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ON THE APPLICATION OF ADAPTIVE CONTROLLERS TO A 25 MW WIND TURBINE

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Abstract. *Floating wind turbines are a promising technology for harnessing wind energy in deep waters, but they face challenges related to control and stability. One of these challenges is the so-called negative damping effect, which may occur beyond the rated wind speed. Classical proportional-integral controllers can mitigate negative damping effects by detuning the controller's frequency below the natural pitch frequency of the platform. However, when applied to very large floating wind turbines, this technique can result in slow controllers due to the small natural pitch frequency of the system. To address this issue, the present study proposes using adaptive super-twisting sliding mode controllers to track the rotational speed of the rotor instead of the classical proportional-integral approach. The study compares the performance of both control strategies in a 25 MW floating wind turbine designed by upscaling the IEA 15 MW. The analyses focus on the rotor speed, power production, and platform behavior subject to uniform and turbulent wind. The results suggest that adaptive controllers can stabilize the platform while maintaining good track of the rated rotational speed and power output of the wind turbine. By avoiding the need for detuning, adaptive controllers can provide faster and more accurate control of the rotational speed, thereby improving the stability and efficiency of floating wind turbines.*

Keywords: *sliding controllers, floating wind turbine, negative feedback, adaptive control.*

1. INTRODUCTION

Wind turbines represent a key technology for facilitating the transition to renewable energy sources. Offshore wind turbines may benefit from higher wind speeds and reduced turbulence levels. Therefore, they have emerged as a viable option for power production in numerous countries. However, the success of offshore wind energy relies on reducing the levelized cost of electricity (Barooni *et al.*, 2022). Consequently, wind turbines have been increasing in size each year, leading to a decrease in the natural frequencies of the system. This trend poses additional challenges for the control systems of floating offshore wind turbines (dos Santos *et al.*, 2022a).

Floating wind turbines may experience the so-called negative damping or negative feedback effects. Such a phenomenon induces large amplitudes of pitch and/or surge oscillations of the platform, leading to the controller's inability to maintain the rated rotational speed of the rotor. Consequently, this situation imposes higher fatigue loads on the structure (Ha *et al.*, 2021).

The initial solution to mitigate negative damping effects suggested detuning the controller (Larsen and Hanson, 2007). This involved setting the natural frequency of the blade pitch controller below the natural frequency of the platform's pitch. Such approach can be readily implemented with classical proportional-integral controllers (PI), which are commonly used for pitch control in wind turbines due to their simplicity. However, for larger wind turbines with smaller natural frequencies, the detuning technique results in slow controllers that struggle to accurately track the rated rotational speed (dos Santos *et al.*, 2022b).

An alternative approach to mitigate negative damping involves incorporating information about the platform motion into the controller. This technique, commonly referred to as floating feedback, aims to improve the stability of the system, resulting in damped or reduced amplitudes of pitch oscillations for the platform (Abbas *et al.*, 2022). In the case of large wind turbines, floating feedback does not guarantee damped oscillations of the platform, especially for operational regimes near the rated condition (dos Santos *et al.*, 2022b).

Alternatives to the collective pitch controller of floating wind turbines include the use of reinforcement learning approaches. However, they add complexity to the control implementation and rely on the training data for accuracy (Xie *et al.*, 2023).

A more recent development on pitch controllers of wind turbines includes the use of adaptive controllers. In this sense, Zhang and Plestan (2020) applied an adaptive super-twisting controller to blade pitch control in the above-rated regime. This strategy was enhanced to reduce the number of parameters to be tunned in the controller, thereby leading to a simplified adaptive super-twisting (Gutierrez *et al.*, 2022) and a self-adaptive super twisting (Mirzaei *et al.*, 2022).

In this sense, this work compares the performance of adaptive controllers with the classical gain-scheduled PI controller. The current application comprehends a 25 MW wind turbine, which has lower natural frequencies of the platform

in comparison with the 5 MW employed by Zhang and Plestan (2020).

2. METHODOLOGY

This work specifically targets the region III of operation of wind turbines. In this region, the objective is to maintain a constant power output equal to the turbine's nominal value for wind speeds above the rated condition. To achieve this, a collective pitch controller is utilized to keep the rotational speed steady at the rated value. To address the challenges posed by negative damping effects, the implementation of floating feedback is adopted to enhance the control performance. Figure 1 provides a schematic of the pitch controller, emphasizing the incorporation of floating feedback in its operation.
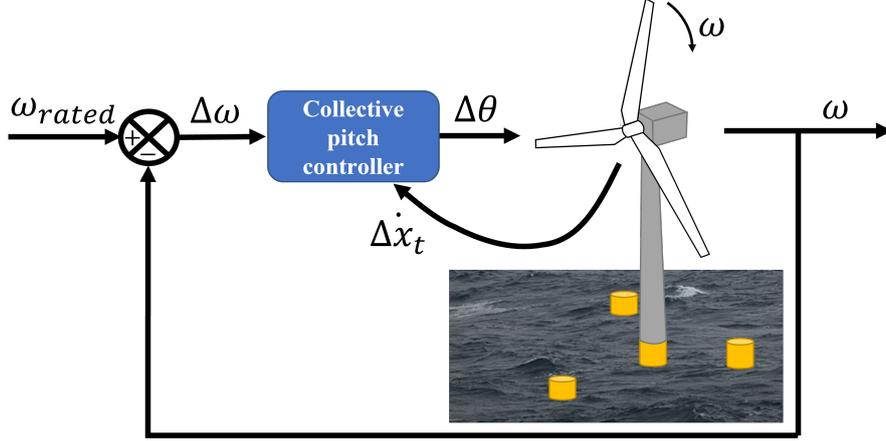

Figure 1. Schematic of the pitch controller.

In the present work, two control approaches are investigated for the collective pitch controller: the classical proportional-integral (PI) control with scheduled gains (Abbas *et al.*, 2022) and the adaptive super-twisting controller (Zhang and Plestan, 2020).

2.1 Proportional-integrative controller

The PI approach for the collective pitch controller is based on the error in rotor speed, $\Delta\omega$, with a gain K_{fb} associated with the floating feedback:

$$\Delta\theta = K_P\Delta\omega + K_I \int_0^t \Delta\omega(\tau)d\tau + K_{fb}\dot{x}_t \,, \tag{1}$$

where $\Delta\theta$ is the blade pitch angle, $\dot{x}_t$ is the tower top velocity and K_P and K_I are, respectively, the proportional and integral gains. Recalling that beyond the rated condition, the rotor dynamics can be represented as a second order system (Jonkman *et al.*, 2009):

$$I\ddot{\psi} + \left[\frac{1}{\omega_{rated}}\left(-\frac{\partial P_{aero}}{\partial\theta}\right)K_P - \frac{P_0}{\omega_{rated}^2}\right]\dot{\psi} + \left[\frac{1}{\omega_{rated}}\left(-\frac{\partial P_{aero}}{\partial\theta}\right)K_I\right]\psi = 0 \,, \tag{2}$$

where I denotes the combined inertia of the rotor and drivetrain, P_{aero} is the aerodynamic power, P_0 is the rated power, ω_{rated} denotes the rated rotor speed, and ψ is the rotor azimuth.

The proportional and integrative gains can be schedule as a function of $-\frac{\partial P_{aero}}{\partial\theta}$. A desired natural frequency $\omega_{0,\psi}$ and damping ratio ζ_ψ can be chosen such that:

$$K_P = \frac{2I\omega_{rated}\zeta_\psi\omega_{0,\psi}}{\left(-\frac{\partial P_{aero}}{\partial\theta}\right)}, \tag{3}$$

and the integrative gain:

$$K_I = \frac{I\omega_{rated}\omega_{0,\psi}^2}{\left(-\frac{\partial P_{aero}}{\partial\theta}\right)}. \tag{4}$$

The PI controller is delivered by the ROSCO implementation (Abbas *et al.*, 2022).

2.2 Adaptive super-twisting controller

The adaptive super-twisting (ASTW) approach depends on a observer s defined as:

$$s = c_1(\omega - \omega_{ref}) + c_2 \dot{x}_t ,$$ (5)

where c_1 and c_2 are constants.

The adaptive gain $\alpha(t)$ is defined by the differential equation (Zhang and Plestan, 2020):

$$\dot{\alpha} = \begin{cases} \omega_1 \sqrt{\frac{k_1}{2}} \, sign(|s| - \mu), \text{ if } \alpha > \alpha_m \\ \chi, \text{ if } \alpha \leq \alpha_m , \end{cases}$$ (6)

and depends on the constants ω_1, k_1, μ, χ and α_m.

Finally, the pitch actuation is defined as a function of $\alpha(t)$, s and $\beta = 2\epsilon\alpha(t)$, being ϵ a constant:

$$\Delta\theta(t) = -\alpha(t) \, |s|^{1/2} \, sign(s) - \int_0^t \frac{\beta(\tau)}{2} \, sign(s) \, d\tau .$$ (7)

2.3 Aero-hydro-servo-elastic simulations

The aero-hydro-servo-elastic simulations in this study employ the finite element code 3DFloat. This software utilizes the blade element momentum theory to provide aerodynamic loads. Wave and current loads are calculated using the Morison's equations (Nygaard *et al.*, 2016). The system also incorporates a comprehensive model of the mooring lines. Additionally, the controllers are implemented in Fortran and integrated with the main software.

3. RESULTS

Previous studies have highlighted the limitations of PI controllers in accurately tracking the rated power of extremely large wind turbines under above-rated conditions (dos Santos *et al.*, 2022a,b). Consequently, this study utilizes a 25 MW floating wind turbine to evaluate the performance of adaptive controllers compared to the classical PI approach. The outer blade geometry, including chords, torsion angles, and airfoils, has been determined by geometrically upscaling the IEA 15 MW turbine (Gaertner *et al.*, 2020) based on the power ratio. Additionally, a comprehensive structural analysis has been conducted to determine the optimal thickness of the spar cap, root reinforcement, and shell skins. These calculations were executed while ensuring compliance with the necessary strength and frequency criteria established by international standards. Figure 2 depicts the 3DFloat model of the floating 25 MW wind turbine.
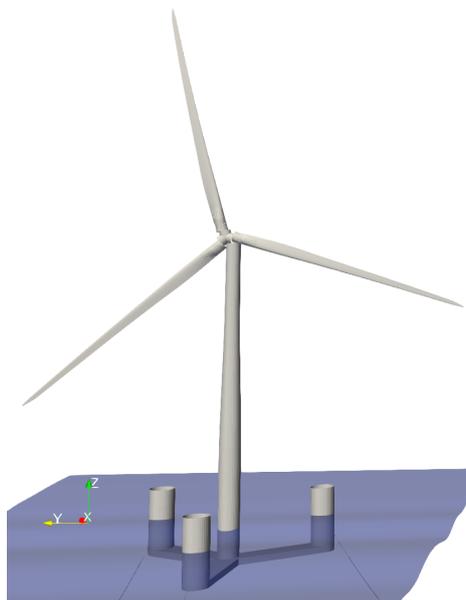

Figure 2. 3DFloat model of the 25 MW wind turbine.

The substructure design was based on the semi-submersible platform UMaine VolturnUS-S (Allen *et al.*, 2021). Its geometry served as a reference for a parametric study aimed at determining the substructure with the minimum mass, assuming a constant steel thickness across all structural members (Abdelmoteleb *et al.*, 2022). Several design constraints were incorporated, including a maximum static pitch of 6 degrees, a stiff-stiff floating tower, and a maximum hull horizontal dimension of 120 m. The floating tower of the 25 MW wind turbine was conceptually upscaled from the UMaine Volturn US-S design (Allen *et al.*, 2021).

Table 1 summarizes relevant frequencies of the system at parked conditions.

Table 1. Relevant frequencies of the floating wind turbine

Mode	Frequency (Hz)
Rated rotor speed	0.0987
Blade edgewise	0.434
Blade flapwise	0.339
Tower bending	0.419
Platform surge	0.0084
Platform pitch	0.0251

The first comparison between the adaptive super-twisting controller and the gain-scheduled PI controller considers uniform wind at $V = 13$ m/s and no wind or waves. Such a comparison investigates the stability of the controllers. Optimum parameters (dos Santos *et al.*, 2022b) were applied to the PI controller ($\zeta_\psi = 2.22$ and $\omega_{0,\psi} = 0.082$ Hz). The parameters of the ASTW controller were defined by trial and error as: $c_1 = 0.3$, $c_2 = 10^{-3}$, $\epsilon = 0.0045$, $\omega_1 = 0.006$, $k_1 = 2$, $\mu = 0.005$, $\chi = \alpha_m = 10^{-4}$. To ensure feasibility, the pitch rate of both controllers was limited to $2°$/s. The results are presented in Fig. 3.
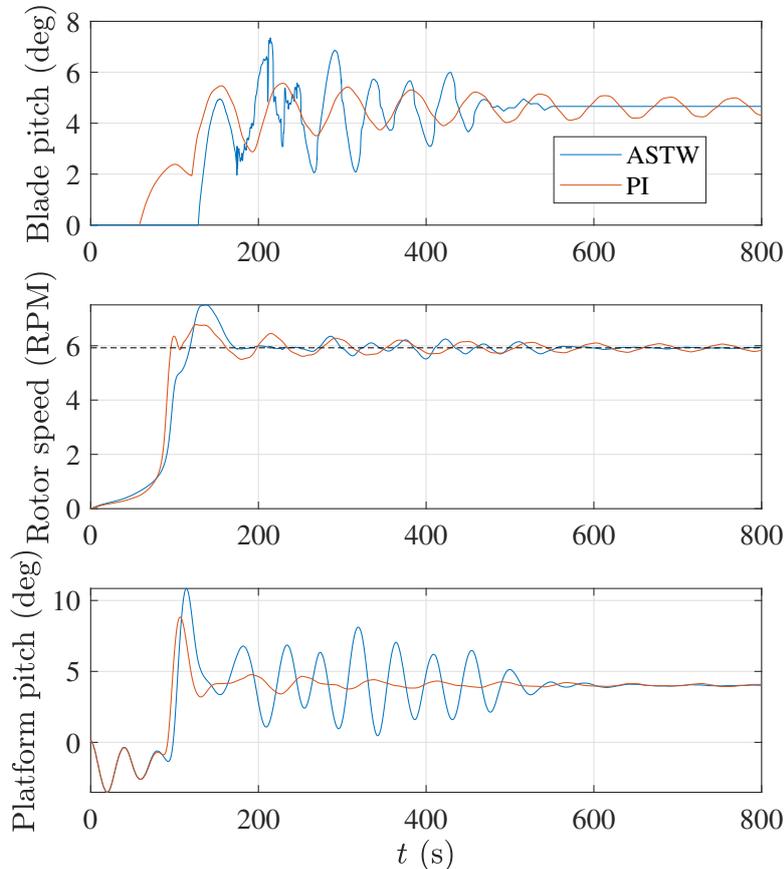

Figure 3. Comparison between the responses of the ASTW and PI controllers at $V = 13$ m/s.

The analysis of the system's behavior in Fig. 3 indicates that the 25 MW wind turbine needs less time to reach a steady-state with the ASTW controller than with the PI controller. However, both approaches deliver stable responses for the platform pitch and rotor speed considering an uniform wind at $V = 13$ m/s.

The operational regime of the floating wind turbines expects disturbances from the environment. In this sense, the 25 MW floating wind turbine was simulated considering cases with irregular waves and turbulent wind. Waves were generated from the Jownswap wave spectrum with significant height 15.6 m and peak period of 16 s. In addition, a turbulence intensity of 5% has been added to the wind with mean speed $V = 13$ m/s. The rotor speed, blade pitch and power output using both controllers are presented in Fig. 4.
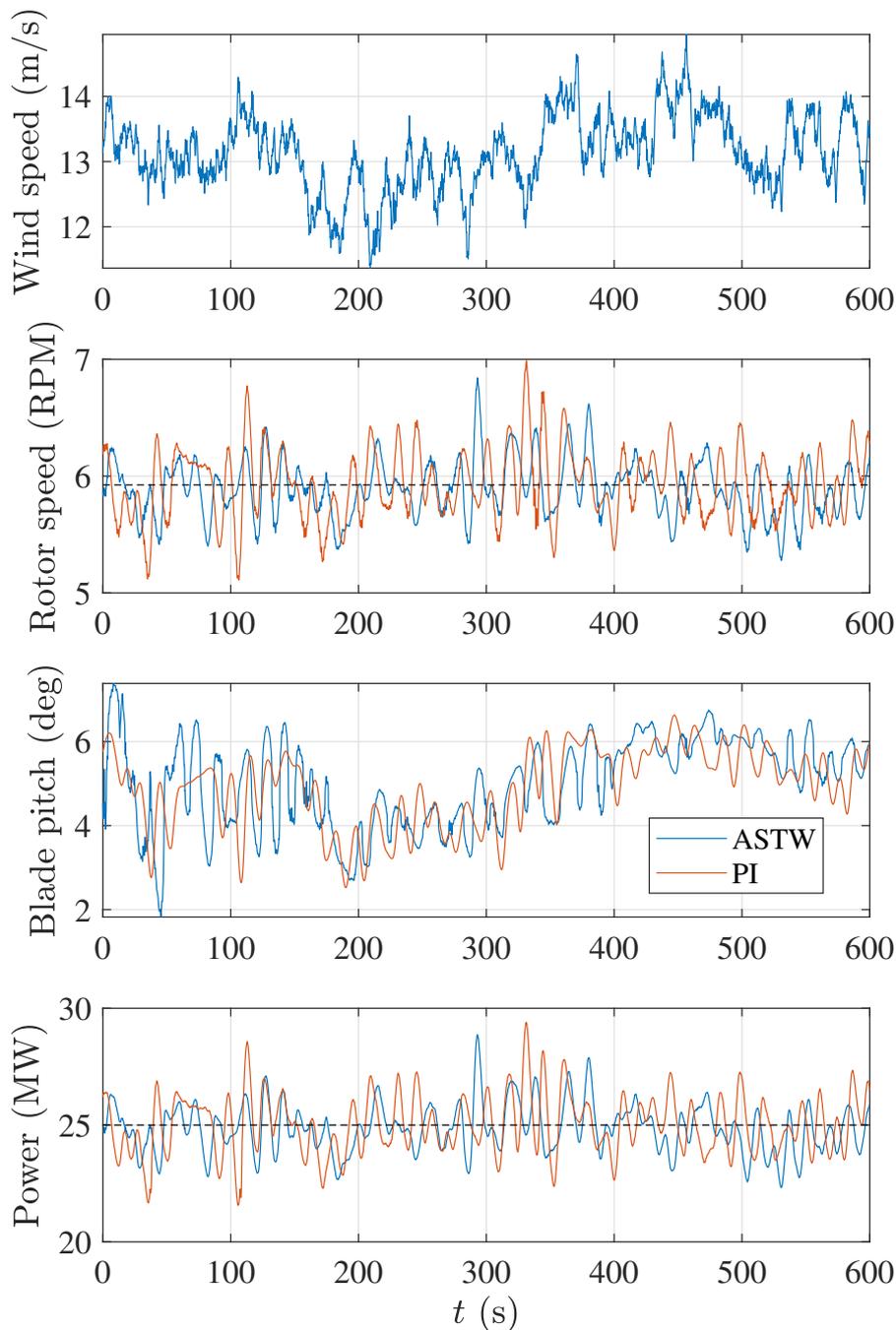

Figure 4. Comparison between ASTW and PI controllers considering turbulence intensity 5%.

The results depicted in Fig. 4 indicate a similar behavior for both controllers, despite of the fact that the ASTW controller performs more frequent blade pitch actuations. Indeed, the PI controller requires a small natural frequency ($\omega_{0,\psi} = 0.082$ Hz) to avoid negative damping effects, which tends to deliver slow responses to environmental disturbances.

Another comparative case investigated a more critical environmental condition, with the same waves, but considering

a turbulence intensity of 15%, which corresponds to a high turbulence level. The results, presented in Fig. 5, demonstrate a notable improvement in the tracking of output power when utilizing the ASTW controller instead of the gain-scheduled PI controller. This result leads to the conclusion that the ASTW controller overcomes the limitations of the PI controller by computing the gains according to the dynamics of the observer in Eq. (5).
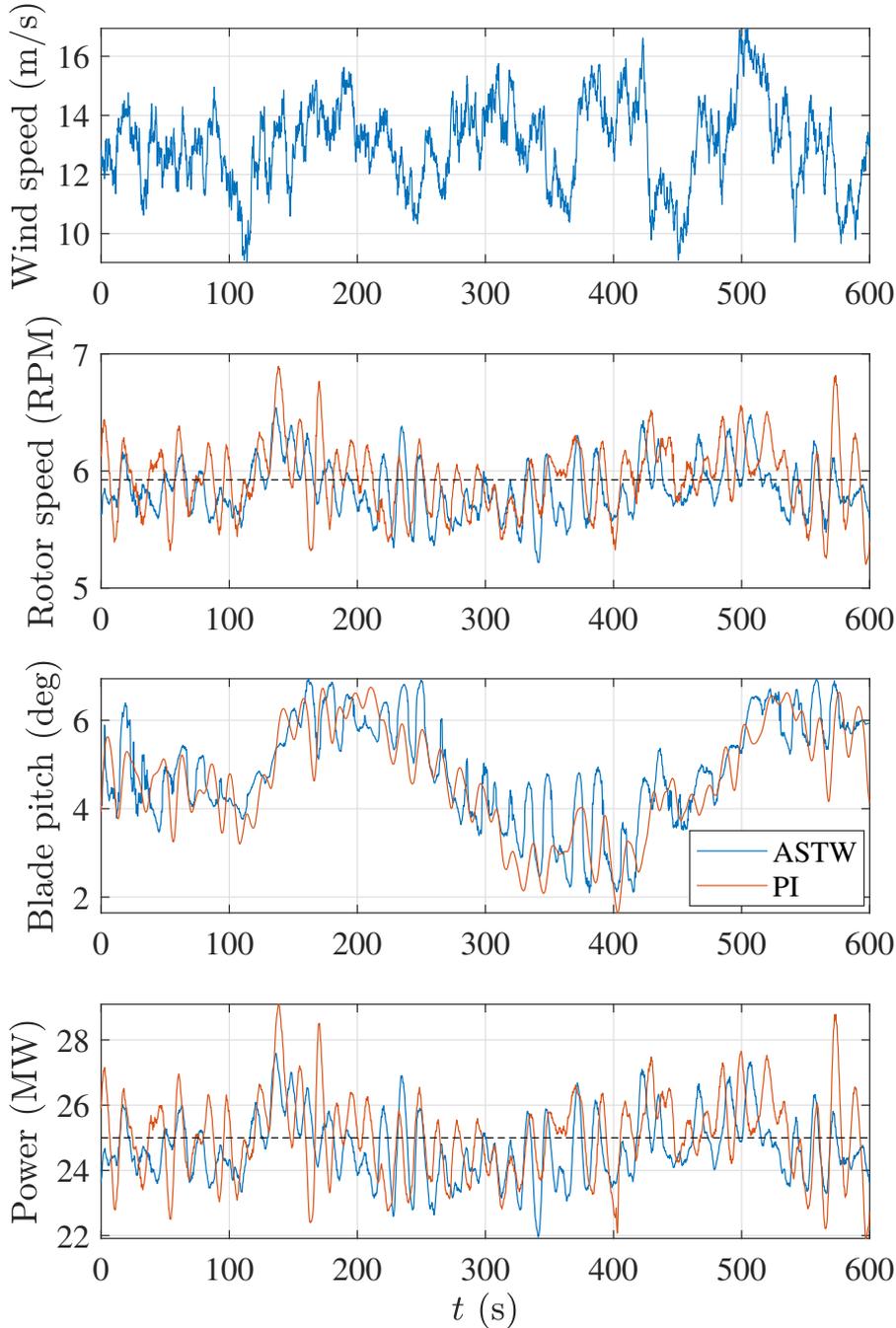

Figure 5. Comparison between ASTW and PI controllers considering turbulence intensity 15%.

Table 2 summarizes the root mean squared error between rated power and rotational speeds when applying the ASTW and PI controllers to the cases with turbulence intensities 5% and 15%. The ASTW controller performs a better track of rotational speed and power in both cases compared to the PI controller. Such a result leads to the conclusion that adaptive controllers represent a better alternative to PI controllers in the case of very large floating wind turbines. Besides, the performance of the ASTW controller can be enhanced if some optimization problem is employed to define the parameters required by the model, similar to the problem solved to define the gains of the PI controller (dos Santos *et al.*, 2022b). In addition, extensions of the ASTW methodology with fewer parameters, such as the simplified adaptive super-twisting (Gutierrez *et al.*, 2022) and a self-adaptive super twisting (Mirzaei *et al.*, 2022) can be tested in the future and compared with the ASTW controller.

Table 2. Root mean squared errors (RMSE) in power and rotational speed

Turbulence level	Controller	RMSE - Rotational speed	RMSE - Power
5%	ASTW	4.17%	4.20%
	PI	5.03%	5.07%
15%	ASTW	4.12%	4.14%
	PI	5.00%	5.05%

4. CONCLUSIONS

This study focused on implementing adaptive controllers in a 25 MW floating wind turbine. The rotor was scaled up from the IEA 15 MW, and a parametric optimization was conducted to design the platform with a central configuration. The system's small natural frequencies impose limitations on the maximum frequency achievable by the PI controller. In contrast, the adaptive super twisting controller exhibited no such limitation, enabling it to effectively track the rotor speed and output power of the system with higher actuation frequencies. In conclusion, this research highlights adaptive controllers as a viable alternative capable of overcoming the limitations of classical PI controllers when applied to large floating wind turbines.

5. ACKNOWLEDGEMENTS

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