Application of a PI-controller to a 25 MW Floating Wind Turbine

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Abstract— **Proportional-integral controllers are extensively applied to the pitch control of wind turbines. Despite its simplicity, this control strategy achieves good performance in onshore applications. However, the application of proportional-integral controllers to floating wind turbines faces some challenges, such as negative feedback due to the platform motion. In this sense, the present work proposes a parametric study to assess the influence of tuning parameters of the pitch controller on the performance of a 25 MW floating wind turbine. Effects of including floating feedback in the control strategy are also investigated. Finally, optimum parameters for a proportional-integral pitch controller are defined for the 25 MW wind turbine.**

I. INTRODUCTION

One important challenge constantly addressed by the wind turbine industry is the reduction of the levelized cost of energy, for which, the rotor size plays an important role [1]. After progressive growths throughout the years, today's wind turbines have larger rotors, higher hub heights, longer blades, and considerably increased rated power capacity. Furthermore, offshore winds have higher speeds, smaller boundary layers, and lower turbulence levels in relation to onshore winds [2]. These factors suggest the development of very large offshore wind turbines, such as the 25 MW wind turbine discussed in this paper.

Bottom-fixed foundations for offshore wind turbines apply to shallow waters. However, as the water depth increases, floating foundations are preferred. Besides the challenges inherent to the structural and floating platform designs, control systems for load alleviation and power tracking of these large machines require special attention. Floating wind turbines are subject to the so-called negative damping effect if the pitching controller lacks proper tuning [3]. The negative damping leads to instabilities or limit cycle oscillations in the platform motion, thereby affecting the tracking of the rotational speed in above-rated conditions.

Several works tackled the development of control strategies for floating wind turbines. Collective and individual pitching control of the blades can be employed to mitigate undesired platform motions and reduce fatigue loads [4]. Gain-scheduled controllers with linear quadratic regulator (LQR) [5] have been successfully applied to wind turbine applications. Several authors applied fuzzy logic [6], artificial neural networks [7] and artificial intelligence techniques [8] to track the power production regardless of turbulent gusts reaching the turbine. Modern control algorithms also consider the prediction of wind disturbances using LIDAR [9].

However, the additional complexity added by sophisticated control strategies seems to be unattractive in comparison to the robustness and simplicity of proportional-integral (PI) controllers [10]. Moreover, PI controllers often achieve a sufficient performance level despite the ease of implementation. Therefore, PI controllers are extensively applied to wind turbine applications. Abbas et al. [11] introduced ROSCO, a baseline PI controller tool easily tuned and exchanged between wind turbines. ROSCO provides an industry-standard control that can be employed by the research community in comprehensive studies about wind turbine behaviors.

Following the trends cited above, the present work investigates how a PI controller performs when applied to a very large wind turbine, namely a 25 MW floating turbine. The challenges imposed by the negative damping are illustrated in a parametric study. Trade-offs in the control design are highlighted and an optimization problem is proposed to lead to optimum controller parameters.

II. METHODOLOGY

The 25 MW baseline rotor design was created by geometrically upscaling the IEA 15 MW turbine [12] based on the power ratio. This upscaling approach defined the outer geometry of the blade. Then, a detailed structural analysis was performed to define the thickness of the spar cap, root reinforcement, and shell skins while meeting strength and frequency requirements based on international design standards.

The substructure design for the 25 MW rotor [13] was obtained through a design space search based on a parametric study of the geometry of the reference semi-submersible platform UMaine VolturnUS-S [14]. The objective of the parametric study was to find the substructure geometry that has minimum steel mass (assuming constant steel thickness across all structural members of the substructure) and satisfies the following basic requirements for a floating wind turbine:

- Maximum static pitch of 6 degrees;
- Minimum rigid body natural periods of 20 s;
- Stiff-stiff floating tower;
- Maximum hull horizontal dimension of 120 m.

A simplified model was used to estimate the natural periods of rigid platform motions and the first tower bending mode. The simplified model is an idealized 2D finite element model of the floating wind turbine, which considers only motions in the surge-heave plane including tower bending, as illustrated in Fig. 1. The floating tower of the UMaine Volturn US-S [14] was theoretically upscaled for the 25 MW design.

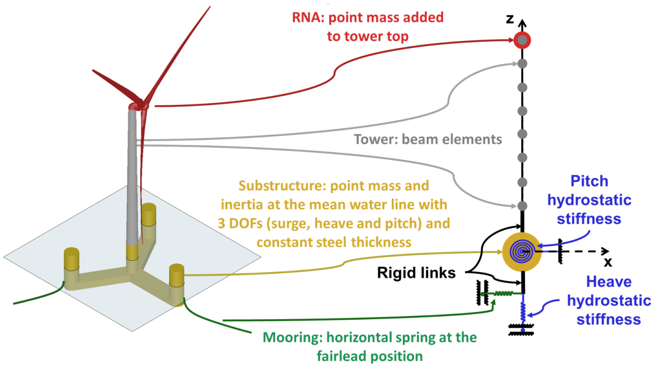

Fig. 1. Simplified 2D model for floating wind turbines.

Table I summarizes relevant frequencies, such as the rated rotor speed, the first natural frequencies of the blade, tower, and rigid body motions of the platform according to the OpenFAST setup at parked conditions.

Torque and pitch controllers are driven by the ROSCO controller version 2.3.0 [15]. The controller employs the gain scheduling approach to define PI gains. Peak shaving (to reduce peaks in structural loading), setpoint smoother (to avoid conflicting behavior between the pitch and torque controllers), and a wind speed estimator are modules available in the ROSCO implementation. Filtered signals of the blade pitch angle, generator speed, estimated wind speed, rotational speed error, and tower-top acceleration prevent the controller from actuating subject to undesired frequencies. The reader is referred to the work by Abbas et al. [11] for a detailed formulation of the controller and its filters.

TABLE I

RELEVANT FREQUENCIES OF THE FLOATING WIND TURBINE

Mode	Frequency (rad/s)
Rated rotor speed	0.620
Blade edgewise	2.727
Blade flapwise	2.130
Tower bending	2.635
Platform surge	0.053
Platform pitch	0.158

This work draws special attention to the above-rated conditions, where the actuation of the pitch controller prevails. Fig. 2 presents a block diagram of the closed-loop control strategy to adjust the operational pitch angle of the floating wind turbine.

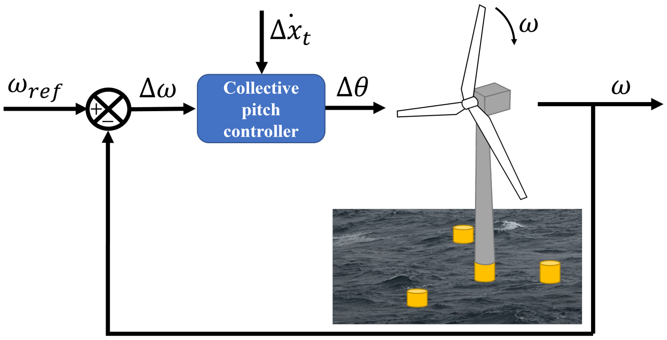

Fig. 2. Schematic of the pitch controller.

By considering a constant power control beyond the rated wind speed, the rotor dynamics can be represented as a second-order system, similar to a mass-spring-dashpot [16]:

$$I\ddot{\psi} + \left[\frac{1}{\omega_{rated}}\left(-\frac{\partial P_{aero}}{\partial\theta}\right)K_P - \frac{P_{rated}}{\omega_{rated}^2}\right]\dot{\psi} + \left[\frac{1}{\omega_{rated}}\left(-\frac{\partial P_{aero}}{\partial\theta}\right)K_I\right]\psi = 0 \qquad (1)$$

where I represents the combined inertia of the rotor and drivetrain, $-\frac{\partial P_{aero}}{\partial\theta}$ is the sensitivity of the aerodynamic power to changes in the blade pitch angle, P_{rated} is the rated power, ω_{rated} is the rated rotor speed, and ψ denotes the rotor azimuth. Given that the sensitivity of the aerodynamic power generally depends on the operational point, the scheduled gains can be selected to achieve a desired system natural frequency (ω_ψ) and damping ratio (ζ_ψ). Then, the proportional gain is given by:

$$K_P = \frac{2I\omega_{rated}\zeta_\psi\omega_\psi}{\left(-\frac{\partial P_{aero}}{\partial\theta}\right)}, \qquad (2)$$

and the integral gain is given by:

$$K_I = \frac{I\omega_{rated}\omega_\psi^2}{\left(-\frac{\partial P_{aero}}{\partial \theta}\right)}. \tag{3}$$

The ROSCO controller also considers floating feedback. To do so, the horizontal velocity of the hub $\dot{x}_t$, which accounts for velocities induced by the platform motion and tower vibrations, is taken into account when computing the pitch actuation, such that:

$$\Delta\theta = K_P \Delta\omega + K_I \int_0^t \Delta\omega(\tau)d\tau + K_f \Delta\dot{x}_t\ , \tag{4}$$

where K_f is the gain associated with the tower-top motion.

Simulations of the 25 MW floating wind turbine were performed using OpenFAST [17] coupled with tuned ROSCO controllers.

III. RESULTS

In previous work [18], the authors demonstrated that the natural pitch period of platforms hosting floating wind turbines increases as the rotor size increases. Such a trend leads to slower controllers designed through the detuning process [3]. In the present effort, the dynamics of the system considering floating feedback are extensively investigated. As depicted in Fig. 3, the application of a PI controller to the 25 MW wind turbine in a bottom-fixed condition allows proper tracking of the rated rotational speed in above-rated conditions. The rated rotor speed of the turbine is $\omega_{rated} = 0.62$ rad/s at $V = 10.7$ m/s. The desired damping ratio and frequency of the controller are taken as $\zeta_\psi = 1.0$ and $\omega_\psi = 0.15$ rad/s, respectively. Peak shaving of 80% has been applied to avoid large values of the thrust force. Fig. 3 analyses the system response to step increments of the wind speed from $V = 10$ to 18 m/s. Neglecting platform degrees of freedom, the rotor speed ω quickly returns to its undisturbed value after each step increment.

On the other hand, the same controller loses its effectiveness when applied to the floating wind turbine (considering $K_f = 0$). In this case, limit cycle oscillations with high amplitude are observed in the platform pitch for wind speeds between $V = 12$ and 15 m/s, which also induce high amplitudes of oscillations in ω. Such behavior is known as negative-damping or negative feedback [3]. An alternative offered by the ROSCO controller feeds back the velocity at the hub to compute the pitch variation (floating feedback - $K_f \neq 0$, *c.f.* Eq. (4)). The floating feedback allows a reduction in the amplitude of pitch oscillations. However, Fig. 3 suggests larger amplitudes of surge oscillations when adopting such an approach. Especially at $V = 12$ m/s, surge oscillations are not damped in the step response analyzed in Fig. 3. Therefore, this step response points out two relevant aspects of the application of control systems to the large 25 MW floating wind turbine: the need for the inclusion of floating feedback into the design of the pitch controller, and the possibility of large surge oscillations in above-rated conditions.

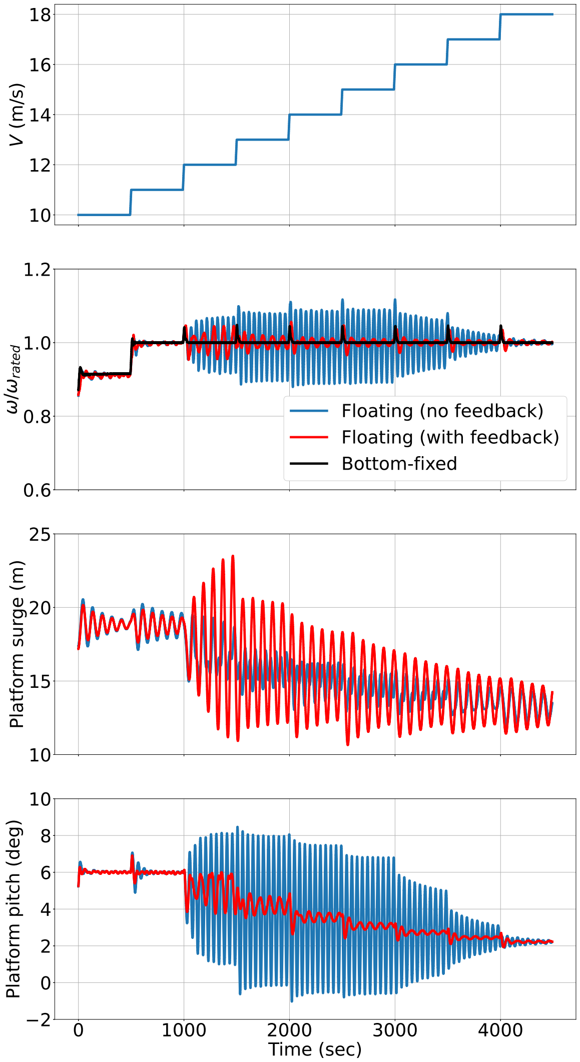

Fig. 3. Step response of the 25 MW wind turbine.

According to Eqs. (2) and (3), two tuning parameters drive the closed-loop response of the pitch controller: the desired damping ratio ζ_ψ and the natural frequency ω_ψ. The platform feedback gain, K_f, depends on the characteristics of the wind turbine according to [11] and does not require tuning. Therefore, a parametric study can be performed to understand how the parameters ζ_ψ and ω_ψ influence wind turbine dynamics. Fig. 4 presents phase portraits of the rotor speed, surge, and pitch oscillations at the critical condition $V = 12$ m/s. In this case, the natural frequency of the pitch controller was fixed as $\omega_\psi = 0.15$ rad/s and the damping ratio varied in the interval $0.5 \leq \zeta_\psi \leq 3.0$. Surge displacements at the water level $x(t)$ and pitch angles $\eta_5(t)$ of the platform reveal limit cycle oscillations in the system response throughout the values of ζ_ψ within the interval of analysis. The amplitude of surge oscillations increases as ζ_ψ decreases. On the other hand, pitching oscillations have higher amplitudes as ζ_ψ increases. The oscillatory behavior of the platform compromises the track of the rated rotor speed, which oscillates around the reference value. As a result of such behavior, the power generated by the wind turbine oscillates around its nominal value.

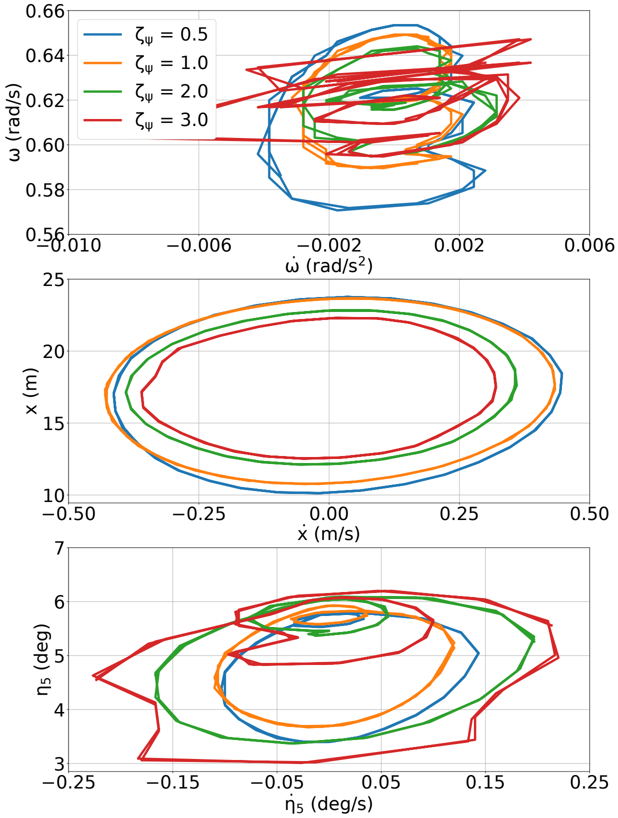

Fig. 4. Effect of the desired damping ratio in the phase portraits of the system ($V = 12$ m/s, $\omega_\psi = 0.15$ rad/s).

Similarly, Fig. 5 investigates the phase portraits when ω_ψ varies in the interval $0.05 \leq \omega_\psi \leq 0.2$ rad/s. Now, $\zeta_\psi = 1.0$ for all the cases. The results consistently indicate that the reduction of ω_ψ also reduces the amplitude of pitching and surging oscillations of the floating platform, and, as a consequence, the amplitudes of limit cycle oscillations in ω. In the case of $\omega_\psi = 0.05$ rad/s, a damped response is observed in the system dynamics. By comparing the results in Fig. 5 and the relevant frequencies presented in Table I, one could be tempted to conclude that limit cycle oscillations are avoided by setting the desired frequency of the controller below the natural surge frequency of the platform ($\omega_\psi \leq 0.053$ rad/s). However, damped surge oscillations are already achieved if $\omega_\psi < 0.09$ rad/s, thereby debunking the previous hypothesis. It is worth mentioning that hydrodynamic damping is expected in the OpenFAST solution due to a frequency-dependent linear radiation damping and a quadratic viscous term.

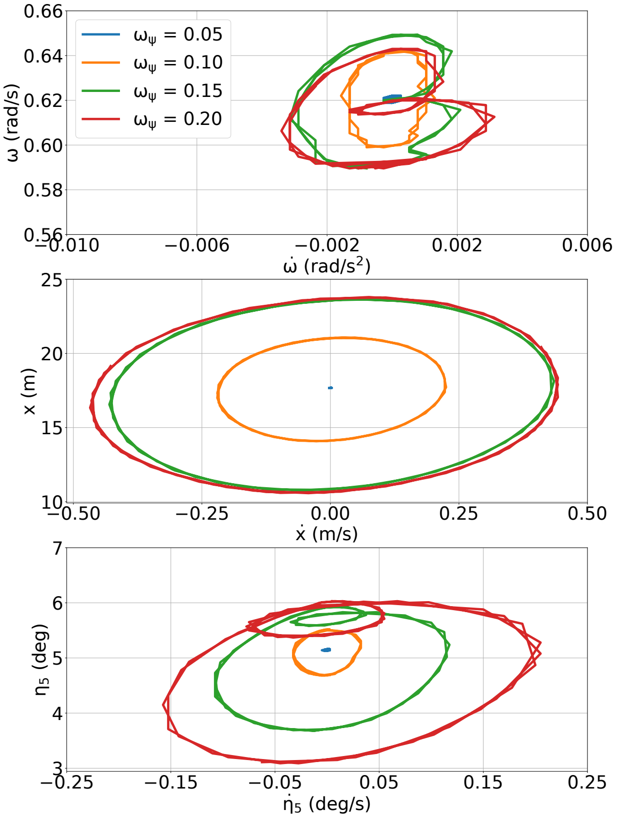

Fig. 5. Effect of the desired natural frequency in the phase portraits of the system ($V = 12$ m/s, $\zeta_\psi = 1.0$).

The trade-off in these results consists in the design of slow controllers to damp surging oscillations of the floating platform. Therefore, the power tracking performance can be compromised during the incidence of turbulent gusts in the turbine rotor. To overcome this trade-off, optimum parameters (ζ_ψ and ω_ψ) can be sought from the ROSCO controller. Based on the performance index discussed by Ebrahim et al. [19], the following optimization problem can be established considering the critical condition at $V = 12$ m/s:

$$\min_{(\zeta_\psi,\omega_\psi)} \frac{1}{t_f} \int_0^{t_f} \left[P(t) - P_{rated}\right]^2 \mathrm{d}t \quad , \tag{5}$$

subject to:

$$\begin{cases} 0.1 \leq \zeta_\psi \leq 5.0 \\ 0.01 \leq \omega_\psi \leq 1 \end{cases} \quad , \tag{6}$$

where t_f is the simulation time and $P(t)$ is the instantaneous generated power. The optimization problem is constrained to avoid unfeasible solutions. In the case of the 25 MW wind turbine, the optimum condition was reached when $\zeta_\psi = 2.22$ and $\omega_\psi = 0.082$ rad/s.

Fig. 6 compares the performance of controllers with different tuning parameters during the incidence of a turbulent gust in the 25 MW rotor: the optimum controller and a baseline case. This baseline controller denotes the parameters that previously proven to damp surging oscillations ($\zeta_\psi = 1.0$ and $\omega_\psi = 0.05$ rad/s). The latter results in poor power tracking performance and large oscillations in rotor speed despite

TABLE II
PERFORMANCE OF THE OPTIMUM CONTROLLER

	ζ_ψ	ω_ψ (Hz)	Maximum overshoot
Baseline controller	1.00	0.050	21.7%
Optimum controller	2.22	0.082	12.8%

damping surge oscillations in the step response. On the other hand, the controller with optimum parameters shows a similar platform behavior, but a better tracking of the rated rotor speed. Table II also presents the maximum overshoot in power during the turbulent response. This overshoot was significantly reduced by employing optimum controller parameters.

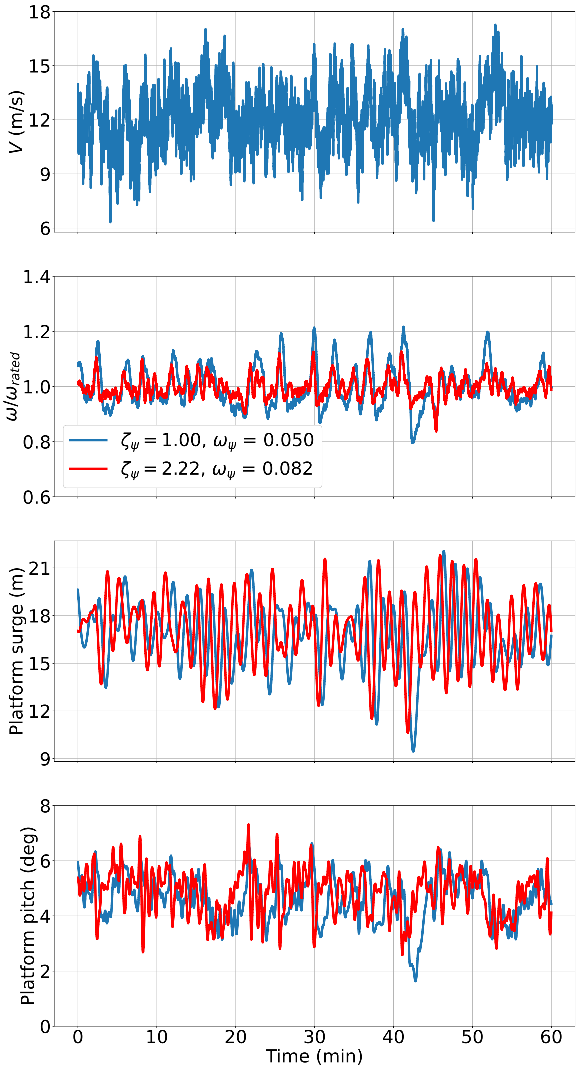

Fig. 6. Response of the pitch controller under a turbulent gust.

Therefore, the design of pitch controllers for very large wind turbines may deal with a trade-off imposed by limit cycle oscillations related to the platform motion. Depending on the tuning parameters of the controller, surge displacements may still have negative feedback during the step response. However, considering the long period usually associated with these oscillations, other sources of damping may be sufficient to maintain an acceptable performance during the operational regime. Especially when considering turbulent gusts, it is expected that the controller keeps a better track of the rotor speed to maintain the quality of the generated power while mitigating fatigue loads. Finally, the control strategy can also allow for larger power excursions in wind farms, assuming that the variations at the individual turbine level might average out over the entire farm.

IV. CONCLUSIONS AND FUTURE WORK

A. *Conclusions*

This work sheds light on relevant aspects concerning the design of controllers for a 25 MW floating wind turbine. Effects of negative feedback lead to limit cycle oscillations in the system dynamics in the above-rated conditions. Such undesired behavior can be diminished or even suppressed by applying floating feedback to the pitch controller. On the other hand, surge oscillations of the platform may still have large amplitudes, which can be reduced by selecting small values for the natural frequency of the controller. As a consequence, the resulting controller can allow for large excursions of the rotor speed during wind gusts. The solution to an optimization problem shows an alternative for this trade-off, thereby reducing the overshoot in rotational speed while keeping an acceptable platform behavior.

B. *Future Work*

In future steps of this work, other control strategies are going to be investigated for their capabilities of reducing the trade-offs between the control of the platform behavior and the tracking of the generated power. The reduction of structural loads and pitching actuation must also be considered. One possible strategy is the use of the nacelle velocity feed-forward. Another possibility is the use of a platform pitch feedback.

V. ACKNOWLEDGMENTS

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REFERENCES

[1] M. Shields, P. Beiter, J. Nunemaker, A. Cooperman, and P. Duffy, “Impacts of turbine and plant upsizing on the levelized cost of energy for offshore wind,” *Applied Energy*, vol. 298, p. 117189, 2021.

[2] J. Li, G. Wang, Z. Li, S. Yang, W. T. Chong, and X. Xiang, “A review on development of offshore wind energy conversion system,” *International Journal of Energy Research*, vol. 44, no. 12, pp. 9283–9297, 2020.

[3] T. J. Larsen and T. D. Hanson, “A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine,” in *Journal of Physics: Conference Series*, vol. 75, p. 012073, IOP Publishing, 2007.

[4] M. A. Lackner, “Controlling platform motions and reducing blade loads for floating wind turbines,” *Wind Engineering*, vol. 33, no. 6, pp. 541–553, 2009.

[5] O. Bagherieh and R. Nagamune, "Gain-scheduling control of a floating offshore wind turbine above rated wind speed," *Control Theory and Technology*, vol. 13, no. 2, pp. 160–172, 2015.

[6] M. Nabipour, M. Razaz, S. G. Seifossadat, and S. Mortazavi, "A new mppt scheme based on a novel fuzzy approach," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 1147–1169, 2017.

[7] C. Wei, Z. Zhang, W. Qiao, and L. Qu, "An adaptive network-based reinforcement learning method for mppt control of pmsg wind energy conversion systems," *IEEE Transactions on Power Electronics*, vol. 31, no. 11, pp. 7837–7848, 2016.

[8] S. Zhao, F. Blaabjerg, and H. Wang, "An overview of artificial intelligence applications for power electronics," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4633–4658, 2020.

[9] D. Schlipf, D. J. Schlipf, and M. Kühn, "Nonlinear model predictive control of wind turbines using lidar," *Wind energy*, vol. 16, no. 7, pp. 1107–1129, 2013.

[10] S. P. Mulders, T. G. Hovgaard, J. D. Grunnet, and J.-W. van Wingerden, "Preventing wind turbine tower natural frequency excitation with a quasi-lpv model predictive control scheme," *Wind Energy*, vol. 23, no. 3, pp. 627–644, 2020.

[11] N. J. Abbas, D. S. Zalkind, L. Pao, and A. Wright, "A reference open-source controller for fixed and floating offshore wind turbines," *Wind Energy Science*, vol. 7, no. 1, pp. 53–73, 2022.

[12] E. Gaertner, J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. Barter, N. Abbas, F. Meng, P. Bortolotti, W. Skrzypinski, G. Scott, R. Feil, H. Bredmose, D. K, M. Shields, C. Allen, and A. Viselli, "Definition of the IEA 15-Megawatt offshore reference wind turbine," 2020.

[13] A. Serag-Eldin, A. S. E. Mendoza, C. R. dos Santos, E. E. Bachynski-Polić, D. T. Griffith, and L. Oggiano, "Preliminary sizing and optimization of semisubmersible substructures for future generation offshore wind turbines," in *Journal of Physics: Conference Series (accepted)*, 2022.

[14] C. Allen, A. Viselli, H. Daghree, A. Goupee, E. Gaertner, N. Abbas, M. Hall, and G. Barter, "Definition of the UMaine VolturnUS-S reference platform developed for the IEA Wind 15-Megawatt offshore reference wind turbine," tech. rep., National Renewable Energy Laboratory, 2021.

[15] NREL, "ROSCO. Version 2.3.0," 2021.

[16] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW reference wind turbine for offshore system development," Tech. Rep. NREL/TP-500-38060, National Renewable Energy Laboratory, February 2009.

[17] J. Jonkman and USDOE, "Fast simulation tool containing methods for predicting the dynamic response of wind turbines," 8 2015.

[18] C. R. dos Santos, A. Serag-Eldin, A. S. E. Mendoza, and E. E. Bachynski-Polić, "Control considerations for very large floating wind turbines," in *14th IFAC Conference on Control Applications in Marine Systems, Robotics and Vehicles*, 2022.

[19] M. A. Ebrahim, M. Becherif, and A. Y. Abdelaziz, "Dynamic performance enhancement for wind energy conversion system using moth-flame optimization based blade pitch controller," *Sustainable Energy Technologies and Assessments*, vol. 27, pp. 206–212, 2018.