022). Application of a PI-controller to a 25MW floating wind turbine. IEEE Conference on Decision and Control. Cancun, Mexico.
[16] Santos, C. R. (2023). On the application of adaptive controllers to a 25 MW wind turbine. COBEM. Floarianópolis: ABCM.