

Design optimization and upscaling of a semi-submersible floating platform

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Abstract

This work examines the procedure of optimizing and upscaling a semi-submersible platform in order to support a predefined wind turbine. Particular challenges related to the design criteria for floating platforms and to technical changes in the turbine design are addressed. The designed floating systems are evaluated regarding their eigenfrequencies, nominal pitch, stability and global performance in selected sea states, using three different analysis methods (simplified spreadsheet calculations, linear frequency-domain analyses in DNV's software HydroD, and detailed time-domain equation-based models in Modelica). By means of the guideline for optimization and upscaling, presented here, support structures for 7.5 MW and 10 MW wind turbines are developed based on a 5 MW design. The procedure allows for improved stability and dynamic performance compared to the baseline design, while also increasing the design efficiency. The optimization process yields a more than 10% lighter total system, which represents a more cost-effective floater solution for the 5 MW wind turbine. The natural periods are increased during optimization from original 17.3 s in heave and 27.0 s in pitch to 20.4 s and 34.7 s, respectively. This improved eigenfrequency performance of the floating system is maintained during upscaling.

Keywords: Offshore wind energy, semi-submersible floating platform, design optimization, upscaling, wind turbine

1. Introduction

Floating offshore wind turbines are taking on more and more prominence, as the industry moves towards larger turbines, farther offshore, in deeper water. The increase in turbine size can reduce the levelized cost of energy, but requires larger support structures capable of carrying those bigger turbines. Rather than redesigning the structure completely, a rational methodology for upscaling an existing floating substructure can improve the efficiency of the design process.

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Existing wind turbines are normally scaled up to larger sizes based on the power rating [1–3]. This simple geometrical upscaling does not, however, account for technological development of the turbine, or the basic equilibrium and stability requirements for floating support structures. Furthermore, the dynamic motions of floating platforms include coupled responses to wind- and wave-induced loads, over a wide range of frequencies, and depend on additional components such as the mooring system. As such, a separate upscaling procedure is needed for floating offshore wind turbine systems.

This study, carried out within the framework of the master’s thesis [4], uses the OC4 semi-submersible platform [5] as starting point. After introducing the applied analysis tools in Section 2, the main criteria when dealing with a semi-submersible floating platform are specified in Section 3, and used for optimizing the original OC4 semi-submersible floater, covered in Section 4. On this basis, a guideline for the upscaling process is developed and presented in Section 5. Following this procedure, upscaled platforms for Fraunhofer’s offshore-adapted wind turbine IWT-7.5-164 (Rev 3, A. Sevinc et al., personal communication, 2015), as well as for the DTU 10 MW reference wind turbine [6] are designed and analyzed, based on simplified spreadsheet applications, linear frequency-domain methods (in DNV’s software HydroD [7]), and detailed equation-based models (in Fraunhofer’s in-house software, based on Modelica [8]). The results of the upscaled floating wind turbine systems are presented in Subsection 5.2. Finally, Section 6 recapitulates the developed rational and optimized upscaling procedure and gives recommendations for future work on upscaling of a semi-submersible floating platform.

Nomenclature

1, 2, 3	Translational degrees of freedom (surge, sway, heave)	
4, 5, 6	Rotational degrees of freedom (roll, pitch, yaw)	
A	Added mass matrix (6×6) with components A_{ij}	[kg, kgm, kgm ²]
A, A_{WP}	(Water plane) Area of cross-section	[m ²]
aim	Aimed parameter	
basis	Parameter of the basic system design	
bot	Bottom end	
C	Stiffness matrix (6×6) with components C_{ij}	[kg/s ² , kgm/s ² , kgm ² /s ²]
CoB, CoG	Center of buoyancy/gravity	
D	Diameter	[m]
d	Distance to the central axis	[m]
F_T	Thrust force	[N]
g	Acceleration due to gravity	[m/s ²]
H_s	Significant wave height	[m]
I, \bar{I}	Global/Local area moment of inertia	[m ⁴]
k	Scaling factor	
M	Mass matrix (6×6) with components M_{ij}	[kg, kgm, kgm ²]
m_{WT}	Mass of wind turbine (tower, nacelle, rotor)	[m]
new	Parameter of the target system design	
opt	Parameter of the optimized system design	
orig	Parameter of the original system design	
T_n, T_p	Natural/Peak period	[s]
x, y, z	Coordinate and direction of surge, sway, heave	
z_{hub}	Hub height	[m]
ρ_{water}	Water density	[kg/m ³]
θ	Pitch angle	[rad] or [°]

2. Analysis Tools

Three primary tools were applied in the analysis of the proposed concepts. First, a spreadsheet tool was developed by the first author in order to carry out the optimization and upscaling processes, including ballast calculations and estimation of stability and natural periods, as well as computations for adjusting drag coefficients and blade-pitch controller gains.

Next, the HydroD software from DNV was used to solve the first order potential flow boundary value problem for the frequency-dependent radiation and diffraction of the rigid hull, which was generated in GeniE [7]. Response amplitude operators were thus obtained, and allowed efficient preliminary estimation of the dynamic behavior of the platform under wave loads. HydroD's functionality for intact stability calculations was used to more accurately assess the righting moment.

Finally, the equation-based software Dymola [9] was used to carry out fully coupled aero-hydro-servo-elastic analyses. The floating wind turbine system was implemented in Modelica [8] by means of models for top structure (rotor, nacelle, controller, tower), support structure, station-keeping system, and environment. Essentially, the model includes generator torque and blade-pitch control logic, aerodynamic loads according to the blade element/momentum theory, hydrodynamic loads according to Morison's equation (with MacCamy-Fuchs correction), as well as geometry-based buoyancy calculation at the instantaneous position. For rotor and tower both rigid and flexible models (Bernoulli beams) were available, while the substructure was modelled as rigid body in the first approach. Additional details regarding the analysis model can be found in [4].

3. Criteria for Optimization and Upscaling

Floating offshore wind turbines are complex systems, that can be optimized with respect to several different aspects, such as costs, reliability, structural integrity, outer dimensions, manufacturability, and so on, which makes it difficult to find an all-in-one solution for an optimized upscaling procedure in just one step. For this reason, certain aspects have to be selected, on which the focus lies during the optimization and upscaling process, developed and presented herein.

The main criteria in this study are stability, eigenfrequencies, and dynamic behavior, as well as a not overly conservative, but still safe, system design. Thus, the desired nominal (static) platform pitch at the rated wind speed is 5° , which leaves a safety factor of at least two for higher loads in fault situations, without exceeding the typical maximum allowable pitch during operation (10°) [10]. Floatability, i.e. static equilibrium at the desired draft, is achieved by adjusting the ballast, depending on the displaced water volume and the actual system weight. Water ballast is used whenever possible in order to minimize the cost, although concrete or other types of ballast may be used in case of space restrictions in the columns. In order to avoid resonance in the frequency range of the wave excitation, as well as to separate the system's eigenfrequencies from each other, natural periods of at least 20 s in heave, more than 30 s in roll and pitch, and around 100 s in surge, sway, and yaw are aimed. The coupled dynamic motions of the floating system have to be incorporated in the turbine controller, which is done by adjusting the blade-pitch controller gains based on the natural frequency in pitch. Table 1 summarizes the desired system characteristics.

Table 1: Desired system performances.

θ_{aim}	$T_{n,1,\text{aim}}$	$T_{n,2,\text{aim}}$	$T_{n,3,\text{aim}}$	$T_{n,5,\text{aim}}$	$T_{n,6,\text{aim}}$
5°	100 s	100 s	20 s	30 s	100 s

Further criteria, such as top structure adjustment, mooring system, as well as aspects like structural integrity, producibility, and costs, are only briefly touched upon in this work. In order to maintain the original hub height, the

bottom part of the tower is cut at the top level of the floater's main column. However, the effect of this modification on the tower eigenfrequencies, as well as the limit of $0.2g$ for the nacelle accelerations [11] are not examined. The mooring system is included in the upscaling procedure to the extent that a predefined stiffness is yielded. Further adjustment for optimizing surge, sway, and yaw natural frequencies is not covered in this approach. Structural scaling is not considered in the presented procedures, as the main focus lies on the hydrodynamic behavior of the floating system. Nevertheless, a simplified strength check for the upper columns, based on equivalent stress computations using the shape modification hypothesis, is included as first assessment for the structural integrity. The only financial aspects, which are covered here, are the aimed reduced amount of used material, as well as the preferred ballast (water). A detailed cost analysis, covering producibility, location, and transportation would definitely supplement this study.

4. Optimization of the OC4 Semi-Submersible Platform

The OC4 semi-submersible platform [5], carrying the NREL 5 MW wind turbine [12], is used as reference structure. As, however, it is found that this floater is over-conservatively designed, quite heavy, and has sub-optimal eigenfrequencies for the rigid body modes of motion, the platform is first optimized, before using it as basis for the upscaling processes.

4.1. Optimization Procedure

Aiming for longer natural periods in heave and pitch, a lighter and cheaper platform, and a less over-conservative but still safe system, the original OC4 semi-submersible platform is optimized by reducing the diameter of the upper column (UC) and changing the ballast position within the outer columns. The scaling of the upper column diameter is determined in two consecutive steps.

First, a heave natural period of $T_{n,3,aim} = 20$ s is defined, and the scaling factor k_3 is introduced in Equation 1. The computation of the natural period in heave is presented in Equation 2.

$$k_3 = \frac{T_{n,3,aim}}{T_{n,3,orig}} = \frac{20 \text{ s}}{17.4 \text{ s}} \quad (1)$$

$$T_{n,3} = 2\pi \sqrt{\frac{M_{33} + A_{33}}{C_{33}}} \quad (2)$$

Reducing the upper column diameter D_{UC} leads to a decrease in the mass component M_{33} and an increase in the added mass component A_{33} , which have approximately a canceling effect on each other. The numerator in Equation 2 can thus be assumed to remain constant when just changing the upper column diameter. The first scaling factor $k_{3,UC}$ for the upper column diameter is therefore determined from the required scaling of the stiffness component C_{33} and the contribution of the upper columns to the total water plane area A_{WP} . Based on Equation 3 the first scaling factor is found to be $k_{3,UC} \approx 0.853$.

$$k_3^{-2} \approx \frac{C_{33,opt}}{C_{33,orig}} \approx \frac{1}{A_{WP}} \left[A_{UCs} k_{3,UC}^2 + (A_{WP} - A_{UCs}) \right] \quad (3)$$

The nominal pitch is already increased from $\theta_{orig} = 3^\circ$ to $\theta = 4.5^\circ$. However, a more critical value of $\theta_{aim} = 5^\circ$ is desired, leading to Equation 4 for the scaling factor k_5 . The nominal pitch, defined by Equation 5, depends on the magnitude and point of attack of the thrust force F_T , as well as the stiffness component C_{55} in pitch.

$$k_5 = \frac{\theta_{aim}}{\theta} = \frac{5^\circ}{4.5^\circ} \quad (4)$$

$$\theta \approx \frac{F_T (z_{hub} - z_{CoB})}{C_{55}} \quad (5)$$

The overturning moment at rated wind speed in the numerator of Equation 5 for the nominal pitch can be assumed to remain approximately constant. Thus, the stiffness component C_{55} has to be decreased by reducing the upper column diameter by a second scaling factor $k_{5,UC}$. This can be computed based on Equation 6, taking the contribution of the upper columns to the stiffness in pitch into account.

$$k_5^{-1} \approx \frac{\rho_{\text{water}} g}{C_{55}} \left[\bar{I}_{y,UCs} k_{5,UC}^4 + A_{UC} \sum d_{UC,i}^2 k_{5,UC}^2 + \left(\frac{C_{55}}{\rho_{\text{water}} g} - I_{y,UCs} \right) \right] \quad (6)$$

The resulting second scaling factor is $k_{5,UC} \approx 0.960$. Together with $k_{3,UC}$, determined in the first step, a total scaling factor of $k_{UC} = k_{3,UC} k_{5,UC} \approx 0.819$ results. This leads, with the original upper column diameter of $D_{UC,orig} = 12.00 \text{ m}$, after rounding up to full decimeter, to an upper column diameter of $D_{UC,opt} = 9.90 \text{ m}$ for the optimized semi-submersible floater.

4.2. Optimized OC4 Semi-Submersible Platform Design

Due to the 17.5% decrease in the upper column diameter, the total system mass is reduced by 10.8%, which reduces the necessary material and related costs. The stability analysis in HydroD yields that almost no stability is lost during the optimization procedure, as shown in Figure 1. The eigenperiods, however, are significantly increased from original 17.3 s in heave and 27.0 s in pitch, to 20.4 s and 34.7 s, respectively, as it can be seen in Figure 2, presenting the time series obtained from free decay simulations in Dymola, based on Modelica.

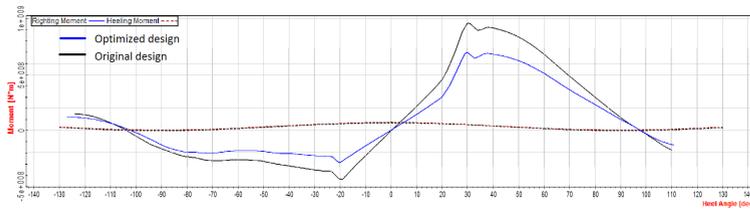


Figure 1: Righting and wind heeling moment curves of the optimized and original OC4 semi-submersible platform designs

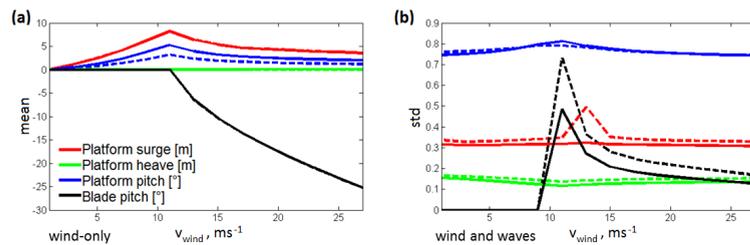


Figure 3: Motions of the optimized (solid) and original (dashed) OC4 semi-submersible platform designs (a) mean; (b) standard deviation

The nominal pitch of 4.5° is more critical than the original value of 3° , but still within the allowable range. The aimed angle of 5° is not obtained, as the optimization calculation is performed just with the stiffness of the floater, excluding the mooring line stiffness. The mean platform motions are only increased in the pitch degree of freedom. The dynamic motions are all similar to those of the original floater. Those results are taken from full system analyses in Dymola, at different wind speeds with either no waves (mean motions) or irregular waves of $H_s = 9.14 \text{ m}$ and $T_p = 13.6 \text{ s}$ (dynamic motions), as presented in Figure 3.

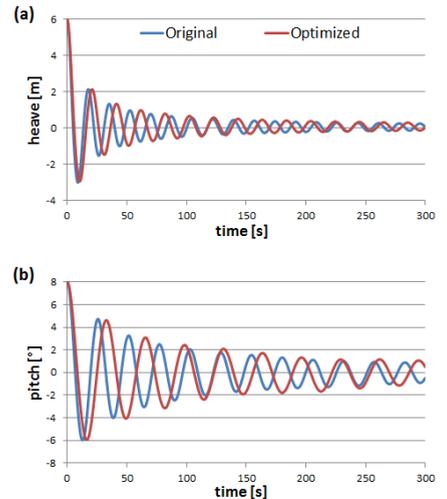


Figure 2: Free decay time series of the optimized and original OC4 semi-submersible platform designs (a) in heave; (b) in pitch

5. Upscaling of the Optimized OC4 Semi-Submersible Platform Design

The optimized OC4 semi-submersible platform, obtained in Section 4, is used as basis for upscaling to any other turbine design.

5.1. Upscaling Procedure

Three different scaling factors are used in the upscaling process. Instead of scaling the platform according to the power rating of the wind turbines, which is a common upscaling method, the main scaling factor k , for most of the platform components, is determined from the ratio of the top structure masses, as given in Equation 7, and thus accounts for technological development, such as changes in blade manufacturing or novel generator systems.

$$k = \sqrt[3]{\frac{m_{WT,new}}{m_{WT,basis}}} \quad (7)$$

Due to the geometrical constraint, because of the predefined target wind turbine, a separate scaling factor k_{MC} for the main column (MC) has to be defined, following Equation 8.

$$k_{MC} = \frac{D_{bot,tower,new}}{D_{MC,basis}} \quad (8)$$

As the overturning moment, defined by thrust force and hub height, is more design- and site-specific than following the theoretical scaling laws, the upscaling procedure aims to maintain the nominal pitch. Thus, a third scaling factor k_{UC} , for the upper column diameter, is introduced, so that Equation 9 is satisfied.

$$\frac{F_{T,basis} (z_{hub,basis} - z_{CoB,basis})}{C_{55,basis}} \stackrel{!}{=} \frac{F_{T,new} (z_{hub,new} - z_{CoB,new})}{C_{55,new}} \quad (9)$$

The parameters of the basic design on the left side of Equation 9 are known, as well as the rated thrust force $F_{T,new}$ and hub height $z_{hub,new}$ of the new wind turbine on the right side. This leaves the position of the center of buoyancy $z_{CoB,new}$ and the stiffness component in pitch $C_{55,new}$, both of the target system, as the only two unknowns in Equation 9. $z_{CoB,new}$ can be approximated to scale with the main scaling factor, as expressed by Equation 10.

$$z_{CoB,new} \approx k z_{CoB,basis} \quad (10)$$

$C_{55,new}$ can be computed using Equation 11, based on the dimensions of the basic design, considering the different scaling of each component, as well as the deviation of the weight from the k^3 -scaling because of the change in buoyancy, compensated by adjusting the ballast amount.

$$\begin{aligned} C_{55,new} \approx & \rho_{water} g \left(k_{UC}^4 \bar{I}_{y,UCs,basis} + k_{UC}^2 A_{UC,basis} \sum d_{UC,i,basis}^2 k^2 \right) + \rho_{water} g I_{y,MC,basis} k_{MC}^4 \\ & + \left[C_{55,basis} - \rho_{water} g \left(I_{y,UCs,basis} + I_{y,MC,basis} \right) \right] k^4 \\ & + \rho_{water} g A_{UCs,basis} \left(k_{UC}^2 - k^2 \right) |z_{bot,UC,basis}| k \left(z_{CoB,basis} - z_{CoG,basis} \right) k \end{aligned} \quad (11)$$

Substituting Equations 10 and 11 in Equation 9, the scaling factor k_{UC} for the upper column diameter can be computed based on parameters of the basic design, known dimensions of the target wind turbine, and the previously determined scaling factors k and k_{MC} .

Considering viscous forces, relevant for floating platforms, the drag coefficients are re-calculated for each upscaled platform component, based on the procedure used in [5]. The tower base is cut at the determined elevation of the main column, so that the original hub height of the target wind turbine is maintained, as mentioned in Section 3. The mooring system is included in a first approach in the upscaling procedure: The anchor radius is scaled with k . The mooring line length and effective length are determined from a predefined mooring stiffness

in surge, which is, in this study, set equal to the original stiffness. As then all components contributing to the system weight are known, the amount of ballast can be adjusted so that equilibrium with buoyancy is obtained. The required ballast is distributed between upper and base columns with the goal of 5° nominal pitch, always taking into account the available inner volume of the columns.

Finally, the coupled motions and low-frequency response of a semi-submersible floating wind turbine system lead to the necessity of adjusting the wind turbine blade-pitch controller gains. The conditional equations, expressed in terms of turbine parameters, as well as damping ratio and natural frequency of the response, associated with the equation of motion for the rotor-speed error, can be taken from [12]. The damping ratio is chosen as 0.7, based on recommendations given in [13]. The natural frequency for the control is computed from the system natural frequency in pitch divided by 1.3. This factor is taken from a comparison of the original gains of the NREL 5 MW [12] and the adjusted gains of the wind turbine for the OC4 semi-submersible floater [5].

5.2. Upscaled Semi-Submersible Platform Designs

This upscaling procedure is carried out for Fraunhofer's offshore-adapted IWT-7.5-164 (Rev 3, A. Sevinc et al., personal communication, 2015), based on [14], and the DTU 10 MW reference wind turbine [6]. The floating wind turbines are pre-analyzed by means of simplified spreadsheet methods, and afterwards modelled and simulated in GenIE/HydroD and Modelica/Dymola. The systems are evaluated regarding their eigenfrequencies, nominal pitch, and stability, taking into account that buoyancy and center of buoyancy vary with the motion of the platform. The results, obtained from both computer programs and the initial hand calculations, are generally comparable for all designed floating wind turbine systems. Furthermore, motion response analyses in selected sea states, based on computations in HydroD, as well as simulations in Dymola without and with irregular waves at different wind speeds are carried out.

For the target wind turbine IWT-7.5-164, the upscaling procedure is applied to the optimized OC4 semi-submersible platform, derived in Section 4. Following the equations in Subsection 5.1, the three scaling factors are computed to be $k = 1.172$, $k_{MC} = 1.077$, and $k_{UC} = 1.282$.

Scaling with those factors yields a well-designed floating wind turbine system, which uses the cheapest possible ballast water, has just a slightly reduced stability compared to the optimized OC4 floater, as presented in Figure 4, but still fulfills all stability criteria sufficiently, and has a slightly increased nominal pitch of 4.8° , which is close to the aimed value of 5° . The eigenfrequencies are comparable to the performance of the optimized OC4 floater design. The mean pitch motions are also similar, while the dynamic pitch motion is slightly decreased, as shown in Figure 5.

All in all, the floating system design for Fraunhofer's offshore wind turbine gives satisfactory results and is expected to remain structurally intact,

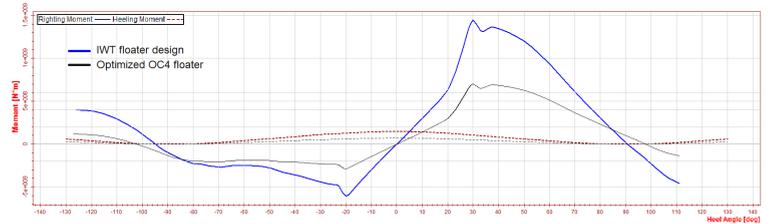


Figure 4: Righting and wind heeling moment curves of the IWT floater in comparison with the optimized OC4 semi-submersible platform design

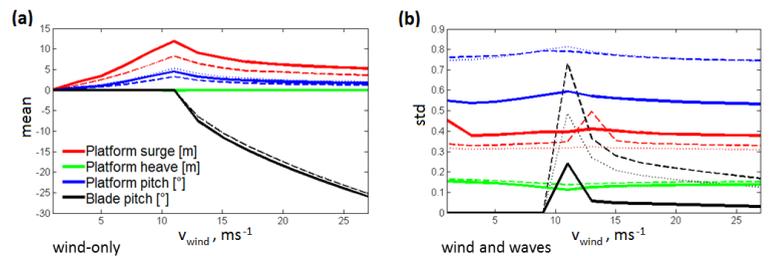


Figure 5: Motions of the IWT floater (solid) in comparison with the optimized (dotted) and original (dashed) OC4 semi-submersible platform designs (a) mean; (b) standard deviation

based on the simplified strength check. The main parameters are presented in Table 2. Further results can be found in [4].

Table 2: Main parameters of the IWT floater.

k	k_{MC}	k_{UC}	θ	$T_{n,1}$	$T_{n,3}$	$T_{n,5}$	$T_{n,6}$
1.172	1.077	1.282	4.8°	136.9 s	20.6 s	33.2 s	113.2 s

For the DTU 10 MW reference wind turbine two floaters are designed, following the given upscaling guideline: one based on the optimized OC4 semi-submersible, the other one based on the floater for the IWT-7.5-164. The obtained platform dimensions are the same except for the upper columns. Figure 6 presents the main parameters of the two floater designs for the DTU 10 MW (for more details see [4]).

The upscaling procedure based on the IWT floater yields a 1 m larger upper column diameter. Consequently, the corresponding floating wind turbine system is 4.5% heavier and needs 2.24E+5 kg more processed steel, is

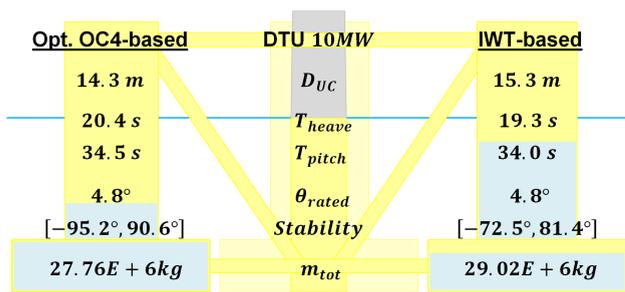


Figure 6: Comparison of the two floater designs for the DTU 10 MW

less (but still sufficiently) stable, has a heave natural period of just 19.3 s, which is thus fallen below the aim of 20 s, and a slightly reduced natural period in pitch, experiences slightly increased dynamic motions in surge and heave, but slightly decreased dynamic motion in pitch, and has a smaller safety factor for the structural strength, compared to the floating wind turbine system for the DTU 10 MW obtained by direct upscaling of the optimized OC4 floater. Both designs, however, have a nominal pitch of 4.8°.

Based on those results, it is recommended to use directly the critically optimized platform design as basis for upscaling, and not an already upscaled floater. By means of a simple check, based on the calculated scaling factors, it could already be assessed ahead of any analysis, whether the natural period in heave would be reduced during upscaling, and thus could become critical. This estimation could be very helpful, as the upscaling procedure does not include the eigenfrequencies, which however are very important for floaters. Even if the basic design is already optimized to higher natural periods, and upscaling has the positive side effect that the natural frequencies would theoretically decrease with the scaling factor to the power of -0.5, an increase in the natural frequencies could still occur if different scaling factors are used, especially if the upper column diameter scales faster than the main components.

6. Conclusion and Recommendation

This work provides a guideline for optimizing and upscaling of a semi-submersible platform, in order to support a predefined larger wind turbine. Floating structures for Fraunhofer's offshore 7.5 MW and the DTU 10 MW reference wind turbines are developed, based on the OC4 semi-submersible platform supporting the NREL 5 MW turbine. The designed floating systems are analyzed with respect to their eigenfrequencies, nominal pitch, stability, and global performance in selected sea states.

As the original OC4 semi-submersible platform is found to be over-conservatively designed, unnecessarily heavy, and lacking in good frequency performance, first, an optimization procedure is applied. By reducing the upper column diameter and adjusting the ballast position within the outer columns, longer natural periods, a reduced floater mass, as well as a less over-conservative, but still sufficient stable system is obtained. This optimized platform design is used as basis for the upscaling to any other larger turbine.

Three different scaling factors, considering technological development, geometrical constraints, and actual loads on the turbine, are used in the upscaling procedure. The mooring system is included in a first approach, and the blade-pitch controller gains are adjusted according to the expected system natural frequency in pitch. The upscaling process is carried out for Fraunhofer's offshore-adapted IWT-7.5-164 and the DTU 10 MW reference wind turbines. The analysis results, obtained from the three different methods (simplified spreadsheet calculations, linear frequency-domain computations in HydroD, and detailed time-domain equation-based models in Modelica), are comparable and satisfying. The structural integrity is checked for the upper columns by a simplified approach.

For a more meaningful assessment of the designed semi-submersible floating wind turbine systems, finite element (beam) models should also be used for implementing the platform in Modelica. Based on this fully flexible system, detailed strength checks for fatigue and ultimate limit states, analyses of relevant relative motions, more extensive full system simulations, as well as a detailed cost analysis should be carried out. Furthermore, the mooring system has to be optimized in another step, to improve the natural frequency performance in surge, sway, and yaw.

Although more detailed analyses and further improvements should be carried out, the presented guideline for optimizing and upscaling a semi-submersible platform already yields reasonable floater designs for predefined larger wind turbines, in a fast and cost-efficient way, and with satisfying results and performances. In addition, the optimization and upscaling procedures could be modified for the different criteria of other types of semi-submersibles, or even spars and tension leg platforms, and thus be applied to other concepts of floating support structures.

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