

Article

Wind Turbine Synchronous Reset Pitch Control

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Abstract: Reset controllers are commonly used to smooth the transient response of systems. We use this technique to improve a standard baseline pitch controller for offshore wind turbines (WTs). The introduction of this strategy enhances the overall performance of the WT. In particular, the fore-aft and side-to-side accelerations of the WT tower are significantly reduced, whilst a steadier power output is obtained, in comparison to the standard baseline pitch controller. Furthermore, our designed pitch control's main advantage, with respect to the baseline, is its ease of implementation and reduced complexity as it does not require a gain-scheduling technique, nor pitch position measurement (thus, it is insensitive to pitch sensor faults). The proposed approach has been simulated on the NREL 5-MW prototype offshore turbine model, mounted on a jacket support. The simulations are carried out using the aero-hydro-servo-elastic simulator FAST, and key observations are thoroughly discussed.

Keywords: wind turbine; FAST; reset control; pitch control

1. Introduction

In the efforts towards decarbonization in the power generation industry, wind energy is playing one of the most important roles, as shown in Figure 1. It will be especially offshore wind energy that will account for the highest contributions due to its large-sized WTs, greater and steadier wind velocities that raise the capability of producing energy at a country-scale level and the fact that new suitable available onshore sites for deployments are becoming scarce particularly in Europe [1]. In order to increase the penetration of offshore wind energy into the energy market, its constant and effective development is required to achieve costs reduction.

The blade pitch control is, among the different WT control strategies, the one that could contribute a greater reduction of the levelized cost of energy [2]. Thus, by controlling the power harnessed at each moment, the blade pitch control enhances the operational flexibility of the WT, as well as providing stability, a greater robustness and a more efficient integration in the power grid. All modern high-power wind turbines (5 MW and above) use adjustable rotor speed operation, as their key advantages are well known, e.g., [3]. The pitch control design contributes also to maintain the wind tower vibrations within acceptable limits. On this matter, in the work by Jonkman et al. [4], a controller for a 5-MW offshore wind turbine is proposed. This has become a commonly-used controller in the industry, and it is nowadays used in research for comparison to new control developments (e.g., [5–8]). Thus, it is used in this work and denoted here as the baseline controller.

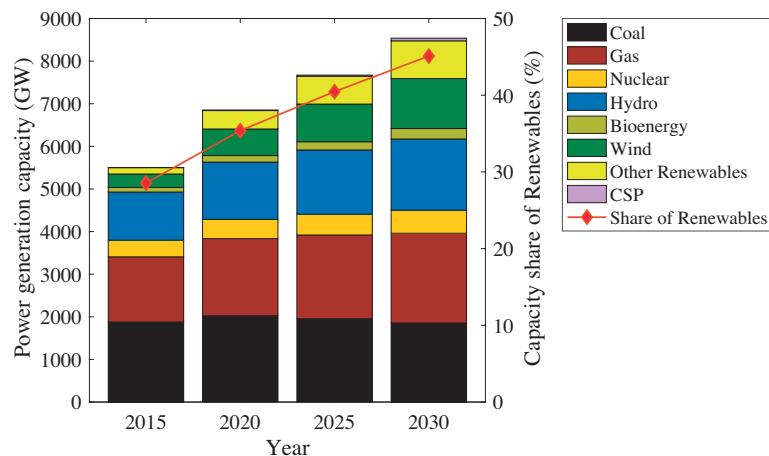


Figure 1. European Union net capacity additions by type and share of electricity from variable renewables in the INDC (intended nationally-determined contributions) scenario. Source: International Energy Agency 2015 [2].

This work provides an improved methodology regarding the pitch control strategy currently proposed for large-scale wind turbines (WTs). In particular, a modification of the baseline controller is presented based on synchronous reset control. This novel modification simplifies the controller complexity leading to a better performance. Regarding the complexity, it does not require a gain-scheduling technique, nor pitch position measurement (thus, it is insensitive to pitch sensor faults). On the other hand, related to its performance and according to the numerical simulations, the fore-aft and side-to-side accelerations of the WT tower are considerably attenuated. This is an important achievement from the structural point of view (e.g., [9]). In addition, the quality of the electrical power generation is also improved.

The remainder of this paper is structured as follows. Section 2 includes a succinct introduction to reset controllers highlighting their main properties. The state of the art of the different WT control strategies is given in Section 3. In Section 4, the wind turbine benchmark is recalled, as well as the baseline pitch and torque controllers. Section 5 presents the design of the synchronous reset pitch controller (SRP). The simulation results obtained with the proposed pitch controller applied to the 5-MW wind turbine benchmark are given in Section 6. Concluding remarks are given in Section 7.

2. Reset Controllers

Reset controllers appeared for the first time in 1958, when J. C. Clegg proposed a reset controller that had the aim of improving the transient response of closed-loop systems [10]. This improvement was advantageous for integral-type controllers due to its ability to reduce the overshooting or phase lagging, increasing the flexibility of the system. Generally speaking, Clegg's main idea was that, whenever the user-defined reset condition, $c(t)$, is met, the reset action is applied to the integral part of the controller, $u(t)$, that is set to a new user-defined reset initial condition, $a(t)$. Due to this resetting condition, the transient response of controlled systems can be manipulated (such as the settling time, the rise time or the overshoot). The equations of this basic reset integrator are [11]:

$$\begin{aligned} \dot{u}(t) &= e(t) \quad \text{when } c(t) \neq 0, \\ u(t^+) &= a(t) \quad \text{when } c(t) = 0, \\ u(0) &= u_0, \end{aligned} \tag{1}$$

where $e(t)$ is the controller input. Figure 2 shows its block diagram representation.

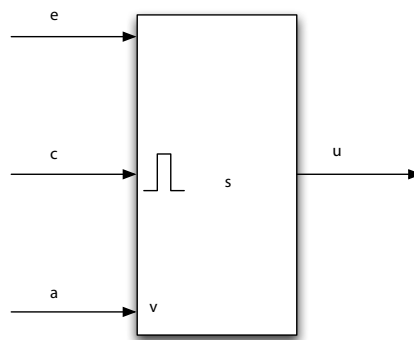


Figure 2. Block diagram of a basic reset integrator [11].

For a review on reset control systems, see [11–15]. In the synchronous case, $c(t)$ may be a time periodic signal to activate the resets at periodic fixed time steps. This approach will be used in this work as it is appropriate for our control aims.

3. State of the Art of WT Pitch Controllers

Wind turbines are complex systems with large flexible structures that work under very turbulent and unpredictable environmental conditions; thus the need for advanced (multivariable and multiobjective) control systems concerned with optimization and quality improvement of the generated power, speed/power regulation and/or the reduction of structural load in wind turbines. This section discusses various advanced control methods that are used in large WT in the full load region. The power production capability of a wind turbine is often presented in relation to wind speed, as shown in Figure 3. From the figure, we see four regions of operation. Region I is the start up stage. As the wind accelerates beyond the cut-in speed, we enter Region II. A common control strategy in this region is to keep the pitch angle constant while controlling the generator torque. At the point where the wind speed is higher than the rated wind speed of the turbine (rated speed), we enter Region III. In this region, the torque is normally kept constant, and the controlling parameter is the pitching angle, thus the importance of the pitch control. This is the region we are concerned with in this paper, i.e., the so-called full load region. The last region is the shutting-down phase (cut-out).

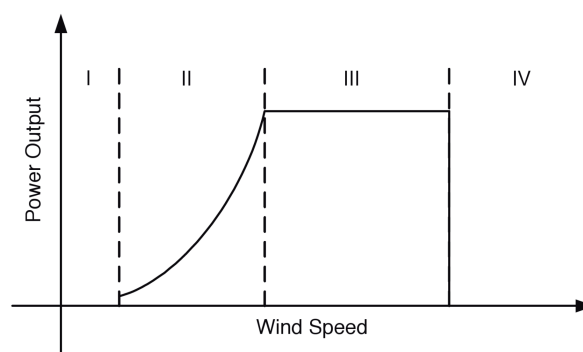


Figure 3. Regions of operation.

In Table 1, different control methods developed for the high wind speed region are given. Most of these methods are based on linear control theory, meaning that they are only effective around a given operation point. Therefore, measures must be taken to compensate for uncertainties resulting from the change of operation point due to the variation of incoming wind speed. Although the PI gain scheduling controller is simple to design and more robust, it has limitations in handling multi-objective problems since it is a single-input single-output controller. Linear quadratic Gaussian

(LQG) methods can offer an optimal solution by trading-off opposing requirements by minimizing a given cost function. In most cases, full system state information is required to design this class of controllers, but not all states are available for measurements; thus the need to design observers to reconstruct unknown states. In the literature, LQG has been applied to regulate the generator speed and reduce the structural loads, where it is assumed that the wind turbine is influenced by disturbances and noise that have some assumed stochastic properties. Due to these requirements, LQG controllers are restricted in terms of applications. Another problem associated with the LQG controller is poor gain margins, which are improved using loop transfer recovery. Fuzzy logic control (FLC) for individual pitch control has been proven to optimize a trade-off among several control objectives, such as to mitigate fatigue loads and regulate output power. The use of classical sliding mode control (SMC) for WT control deals efficiently with the power regulation objective and provides the advantage of robustness against system uncertainties and perturbations, such as measurement noise. Although classical SMC has shown good performance in an uncountable number of applications, its well-known drawback has been the discontinuous behavior of the computed control inputs that may derive it into a high-frequency oscillation known as chattering (see [16]). Among the great variety of chattering suppression methods, so-called high-order sliding mode control has been intensively studied within the last decade. As noted, individual pitch control leads to increased pitch duty cycle, which may in turn cause the early failure of pitching mechanism. To tackle this problem, model predictive control (MPC) has been considered in many studies, since it can explicitly take into account constraints during the design stage to avoid the violation of pitching actuator limits. To further improve the performance of MPC, LIDAR (light imaging, detection and ranging) measurements can also be used to improve its reaction time.

Table 1. Comparison of control methods in the full-load region of operation [17].

Control Strategy	References	Gain	Description
PI-controller (gain scheduling)	[4,18]	Variable	Single input single output (SISO) controller simple to design and robust.
Linear quadratic Gaussian (LQG)	[19,20]	Fixed	Need to design observers to reconstruct unknown states.
Fuzzy logic control (FLC)	[21,22]	Fixed	Uncertainty modeling and treatment of qualitative magnitudes not properly described by binary concepts.
Sliding mode control (SMC)	[9,23]	Fixed	Robustness against system uncertainties and perturbations.
Model predictive control (MPC)	[7,24,25]	Variable	Input and output constraints handling, as well as on-line optimization.

Finally, for a comprehensive state of the art of WT controllers, please see references [26–28].

4. Reference Offshore Wind Turbine

In this work, the National Renewable Energy Lab (NREL) offshore 5-MW baseline wind turbine given in [4] is used. As a system that represents the current state of the art in an offshore WT, this baseline turbine concept has been extensively employed in studies by the wind energy research community and has supported numerous research topics including, for instance, aerodynamics, offshore dynamics or design control code development, e.g., [8,28]. Its main data are summarized in Table 2. In this work, as a research object, the jacket support platform is selected as the turbine support structure [29].

In this work, sensors are modeled in Simulink by adding signals from band-limited white noise blocks, which are parameterized by noise power, to the actual variables provided by FAST; see [17]. These random noise blocks represent measurement noise either due to the measuring principle or due to electrical noise in the system. Table 3 shows the simulated sensors and its noise power.

Table 2. Main data of the offshore NREL 5-MW wind turbine [4].

Property	Value	Unit
Nominal Power ($P_{e,n}$)	5	MW
Blade number	3	-
Blade pitch angle range (β_r)	[0, 90]	deg
Maximum blade pitch angle rate ($\dot{\beta}_r$)	8	deg/s
Rotor diameter	126	m
Hub height	90	m
Cut-in wind speed	3	m/s
Rated wind speed	11.4	m/s
Cut-out wind speed	25	m/s
Nominal generator speed ($\omega_{g,n}$)	1173.7	rpm
Nominal torque (τ_r)	40,681.5	Nm
Generator torque range (τ_r)	[0, 47,402.91]	Nm
Maximum generator torque rate ($\dot{\tau}_r$)	15,000	Nm
Gearbox ratio	97	-
Generator efficiency (η_g)	98	%

Table 3. Simulated sensors and their associated noise power [17].

Sensor type	Noise Power	Unit
Generator speed	2×10^{-4}	m/s
Pitch angle of i -th blade	1.5×10^{-3}	deg

In [4], standard baseline pitch and torque controllers are given for the 5-MW reference WT. These controllers are frequently used in the industry, and they are used in research, in conjunction with the FAST (Fatigue, Aerodynamics, Structure and Turbulence) software, for the comparison to new control developments. See Section 7 of [4] for a high level detailed explanation about the development of the wind turbine's baseline control system. In the following sections, these controllers are briefly recalled in the full-load region of operation along with the blade-pitch actuator model and the generator-converter model.

As is typical in utility-scale megawatt wind turbines, both the generator-torque and blade-pitch controllers use the generator speed measurement as a feedback input. To mitigate high-frequency excitation of the control systems, the generator speed measurement is filtered, for both the torque and pitch controllers, using a recursive, single-pole low-pass filter with exponential smoothing [4].

4.1. Baseline Pitch Controller

In the above-rated wind speed region, the baseline pitch controller is a collective gain-scheduling PI-controller on the error between the filtered generator speed and the rated generator speed. That is,

$$\beta_c(t) = K_p(\theta)(\hat{\omega}_g(t) - \omega_{g,n}) + K_i(\theta) \int_0^t (\hat{\omega}_g(\tau) - \omega_{g,n}) d\tau, \quad (2)$$

where $\hat{\omega}_g$ is the filtered generator speed, $K_p(\theta)$ and $K_i(\theta)$ are the proportional and integral gains and β_r is the pitch servo set point. The gain-scheduled parameters depend on θ , which is the rotor-collective blade-pitch angle from the previous controller time step. The blade-pitch rate limit is set to $8^\circ/\text{s}$ in absolute value, and the minimum and maximum blade-pitch settings are 0° and 90° , respectively [4].

4.2. Baseline Torque Control

In the full load region, the generator-torque controller's objective is to held constant the generated power. Thus, the generator torque, τ_c , is inversely proportional to the filtered generator speed, $\hat{\omega}_g(t)$ (see [4]),

$$\tau_c(t) = \frac{P_{e,n}}{\hat{\omega}_g(t)}, \quad (3)$$

where $P_{e,n}$ is the nominal generator power.

The torque control is saturated to a maximum of 10% above rated, or 47,402.91 Nm. A torque rate limit of 15,000 Nm/s is also imposed [4]; see Table 2.

4.3. Blade-Pitch Actuator

The FAST model does not include any blade-pitch actuator dynamic effects. Here, a second order pitch actuator model is used [17],

$$\ddot{\beta}_r(t) + 2\zeta\omega_n\dot{\beta}_r(t) + \omega_n^2\beta_r(t) = \omega_n^2\beta_c, \quad (4)$$

where ζ is the damping factor and ω_n is the natural frequency. In this work, the values $\zeta = 0.6$ and $\omega_n = 11.11$ rad/s are used [17].

In order to provide a more realistic actuator model, the non-linear backlash phenomenon is included. According to the hydraulic pitch actuator general specifications stated in [30], a realistic dead band value for our backlash model is 0.5° .

4.4. Generator-Converter Model

The generator power converter can be modeled as [17],

$$\dot{\tau}_r(t) + \alpha_{gc}\tau_r(t) = \alpha_{gc}\tau_c(t), \quad (5)$$

where τ_c is the reference torque given by the controller and τ_r is the real torque. In addition, α_{gc} is a dimensionless constant value given by the generator turbine characteristics. In this work, following [17], we set $\alpha_{gc} = 50$.

Finally, the power produced by the generator can be captured by using [17],

$$P_e(t) = \eta_g\omega_g(t)\tau_r(t), \quad (6)$$

where ω_g is the generator speed and η_g is the generator efficiency (see Table 2).

5. Synchronous Reset Pitch Controller

In this section, the proposed pitch controller is explained. It is a redesign of the baseline controller.

Firstly, as already said, a reset integrator is introduced in the integral part. The steps to design this synchronous integral reset are as follows.

1. *Controller input:* The error in the regulation of the generator speed is used as the controller input, that is $e(t) = \hat{\omega}_g(t) - \omega_{g,n}$.
2. *Reset condition:* A time periodic signal to activate the resets at periodic fixed time steps is used. In particular, $c(t) = \sin(2\pi ft)$. The frequency is taken as $f = 30$ Hz after developing a simple trial-and-error analysis comprising values between 1 Hz and 40 Hz.
3. *Reset initial condition:* The mean value of the pitch control baseline simulations, when operating in the overload region, is about 15° . Therefore, the reset initial condition, $a(t)$, is set to this value. Intuitively speaking, with this action, the integral part of the reset-controller will approximately follow this average.

Secondly, the proportional and integral gains are fixed. That is, there is no need for a gain-scheduling; therefore, we set $K_i = 0.002420590$ and $K_p = 0.005648043$. These values correspond to the gain scheduling parameters of the baseline controller when $\theta = 15^\circ$.

The proposed controller will be denoted as the synchronous reset pitch (SRP) controller throughout this work.

5.1. Brief Comments on Stability

The baseline pitch controller is in fact an auto-tuning PID controller and developed with barely a stability proof [4]. However, some insight on stability issues can be inferred for our proposed reset control by taking into account the main assumptions done for the torque baseline controller. As previously said, the used torque controller has the objective of regulating the generator power to its nominal value by applying a bounded control torque, thus implying that rotor speed is also bounded. Then, the generator speed error is bounded, and therefore, the proportional part of the reset pitch control is also bounded. Finally, as we are using integral synchronous resetting, its integral part is also bounded. Then, it follows that the proposed reset pitch controller supplies a bounded signal. Hence, and from Equation (4), BIBO stability can be concluded for the pitch dynamics.

Finally, note that a formal analysis is beyond the scope of this paper; however, it will be covered in our future work.

6. Simulation Results

This section presents the performance evaluation of the proposed pitch controller with respect to the baseline one.

The stochastic, full-field, turbulent-wind simulator Turbsim [31] has been used to generate the wind speed used in the simulations. Figure 4 shows the effective wind speed that reaches values above the rated power operating conditions, as this work focuses on this region. The maximum and minimum wind speeds are 24.02 and 13.52 m/s, respectively, with a mean speed of 18.49 m/s, while the rated wind speed for the offshore NREL 5-MW wind turbine is 11.4 m/s. It is clearly observed that it is a non-stationary wind profile.

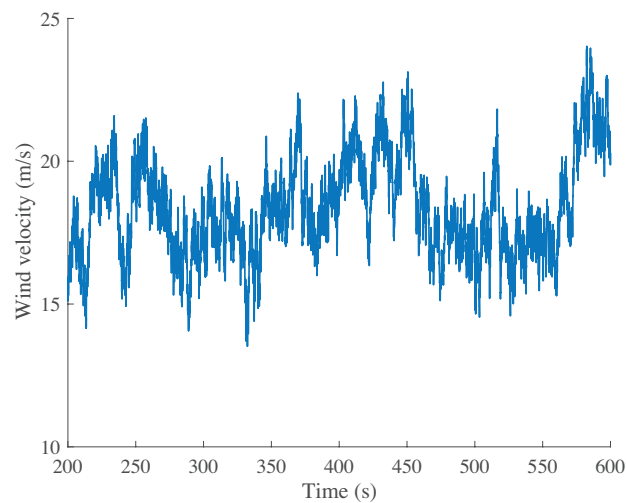


Figure 4. Effective wind speed.

The following performance indices are employed, to present a comparison between the tested controllers [32]:

$$J_p(t) = \int_0^t |P_e(\tau) - P_{e,n}| d\tau, (J) \quad (7)$$

$$J_{ass}(t) = \int_0^t |a_{ss}(\tau)| d\tau, (m/s) \quad (8)$$

$$J_{afa}(t) = \int_0^t |a_{fa}(\tau)| d\tau, (m/s) \quad (9)$$

where $a_{fa}(t)$ and $a_{ss}(t)$ are the fore-aft and the side-to-side accelerations, respectively, at the tower top.

Remark 1. In the numerical simulation, time goes from zero to 600 s. However, the results only consider the time interval between 200 and 600 s to avoid the transient due to initialization of the numerical simulations as in [24,33].

6.1. Results and Discussion

Figures 5–15 show the performance of the WT. These figures compare the results of the baseline control and the SRP control. At a glance, it is observed that all indices are reduced by the proposed SRP. In particular, the regulation of the generated power is enhanced, as can be seen in Figures 5 and 6. It is noteworthy that the fore-aft and side-to-side accelerations are significantly reduced, as shown in Figures 7–10.

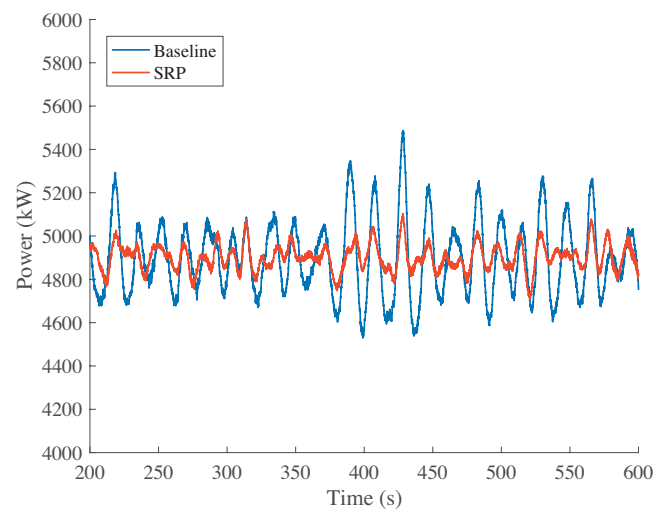


Figure 5. Electric power.

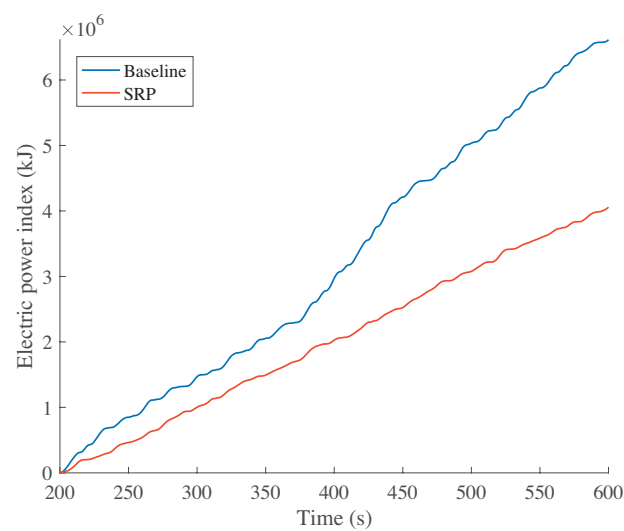


Figure 6. Electric power index, J_p .

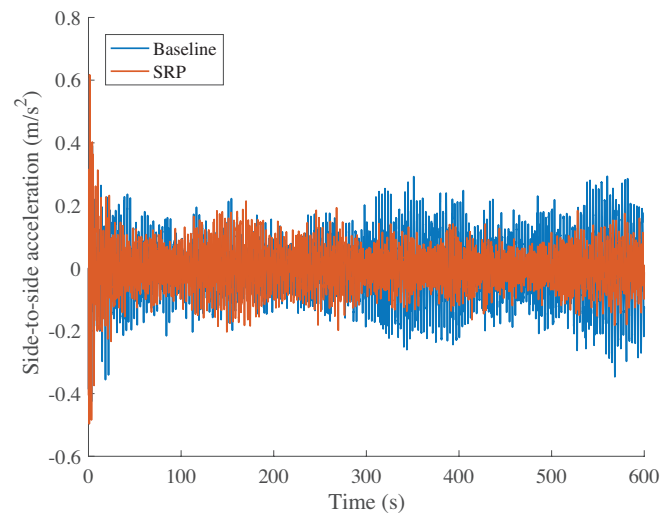


Figure 7. Side-to-side acceleration at the tower top, a_{ss} .

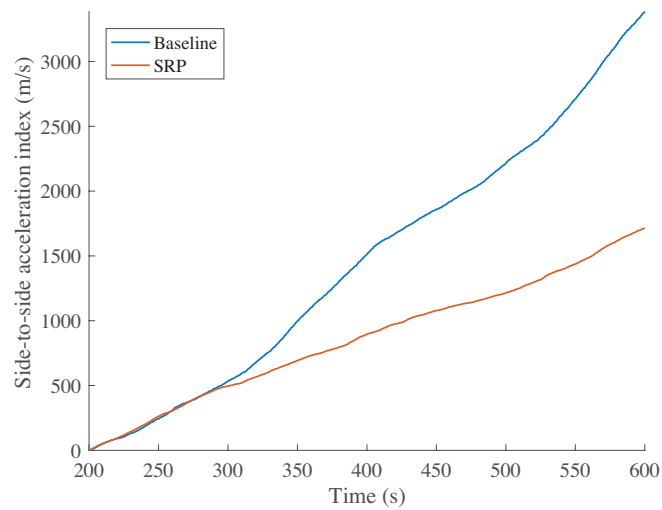


Figure 8. Side-to-side acceleration index, J_{ass} .

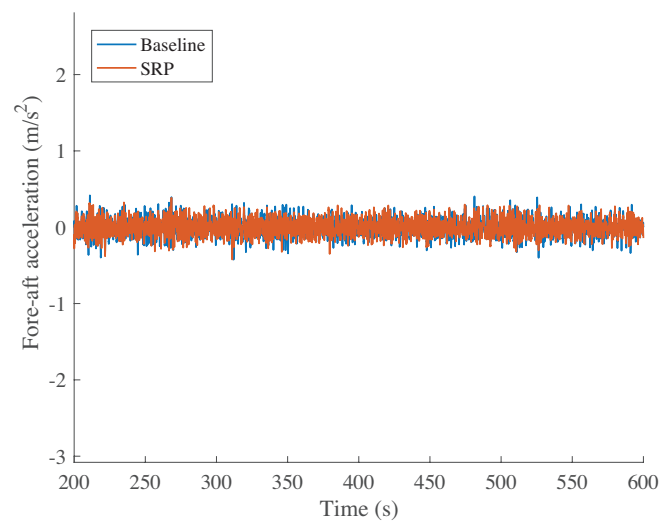


Figure 9. Fore-aft acceleration at the tower top, a_{fa} .

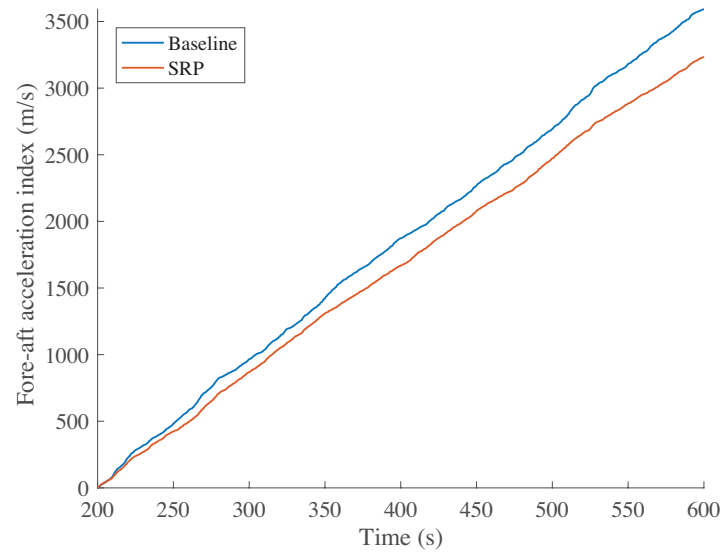


Figure 10. Fore-aft acceleration index, J_{afa} .

With respect to the pitch control signal, β_c , it reflects the resets' influence by the appearance of high frequencies (see Figures 11 and 12). Nevertheless, the general trend of the signals is similar in both simulations, the displacement of the average from 15° (baseline) to 12° (SRP) being the only difference to note. With respect to the real pitch signal, β_r , shown in Figure 13, the effect of the backlash phenomena by the appearance of dead-band regions in which the blade is stuck is relevant. The dead-band regions are increased in the simulation with the SRP control, probably motivated by the high frequencies coming from the control signal.

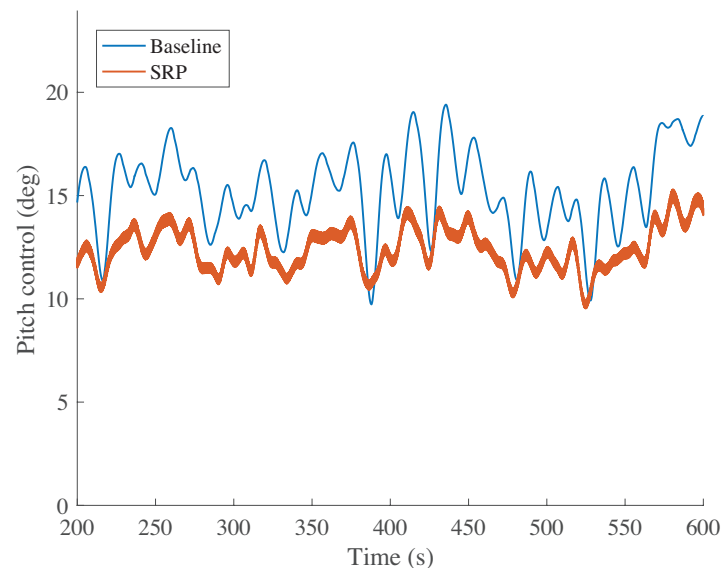


Figure 11. Pitch control signal, β_c .

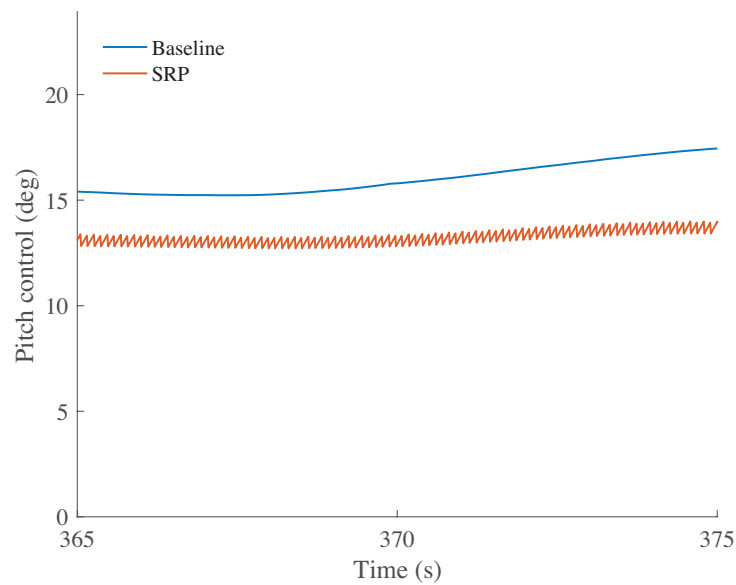


Figure 12. Detail of the pitch control signal, β_c , between 365 s and 375 s.

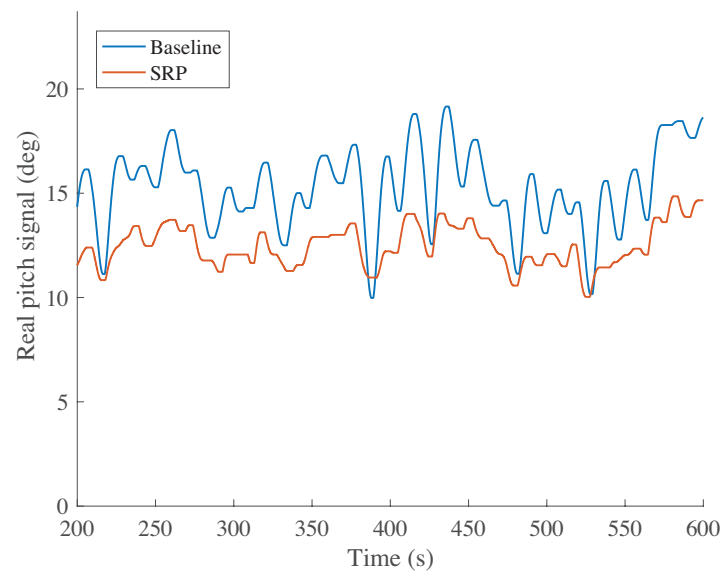


Figure 13. Real pitch actuator signal, β_r .

Regarding the generator, its speed and torque are depicted in Figures 14 and 15, respectively. Both characteristics of the generator are complemented since the electric power output is the outcome of their multiplication, as defined in Equation (6). As shown in Figure 14, the generator speed is similar for both controllers, although instead of ranging around 1200 rpm (baseline), it is now close to 1500 rpm (SRP). Finally, as a consequence of the higher generator speed, the torque control for the SRP is around 30 kNm, whilst for the baseline control, it is close to 40 kNm, as observed in Figure 15.

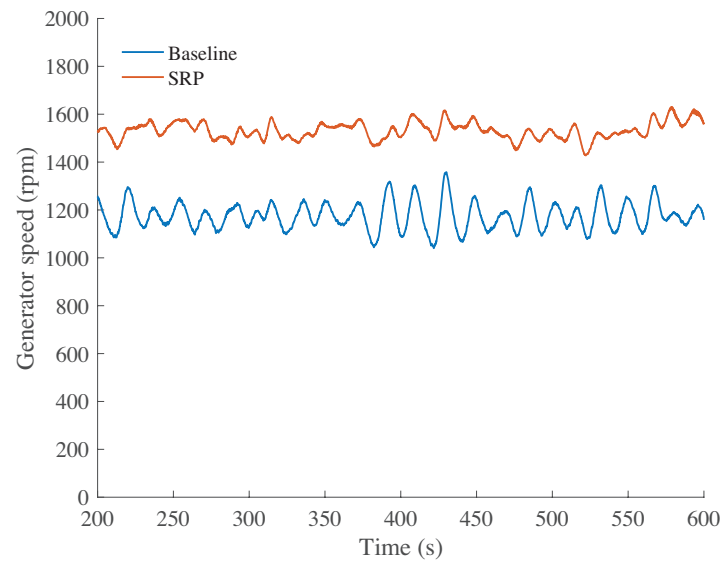


Figure 14. Generator speed, ω_g .

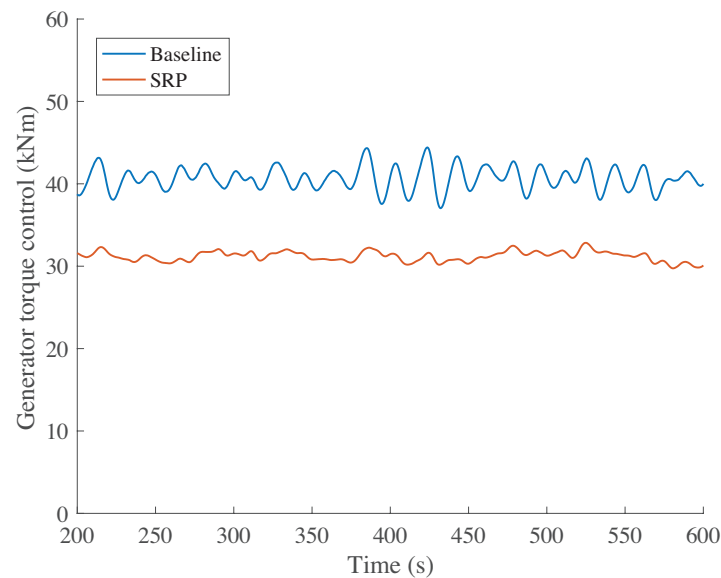


Figure 15. Generator torque control, τ_c .

The platform rotational (pitch and roll) and translational (surge and sway) data are shown in Figure 16. A reduction is obtained in all of the displacements with the proposed SRP, with respect to the baseline controller. Similarly, the tower base and tower top fore-aft and side-to-side shear force data are shown in Figure 17. Again, with respect to the baseline controller, a reduction is observed with the proposed SRP.

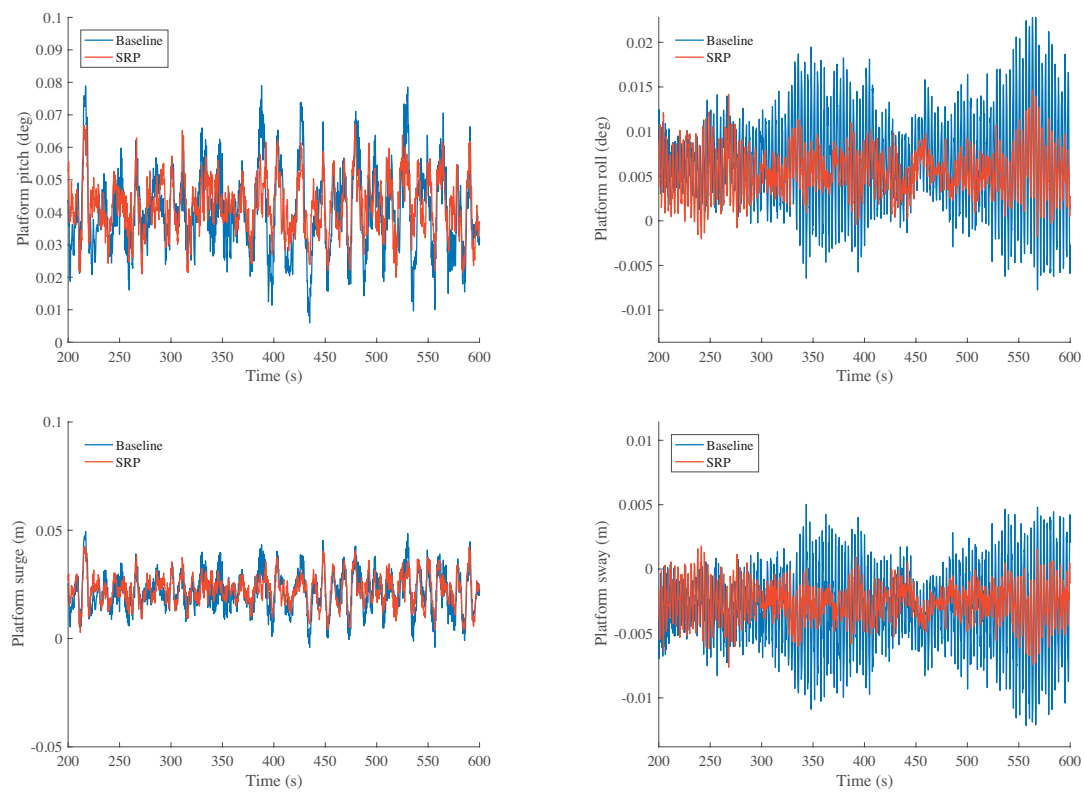


Figure 16. Platform rotational (top) and translational (bottom) data.

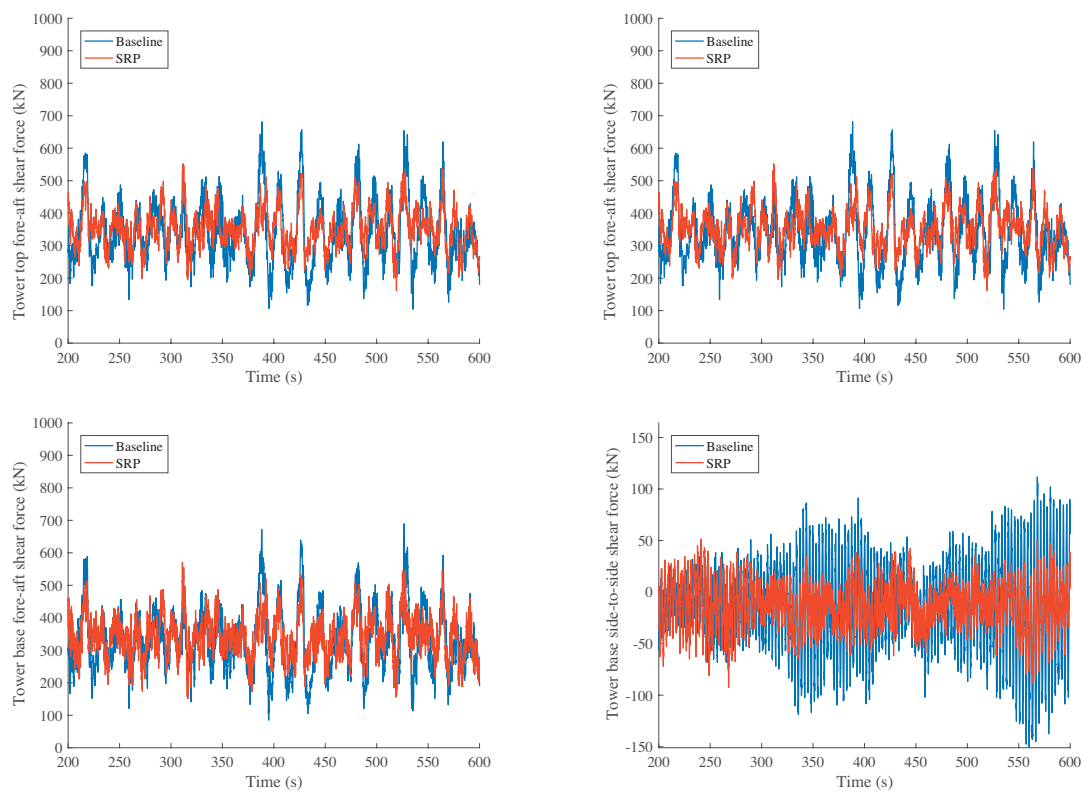


Figure 17. Tower top (top) and tower base (bottom) shear force.

7. Conclusions

This work addressed the design of a synchronous reset pitch (SRP) control for a large off-shore wind turbine with a jacket platform operating in the full-load region. With respect to the baseline, the proposed SRP turns out to be a controller with a reduced complexity as it does not require a gain-scheduling technique, nor the pitch position measurement as input. Furthermore, it improves the overall performance of the wind turbine, with respect to the baseline. In particular, the fore-aft and side-to-side acceleration are significantly reduced, and the generated power is better regulated. In a nutshell, the designed SRP is a simpler, but more efficient controller when compared to the baseline.

Moreover, this paper demonstrates that the SRP can have a decisive role in the process of providing WT with the advantageous levels of stability and robustness required by the offshore operation. The implementation of the SRP ameliorates the WT performance by reducing its vibrations and increasing the flexibility of the power harnessed from the wind. Consequently, the reset control systems can have a crucial function in the deployment of offshore wind farms.

Finally, the main advantage of the proposed controller, besides all of the improvements mentioned in this paper, is its ease of implementation. It only requires changes in the software algorithm, thus being an inexpensive measure that can be rapidly implemented not only in new WT, but also in already existing ones, as long as those are gifted with a control system.

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Abbreviations

The following abbreviations are used in this article (in alphabetical order):

BIBO	bounded-input bounded-output
FAST	Fatigue, Aerodynamics, Structure and Turbulence
FLC	fuzzy logic control
INDC	intended nationally-determined contributions
LQG	linear quadratic Gaussian
MPC	model predictive control
NREL	National Renewable Energy Lab
PID	proportional-integral-derivative
SISO	single input single output
SMC	sliding mode control
SRP	synchronous reset pitch controller
WT	wind turbine

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