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Marine Wind Turbine PID-PID Torque Control with Vibration Reduction

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Abstract: Marine turbines are an alternative for the production of clean energy in countries where the use of land turbines is limited. However, these systems, especially floating turbines, present a series of control challenges due to their non-linear dynamics and strong wind and wave loads. In this work, a dual control architecture is proposed consisting of two conventional Proportional-Integral-Derivate (PID) controllers that have been tuned with genetic algorithms. One of them is responsible for achieving maximum power in the operating region where torque control is applied, and the other tries to reduce the oscillations of the turbine that cause its efficiency to decrease and produce structural fatigue. Furthermore, the benefits of including the gain scheduling based on wind speed in this dual structure have been studied. This dual control structure has been shown in simulation to be useful for both objectives.

Keywords: Proportional-Integral-Derivate (PID), Maximum Power Point Tracking (MPPT), Genetic Algorithms (GA), Gain Scheduling, Floating Offshore Wind Turbine (FOWT).

1. INTRODUCTION

Wind energy has achieved great development as an alternative to other types of more polluting energy sources. This is due, on the one hand, to the fact that wind is an autochthonous and unlimited resource. On the other hand, wind technology has been developing for several decades, which has made it possible to achieve great efficiency in the production of clean energy (Zhou et al. 2023).

However, the very widespread onshore wind turbines (WT) present some disadvantages and limitations that have limited their deployment in some countries. An important factor is the higher volatile wind speed in land environments, which negatively impacts the energy production process and quality (Diógenes et al. 2020). Moreover, stronger and more stable wind speeds can be found in offshore spaces, making it possible to generate a bigger amount of energy with this technology. This has led to giving way to offshore turbines, first coastal, that is, bottom-fixed, and more recently floating offshore wind turbines (FOWT).

However, these floating systems present challenges for control due to their non-linear dynamics and the strong wind and wave loads to which they are subjected to (Sierra-García, and Santos 2021). These external conditions and motions that affect the platform and the structure of the wind turbine provoke the performance of the system to be worsen. This is evidenced in the difficulties in power regulation, both in the maximum power point tracking control and pitch regulation (Shah et al. 2021). This makes them complex to be controlled. Even more, the structural vibrations they present reduce their useful life and increase the need and cost of maintenance (López-Romero and Santos Peñas 2023).

To contribute to improving these two objectives, this work proposes a dual control architecture formed by two conventional PID controllers. One of them is responsible for achieving maximum power in the operating region where torque control is applied, and the other tries to reduce the oscillations of the turbine that cause its efficiency to decrease and produce structural fatigue. The controllers have been tuned with genetic algorithms with a cost function that reflects this double objective. Furthermore, this scheme has been compared with an implementation of the both controllers with gain scheduling (GS), depending on wind speed, and also it has been evaluated against the baseline controller proposed in the reference WT simulation software OpenFAST (NREL 2023). The control strategy based on the two PID regulators has shown to be efficient in simulation for both objectives, contributing to the study of the MPPT control.

This work continues the line found in the literature on MPPT control based on conventional techniques, such as the following. In (Bekiroglu and Yazar 2022) the authors propose the application of a PID controller in the rotor-side converter, in order to control the power produced by the wind turbine using the reference torque generation. In (Zhang et al. 2023) different classic MPPT control strategies are analyzed. The study covers the tip speed ratio (TSR) algorithm, hill climbing search (HCS) control, optimal torque (OT) control, and power signal feedback (PSF) control, where the OT has shown to be a highly efficient and simple MPPT method. More information on these classic controllers is given in (Raouf et al. 2023). Also, advanced techniques are considered in wind power control, as presented in (Nouriani and Moradi 2022), where the authors describe the application of sliding mode control and a backstepping controller based on a Laupunov function. This article also includes hybrid controllers such as a PI-Neural Network and a H_∞ and feedback linearization controller, showing the advantages of the hybridization of classic and intelligent control. In (Jiang et al. 2023) a model predictive controller is proposed based on the TSR principle for WT MPPT, using a control variable and a feedback linearization to overcome the nonlinearity and time-varying states of the system. Fuzzy logic controllers (FLCs) are also applied for wind turbine control. In (Noureddine et al. 2022) the authors suggest a combined Fuzzy PI controller and a Fuzzy Fractional Order PI controller for capturing maximum energy from the wind. Other intelligent approaches can also be found (Muñoz et al. 2024; Serrano et al. 2022; Sierra-García and Santos 2021; Umar et al. 2023).

The rest of the paper is structured as follows. Section 2 summarizes some fundamental concepts of wind turbines. In Section 3 the proposed control architecture based on PIDs is described. Section 4 discusses the results obtained. The paper ends with the conclusions and future works.

2. WIND ENERGY GENERATION

Wind turbines produce wind energy by taking advantage of the wind that affects the blades. They transform the mechanical energy produced by the rotation of the blades into electrical energy. However, not all the wind can be used. On the one hand, there is the Betz limit, which says that a maximum of 59% efficiency can be achieved. On the other hand, depending on the speed of the wind, more or less energy is generated.

The output power produced by the wind turbine can be expressed as in (1).

$$P = C_p(\lambda,\beta)\frac{\rho\pi R^2 {V_w}^3}{2} \quad (1)$$

where ρ (Kg/m^3) is the air density; V_w (m/s) is the velocity of the wind and R (m) is radius of the rotor, that is, the length of the blades. The power coefficient, C_p, is specific for each turbine and it depends on the tip speed ratio, TSR (λ), and the angle of the blades or pitch angle, β.

The TSR is mathematically obtained as the ratio between the tip blade speed and the input wind speed, as in (2), where ω_t (rad/s) is the rotor speed.

$$\lambda = \frac{\omega_t\, R}{V_w} \quad (2)$$

Depending on the wind speed, there are different operation regions (Fig. 1).

The control system is crucial in wind turbines and its objective is to achieve maximum power in the different operating zones of the turbine, for any wind speed. In this work, a control strategy is proposed for region 2 or Maximum Power Point Tracking (MPPT), which is between the minimum wind speed for the turbine to start operating (cut-in-speed) and its rated value. From this nominal wind speed, which is specific for each turbine, the angle of the blades is regulated to reduce the loads on the device and maintain energy production at its maximum value.

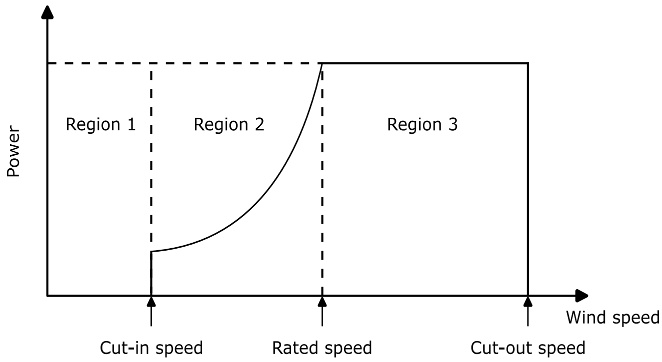

Figure 1. Wind turbine operating regions.

The MPPT control aims at tracking the power curve of the turbine, (C_p, λ, β), controlling the rotational speed. This control involves the mechanical and electrical components of the WT. The mechanical model can be represented by (3) (Ospina and Santos 2023). This dynamic equation relates the transmission of torque from the generator and the rotation movement.

$$T_t = \frac{\dot{\omega}_g\left(J_t + gb^2 J_g\right)}{gb} + gb \cdot T_{em} \quad (3)$$

where T_t and T_{em} are the rotor torque and electromagnetic torque, respectively $(N \cdot m)$; J_t and J_g, are the rotor and generator inertias, respectively $(Kg\ m^2)$; gb is the gearbox ratio, and $\dot{\omega}_g$ is the generator acceleration (rad/s^2).

The optimum electromagnetic torque can be obtained varying the generator and rotor speeds to maximize power extraction. Direct speed control (DSC) (Muñoz-Palomeque et al. 2023) is used to obtain the optimal speed reference, ${\omega_g}^*$ (4), for maximum efficiency in the MPPT region.

$${\omega_g}^* = \sqrt{\frac{T_t}{K}} \cdot gb \quad (4)$$

where T_t is the rotor torque estimated from the mechanical model by (3), and the constant K is the optimal parameter that summarizes the aerodynamics of the wind turbine model. This constant is calculated as follows:

$$K = \frac{\rho\pi R^5}{2} \cdot \frac{{C_p}^*}{\lambda^{*3}} \quad (5)$$

In this expression, ${C_p}^*$ and λ^* are the optimal power coefficient and optimal TSR, respectively. In this way, the reference speed is calculated in terms of the actual mechanical coupling and aerodynamics for tracking the best WT power curve.

3. PID-PID CONTROL ARCHITECTURE

In this study, a control strategy is proposed that combines two complementary PID controllers in the MPPT region of a floating wind turbine. The first PID is applied for MPPT operation, establishing the relationship between speed and electromagnetic torque, while the second PID acts on structural vibrations, adjusting the electromagnetic torque based on the value of the acceleration measured at the top of the tower. In Fig. 2, this control architecture is presented and the two PIDs can be identified.

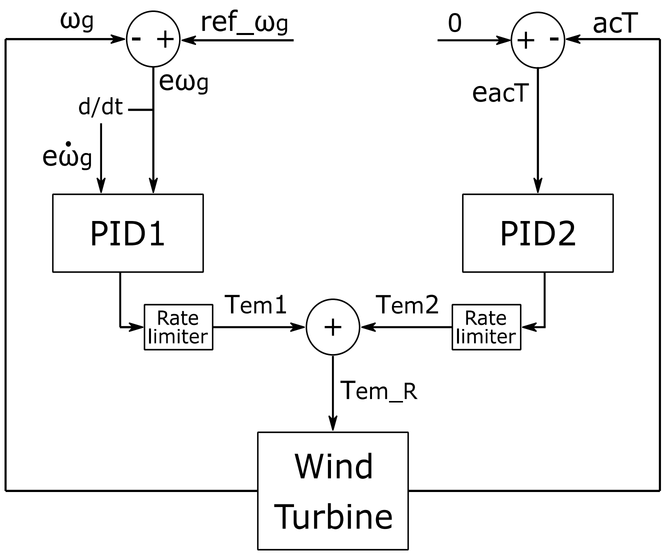

Figure 2. MPPT dual PID control

Two control strategies have been considered, which have been compared with each other and with the OpenFAST baseline control. The latest is a speed-torque curve-based controller, defined in terms of the known rated torque and speed information of the turbine.

1. MPPT PID + structural PID controllers to the wind speed range of WT region 2.

2. Gain scheduling MPPT PI + gain scheduled structural PI controllers applied to the wind speed range of region 2 of the WT. The wind range is divided into three sub-ranges with a specific PI configuration applied in each section.

The PID parameters are obtained using genetic algorithms (GA). This technique is selected because of its great capacity in solving optimization problems. The GAs are implemented in two stages. First the PID of the MPPT control is tuned meanwhile the structural controller is inactive, and then the PID parameters for vibration reduction are tuned also with GA meanwhile the MPPT controller is active with the gains previously tuned.

For the MPPT controller, the fitness function used is the generator speed mean absolute error (MAE), calculated as:

$$MAE_{e\omega_g} = \frac{\frac{1}{n}\sum_{i=1}^{n}\left|e\omega_g\right|}{max\left(\left|e\omega_g\right|\right)} \tag{6}$$

For the vibration reduction controller, the fitness function uses the error signal of the tower top acceleration:

$$MAE_{eac_T} = \frac{\frac{1}{m}\sum_{i=1}^{m}\left|eac_T\right|}{max\left(\left|eac_T\right|\right)} \tag{7}$$

where n is the number of samples of the angular speed, and $|e\omega_g|$ is the absolute value of the rotation speed error; m is the number of samples of the tower top acceleration, and $|eac_T|$ is the absolute value of the tower top acceleration.

During the GA application, the parameters of the PIDs are restricted to values higher than zero. The algorithm uses a random initialization of the population, which is run offline for searching a controller configuration that solves the MPPT and vibration problems. The GAs are applied for 8 hours until the convergence at a local minimum is achieved.

3.1 MPPT PID control + Structural PID control

The parameters that are tuned with GA are the gains of the two PIDs, that is, Kp1, Ki1, Kd1 and Kp2, Ki2, Kd2. The values obtained are:

PID1 (MPPT control): Kp = 1.50; Ki = 1.43; Kd = 0.58

PID2 (vibrations control): Kp = 1.20; Ki = 0.28; Kd = 1.46

3.2 Gain scheduling MPPT PID control + Gain scheduling Structural PID control

In this case, a gain scheduling scheme is proposed depending on the wind range. It has been divided into three sections, and in each of them the GS-PID is tuned, which is a PI since Kd=0.

The ranges of each section are between a minimum wind speed, $Vmin_i$, and the maximum speed of that section, $Vmax_i$, where i is the section, i = 1, 2, 3. Thus, $Vmax_1$=$Vmin_2$ and $Vmax_2$=$Vmin_3$ (see Fig. 3). For the WT we are working on, the minimum wind speed is $Vmin_1$ = 8.5 m/s and the maximum value is $Vmax_3$ = 11.5 m/s.

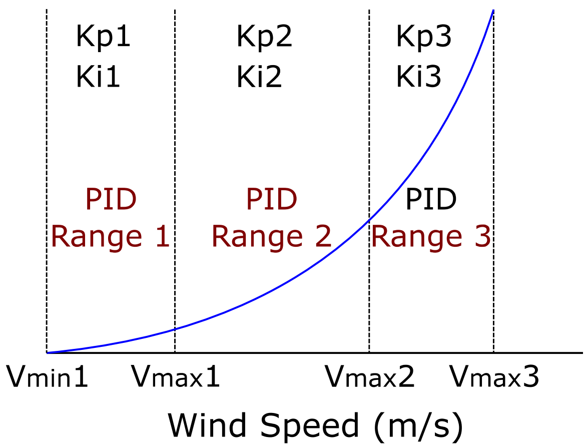

Figure 3. Gain scheduling scheme based on wind speed

In this case the parameters that are adjusted with GAs are Kp1, Kp2, Kp3, Ki1, Ki2, Ki3, Vmax1, Vmax2. The values are shown in Table 1.

Rate limiters after the control signals are included. These components allow the control output not to change abruptly in the face of big changes in the signal due to the switching between gain scheduling controllers, until the signal reaches the steady state.

Table 1. Gain scheduling PID

	Range 1		Range 2		Range 3	
	PID 1	PID 2	PID 1	PID 2	PID 1	PID 2
Kp	0.0001	2.6558	1.6107	2.0037	0.9219	2.4740
Ki	2.8982	1.7680	1.3828	3.0970	1.6288	0.3384
Vmin	8.5000	8.5000	8.7508	8.6142	9.4019	9.2502
Vmax	8.7508	8.6142	9.4019	9.2502	11.5000	11.5000

4. RESULTS AND DISCUSSION

We have worked with a 5MW floating wind turbine with a nominal generator rotation speed of 1200 rpm. The Cp is 0.48 and the TSR is 7.6. In the experiments, the simulation time is 300 seconds. The wind signal is random in the range between 8.5 and 11.5 m/s (Fig. 4), top. Waves with amplitudes ranging up to a maximum of 3.8 m have been included (Fig. 4), bottom.

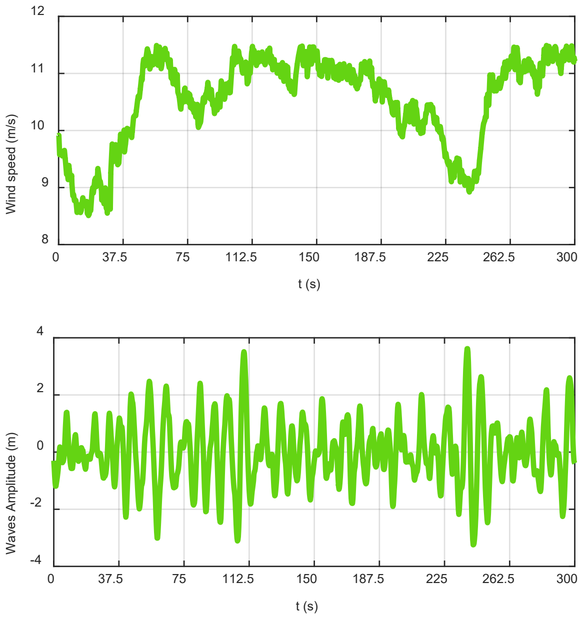

Figure 4. Wind speed input (top) and amplitude of waves (bottom).

Fig 5 shows the reference signal of the electromagnetic torque obtained as the outcome of the PID-PID controller application. Besides, Fig. 6, top, shows the output power of the wind turbine with the PID-PID configuration vs. the results obtained with the reference software OpenFast. Fig. 6, bottom, represents the Tower Top Displacement (TTD) that measures the vibration with this configuration. It is noticeable how the PID-PID controller reduces the TTD and thus the vibration, and the power is much more stable.

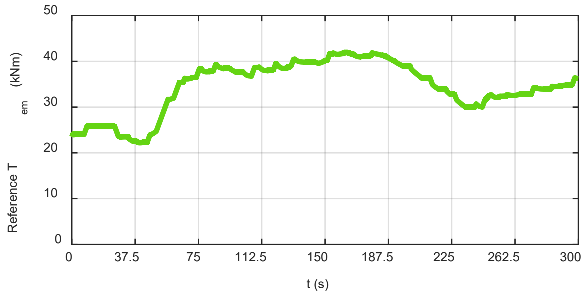

Figure 5. Reference electromagnetic torque obtained with the PID-PID control application

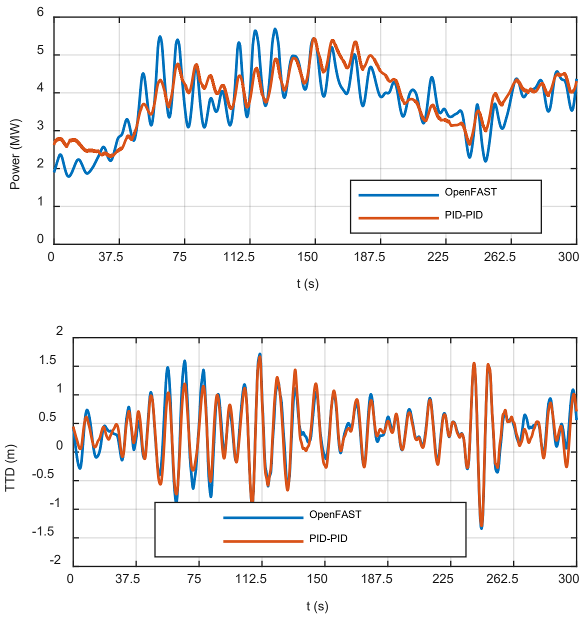

Figure 6. Output power (top) and TTD (vibrations) (bottom), with the PID-PID control configuration

Similarly, Fig. 7 illustrates the electromagnetic torque generated by the Gain Scheduling (GS) PID-PID controller designed to regulate the speed and to track the maximum power point. As a result, Fig. 8, top, shows the output power of the wind turbine with the Gain Scheduling PID-PID configuration vs. the results obtained with the reference software OpenFast. Fig. 8, bottom, represents the Tower Top Displacement (TTD) or vibrations. In this case, it is possible to observe that it even provides higher power, especially in the last part of the simulation.

The comparison results are shown in Table 2. The vibration suppression rate has been calculated as:

$$SR = \frac{\sigma_{FAST} - \sigma_{PID}}{\sigma_{FAST}} \cdot 100\% \qquad (8)$$

where σ_{FAST} is the standard deviation of the tower top displacement (TTD) obtained with the MPPT controller that OpenFast has embedded and σ_{PID} is the TTD standard deviation obtained with the corresponding PID-PID control architecture.

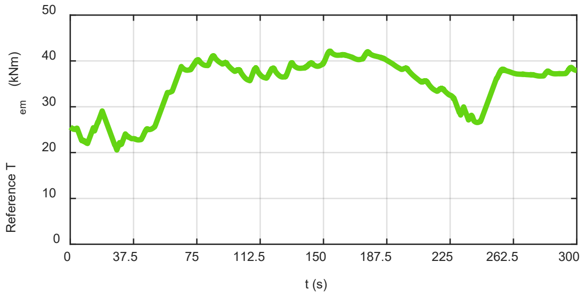

Figure 7. Reference electromagnetic torque obtained with the Gain Scheduling PID-PID control application

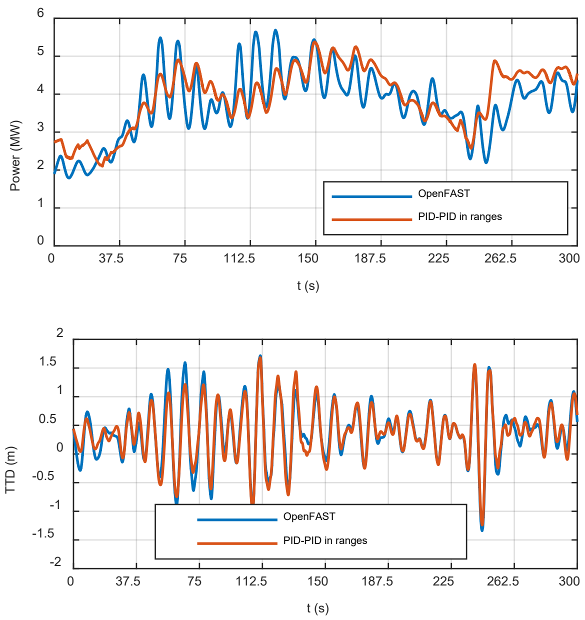

Figure 8. Output power (top) and TTD (vibrations) (bottom), with the Gain Scheduling PID-PID control

Table 2. Comparison results of the control configurations

Parameter	PID-PID	Gain Scheduling PID-PID	Open FAST
Power [MW]	3.886	**3.942**	3.757
Average Deflection [m]	**0.358**	0.368	0.373
% over FAST (avrge. Defl.)	**-3.968**	-1.228	---
Average MSE TTD	**0.342**	0.349	0.378
% over FAST (average MSE)	**-9.561**	-7.835	---
MSE Accel. Tower Top	2.189	**2.177**	2.509
% over FAST (MSE Accel. Tower Top)	-12.713	**-13.234**	---
% Vibration Suppression Rate	5.448	**5.643**	---

The two objectives pursued with turbine control are power generation and vibration reduction. Regarding the first, the two configurations with PID increase the power production compared to the OpenFAST control, with the program gain scheme being the one that generates the most energy. The difference is small because in all cases the controllers are efficient.

Regarding the reduction of the amplitude of the tower displacements (TTD), the best control strategy is that of the two PIDs, although the gain scheduling strategy also manages to reduce vibrations with respect to that of OpenFAST. This suggests that the variable wind speed is not the one that most influences the vibrations, since it is the one that has been considered for the gain scheduling.

However, the GS-PID control is the one that achieves a greater reduction in the acceleration of the tower movement, which can be attributed to the fact that it slows down the frequency of the oscillation, which is a very positive result since it is a factor which significantly influences the fatigue of the structure.

5. CONCLUSIONS AND FUTURE WORK

In this work, two control structures based on PID controllers are proposed for a floating wind turbine, achieving satisfactory results regarding a twofold objective: to maximize energy generation in region 2 of operation of the wind turbine and to reduce vibrations.

The wind turbine has been simulated and subjected to wind and waves, and both control strategies improve the results obtained with the controller embedded in the OpenFAST reference software. More energy is finally produced by using the PID-based controllers, while the structural deflection and oscillations are reduced.

Applying the scheduling PID control strategy shows to be a viable alternative for wind turbine control operation, acting efficiently on a complex system with harsh environmental conditions with favorable results.

In future works, another variable for gain scheduling could be explored, such as the frequency of wave, or turbine oscillation frequency. Also, the scheduling control strategy can be further studied to improve the adaptation to the dynamics generated by meteorology conditions in offshore wind systems.

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