NONLINEAR CONTROL OF FLOATING OFFSHORE WIND TURBINES USING INPUT/ OUTPUT FEEDBACK LINEARIZATION AND SLIDING CONTROL

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ABSTRACT

Input/ output feedback linearization and smoothed sliding control methods are used to control a floating offshore wind turbine on a barge platform in high wind speed in order to regulate the power capture. The model of the turbine has the blade pitch angle as the input, generator speed, platform pitch angle and its derivative as the measurements, and wind speed as a disturbance. The designed controllers have been applied to the simplified model of the plant which is used for controller design and also a more complex model which considers all six degrees of freedom for platform movements. Moreover, their performance is compared with the baseline controller for floating offshore wind turbines [1]. Both nonlinear controllers have improved the power regulation compared to the baseline controller. Also, sliding control has been shown to have better performance than the input/ output controller, since it can consider the uncertainty of the disturbance signal in the controller design.

INTRODUCTION

Wind energy, as a renewable energy, is becoming more and more popular due to its cleanness and sustainability [2]. There are vast areas of sea in addition to land, available for installation of wind turbines. The reasons for offshore installation are stronger, more stable wind at sea and also less noise and visual impact compared to onshore installation. The offshore installation is realizable using a floating platform [1].

To make wind energy competitive with fossil fuel energy, the price of electricity produced by wind turbines should be reduced. The wind energy price can be reduced by increasing energy efficiency, increasing the lifetime of this expensive device, as well as reducing maintenance costs.

One of the most economical ways for achieving these objectives without involving any additional hardware or modification to the structure is using feedback control. Increasing the energy efficiency for low wind speed, and regulating the energy capture for high wind speed is one of the control objectives. The other objective is reducing the platform movement; This movement induces large structural load on the system that can reduce the lifetime of the turbine as well as increasing the maintenance costs. In this paper, the high wind speed condition is considered and the objective of reduction in platform movement is not explicitly considered in the design, but it is analyzed for the obtained controllers.

The mathematical model needed for designing a controller for floating offshore wind turbine is developed in [1, 3, 4]. This model is implemented in software called *FAST* (Fatigue, Aerodynamics, Structures, and Turbulences)[1] which was developed at the National Renewable Energy Laboratory (NREL) in US [5].

A common control method for high wind speed is using a PI gain-scheduled controller to control the blade pitch angle, this method is used as a baseline controller to compare the performance; this controller can not guarantee stability [1]. Several other controllers are designed for floating offshore wind turbines; see [4, 6–8].

In this paper, two nonlinear controllers using input/output feedback linearization and smoothed sliding control are designed. The simulations are conducted using both the simplified

[1] http://wind.nrel.gov/designcodes/simulators/fast/.

plant model (used in controller design) and also the complete nonlinear model in the software *FAST*. The objective of these controllers is defined to regulate the power capture, and these controllers were successful in achieving this objective and they could outperform the performance of the baseline controller.

This paper is organized by first obtaining the model of the system used in controller design. Then, having the control objective defined and examining the accessibility of the system, the nonlinear controllers are then designed. In the next section, these nonlinear controllers are applied to both the simplified model and the more complex model.

MODELING

To design a controller, it is important to acquire an accurate mathematical model for the plant. An accurate mathematical model for a floating offshore wind turbine is described in [1] which is implemented in the software *FAST* [5] by Jonkman. This nonlinear model has large numbers of degrees of freedom which is computationally expensive for the controller design stage, therefore, a simplified model of the turbine is obtained where the states and control inputs are defined as:

$$\begin{aligned} x &=: [Platformpitchangle\ (p), \\ &\quad platformpitchanglerate\ (\dot{p}),\ rotorspeed\ (\omega_r)], \\ u &=: [Bladepitchangle(\beta)], \\ d &=: [windspeed]. \end{aligned} \tag{1}$$

A typical floating offshore wind turbine is illustrated in figure 1. Wind can affect platform pitch movement more than other platform degrees of freedom, also this movement can degrade the power capture by deviating the relative direction of wind with respect to the rotor plane. Therefore, this degree of freedom is considered in the simplified model.

Linear parameter varying (LPV) model

The simplified linearized model of the turbine at different operating points, specified by different blade pitch angles, can be obtained from the software. Using these models at different blade pitch angles, the LPV model as a function of blade pitch angle (β) is obtained utilizing curve fitting techniques.

$$\dot{x} = A(\beta)x + B(\beta)u + B_d(\beta)d \tag{2}$$

The parameters in (2) are parameterized as:

$$\begin{aligned} A(\beta) &=: A_0 + A_1\beta + A_2\beta^2, \\ B(\beta) &=: B_0 + B_1\beta + B_2\beta^2, \\ B_d(\beta) &=: B_{d0} + B_{d1}\beta + B_{d2}\beta^2, \end{aligned} \tag{3}$$

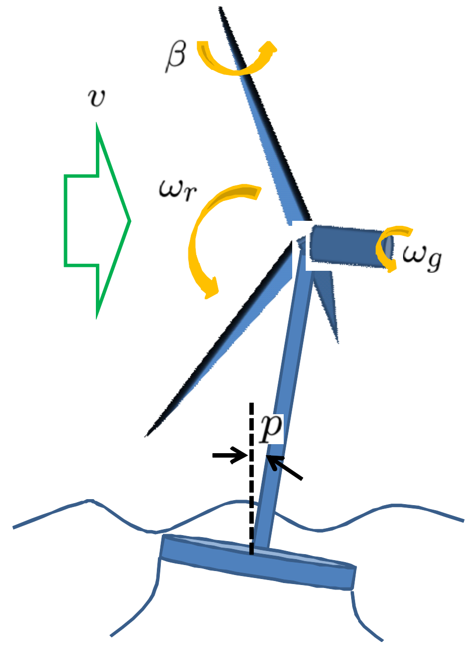


Figure 1. An illustration of a floating offshore wind turbine system.

where,

$$A_0 = \begin{bmatrix} 0 & 1 & 0 \\ -2.962\times10^{-1} & -8.325\times10^{-2} & -5.781\times10^{-2} \\ -3.267\times10^{-2} & -1.102\times10^{0} & -5.461\times10^{-2} \end{bmatrix},$$

$$A_1 = \begin{bmatrix} 0 & 1 & 0 \\ 3.078\times10^{-3} & 2.012\times10^{-1} & 6.744\times10^{-3} \\ 6.520\times10^{-2} & -4.796\times10^{0} & 1.660\times10^{-1} \end{bmatrix},$$

$$A_2 = \begin{bmatrix} 0 & 1 & 0 \\ -1.376\times10^{-2} & 2.954\times10^{-1} & 0 \\ -5.950\times10^{-1} & 0 & -3.340\times10^{0} \end{bmatrix},$$

$$[B_0, B_1, B_2] =$$

$$\left[\begin{array}{c|c|c} 0 & 0 & 0 \\ -5.614\times10^{-2} & -4.906\times10^{-2} & 0 \\ -4.501\times10^{0} & -2.110\times10^{-2} & 0 \end{array}\right]$$

$$[B_{d0}, B_{d1}, B_{d2}] =$$

$$\begin{bmatrix} 0 & 0 & 0 \\ 1.301 \times 10^{-3} & -3.447 \times 10^{-4} & 3.896 \times 10^{-4} \\ 7.256 \times 10^{-2} & 5.046 \times 10^{-3} & 2.096 \times 10^{-2} \end{bmatrix}$$

This LPV model is considered as a simplified nonlinear model used for controller design, since it does not consider other turbine's degrees of freedom.

Dynamic Extension

The dynamics of the system presented in (2) is in the general form of

$$\dot{x} = f(x,u) + g(x,u) \times u \tag{4}$$

where u represents the control input, blade pitch angle. Using the dynamics extension method [9], this form (4) is converted to the form (5) which is more common in nonlinear control.

$$\dot{x} = f(x) + g(x) \times z \tag{5}$$

The following equation is utilized for the dynamics extension.

$$x4 = u, \tag{6}$$

$$\tau \times \dot{x4} + x4 = z \tag{7}$$

where z is our new control and $1/\tau$ determines the bandwidth frequency of the low pass filter on our control input. The new control z can be obtained from different nonlinear methods and the original control input u is constructed using the first order filter defined by (7).

CONTROLLER DESIGN

In this section, first the control objective is defined followed by the investigation of the accessibility and distinguishability of the system. Then, the control methods are explained.

Control Objective

The wind turbine is assumed to be operating in high wind speed (ranging between $11.4 - 25m/s$) which is the most common region for offshore wind turbines. In this operating region, the power that can be captured by the blades is higher than the rated power of the turbine, therefore the objective will be the power capture regulation. The power captured by the turbine is written as

$$P = T_g \times N \times \omega_r \tag{8}$$

where T_g, N, ω_r are generator torque, gearbox ratio and rotor speed, respectively. One common strategy in wind turbine industries is to fix the generator torque in this region. Therefore, the power regulation objective is transformed to the regulation of rotor speed (ω_r) or equivalently generator speed ($\omega_g = N_r$). The other objective which is not considered in the controller design is the minimization of platform movement. This objective is analyzed after conducting the simulation.

To evaluate the designed controllers, the root mean square (rms) values of states are compared. Also, the rms value for the rate of blade pitch angle is a good nomination to compare the actuator activity [10].

Accessibility and Distinguishability [11]

The first step for designing any controller, is to examine whether the states of the system can be controlled using the given actuators (accessibility) and also if the sensors are enough for constructing the states which are going to be used in the controller (distinguishability). It is assumed that there are enough sensors to measure all the states as well as the blade pitch angle. Therefore, this system is distinguishable.

The accessibility of the system is examined by obtaining the following matrix;

$$\hat{C} = [g, ad_f g, ad_f^2 g, ad_f^3 g] \tag{9}$$

The rank of matrix $\hat{C}$ has been investigated in MATLAB, and it has 4 linearly independent columns which means that this system is accessible.

Input/Output Feedback Linearization

As mentioned in this section, the control objective is simplified as the regulation of rotor speed. The rotor speed, the third state in (1), is selected as the output for feedback linearization. The control input will appear in the equations by taking the derivative of this signal two times. Therefore, this system has relative degree 2.

$$y = x_3, \tag{10}$$

$$\dot{y} = \dot{x_3} = f_3(x) + gd_3(x) \times d \tag{11}$$

$$\ddot{y} = L_f(\dot{x_3}) + L_g(\dot{x_3}) \times z + L_g d(\dot{x_3}) \times d + gd_3 \times \dot{d} \tag{12}$$

Based on Input/ Output linearization theory [15], the second derivative of y here is defined as the synthetic input.

$$v = \ddot{y}, \tag{13}$$

$$\ddot{y} = L_f(\dot{x_3}) + L_g(\dot{x_3}) \times z + L_g d(\dot{x_3}) \times d + gd_3 \times \dot{d} \tag{14}$$

$$z = \frac{v - L_f(\dot{x_3}) - L_g d(\dot{x_3}) - gd_3 \times \dot{d}}{L_g(\dot{x_3})} \tag{15}$$

The synthetic control is constructed in such a way to force the regulation of the third state (x_3 rotor speed). This regulation is defined in (16) by a second order term having eigenvalues at $-\lambda$ as a design parameter.

$$(\frac{d}{dt}+\lambda)^{(2)} \times (y-y_d) = 0 \tag{16}$$

where y_d is the desired rotor speed. Therefore, the synthetic control will be

$$v = -\lambda^2 \times (y-yd) - 2 \times \lambda \times \dot{y} \tag{17}$$

The control law will utilize (15) and (17) in order to generate the control input z. As one can see, the value of signal z depends on the derivative of wind speed $\dot{d}$ which can not be accurately measured.

Internal Dynamics The dynamics system has dimension 4, but the relative degree of y is two. Therefore, the other two dimensions of the state space should be investigated in order to ensure stable dynamics.

It could be hard to distinguish the states of internal dynamics, therefore, the dynamics equation is written for all the sates except controlled state x_3 which is the output used in feedback linearization.

$$\begin{aligned} \dot{x_1} &= \psi_1(x,z), \\ \dot{x_1} &= \psi_2(x,z), \\ \dot{x_4} &= \psi_4(x,z). \end{aligned} \tag{18}$$

The control input z given in (15) is substituted in (18). Then, the zero dynamics is obtained by assuming that the controlled state (x_3) has converged to zero;

$$\begin{aligned} \dot{x_1} &= \psi_1(x_1,x_2,x_4), \\ \dot{x_2} &= \psi_2(x_1,x_2,x_4), \\ \dot{x_4} &= \psi_4(x_1,x_2,x_4). \end{aligned} \tag{19}$$

In order to make the analysis easier, this zero dynamics is linearized and the eigenvalues for the linearized system is calculated. The obtained eigenvalues were all negative; therefore, all of the states for this system are stable. Two of these eigenvalues are near zero which are related to the platform pitch movement and its rate, since they are hard to be controlled by the blade actuator.

Sliding Control

In previous section, the input/output feedback linearization controller was designed. According to (15), this method needs the derivation of the disturbance signal (d wind speed) to obtain the control input. However, wind speed is a noisy signal and it is not practical to calculate its derivative. Therefore, the sliding control approach is used by considering the derivative of disturbance as a summation of a deterministic and an uncertain part.

$$\dot{d} = \hat{\dot{d}} + \tilde{\dot{d}} \tag{20}$$

By investigating several realistic wind speed profiles generated by software *TurbSim* [13], the following values were approximated.

$$\hat{\dot{d}} = 0 \tag{21}$$

$$\alpha = max(\tilde{\dot{d}}) = 1.5m/s^2 \tag{22}$$

The sliding surface is defined in order to bring the rotor speed regulation error to zero. Since, the system is not in a canonical form, the reduced order sliding surface is used. According to (14), the system has relative degree 2 and the sliding surface will be defined as;

$$S = (\frac{d}{dt}+\lambda) \times (y-y_d) = \dot{y} + \lambda \times (y-y_d), \tag{23}$$

and the derivative of the sliding surface is obtained as,

$$\dot{S} = \ddot{y} + \lambda \times \dot{y} = L_f(\dot{x_3}) + L_g(\dot{x_3}) \times z + L_g d(\dot{x_3}) \times d + gd_3 \times \dot{d} + \lambda \times \dot{y}. \tag{24}$$

In the sliding control, the Lyapunov function can be defined using the following equality;

$$v = \frac{1}{2} \times S^2 \tag{25}$$

In order to guarantee the asymptotic stability of the sliding surface, the following inequality should hold,

$$S \times \dot{S} \leq -\eta \; S \; sat(S/\phi), \; |S| \geq \phi \tag{26}$$

where ϕ is the region that sliding surface will end in. This region is defined based on the desired steady state value of regulation error (ε) and the value of λ. The desired steady state value of ε can be obtained by adjusting the values of ϕ and λ.

$$\phi = \lambda \times \varepsilon \tag{27}$$

The control input z can be written as

$$z = \frac{-L_f(\dot{x_3}) - L_g d(\dot{x_3}) - gd_3 \times \hat{\dot{d}} - \lambda \times \dot{y} - (\eta + \alpha) sat(S/\phi)}{L_g(\dot{x_3})} \tag{28}$$

where α is defined as the maximum amount of the uncertain signal given in (22). Hence, (26) can be written as

$$S \times \dot{S} \leq gd_3 \times \tilde{\dot{d}} - (\eta + \alpha)\ S\ sat(S/\phi) \leq -\eta\ S\ sat(S/\phi),\ |S| \geq \phi \tag{29}$$

The *sat* function is used in the control input to prevent the excitation of unmodeled dynamics by the signum function. Also, this *sat* function helps to prevent the saturation of control inputs due to the actuators physical limitations. The condition given in (29) will guarantee that S will be kept smaller than ϕ in steady state, and according to (27), the maximum error, ϕ/λ, is predicted in steady state.

Internal Dynamics The procedure for analysis of internal dynamics is similar to the input/ output controller. However, the sliding control law (28) should be substituted in (18). The calculated eigenvalues for all states are negative and this system is stable. As explained in the previous section, the eigenvalues close to zero are related to the platform pitch movement which is hard to be stabilized and controlled by the given actuator.

SIMULATION RESULTS

The nonlinear controllers are designed using input/output and sliding mode control. In this section, first the effects of tuning parameters on the performance of these controllers are explained. Then, the simulation results for one tuned input/output and sliding mode control are presented[2]. These simulation results are presented in two sections. In the first section, the simulations are conducted using the simplified model of the turbine which is used in the controller design. This simplified model only consider platform pitch movement as the platform degree of freedom. In the second section, the designed controllers are applied to the more complex model of the turbine which consider all six degrees of freedom for the platform; this model is available in software *FAST*. Moreover, the performance of these controllers are compared with the baseline controller which is a gain-scheduling PI controller [1].

In order to avoid the randomness effect of wind speed, the simulation are done using different wind speed with the same statistical properties; the results are averaged and presented in Tables 1 and 2. Table 1 shows the results for the input/ output controller. According to (16), by increasing λ, the closed loop eigenvalues are moved to the left, which lead to faster convergence of generator speed. In this case, the generator speed error reduces at the cost of increased actuator activity. Also, the platform movement is reduced while it is not considered as a control objective; this result can be a consequence of smaller fluctuation in generator speed and therefore power capture.

[2]The parameters are selected as; $\phi = 0.03$, $\lambda = 4$, $\eta = 0.4$ and $\tau = 0.001$.

Table 1. THE PERFORMANCE OF INPUT/ OUTPUT CONTROLLER.

λ	2	4	6
rms($\dot{\beta}$)	0.66	0.94	1.18
rms(ω_r)	13.38	10.74	9.32
rms(p)	0.79	0.66	0.62
rms($\dot{p}$)	0.35	0.29	0.27

Table 2. THE PERFORMANCE OF SLIDING MODE CONTROLLER.

λ	4	2	4	6	4
ϕ	0.1	0.03	0.03	0.03	0.01
η	0.4	0.4	0.4	0.6	0.4
ϕ/λ	0.025	0.015	0.0075	0.0075	0.0025
rms($\dot{\beta}$)	1.62	2.08	2.26	2.48	2.84
rms(ω_r)	3.93	3.63	3.30	3.17	2.83
rms(p)	0.60	0.59	0.58	0.58	0.57
rms($\dot{p}$)	0.29	0.31	0.31	0.31	0.30

The simulation results for the sliding mode control are shown in Table 2. As mentioned in (27), the ratio of ϕ/λ determines the error in generator speed regulation. The reduction of this ratio reduces the generator speed fluctuation at the cost of increased actuator activity. Convergence of generator speed and sliding surface can be improved by increasing the values of λ and η, respectively. The increase for each of these values will improve generator speed regulation at the cost of more actuator activity. The platform movement is almost the same in these cases.

The next sections show the simulation results for the simplified and more complex model. In both sections, the wind speed is generated by software *TurbSim* [13] which generates realistic wind speed. This wind profile is shown in Figure 2.

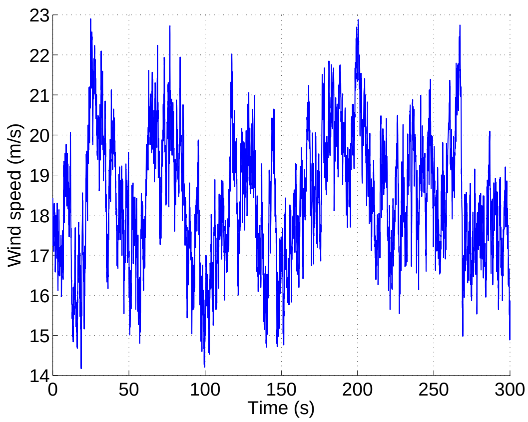


Figure 2. Wind speed profile used in simulations

Simplified Model

The two nonlinear control strategy have been applied to the LPV model of the system. This simplified model was used to design these controllers. Figure 3 shows the regulation of generator speed. As one can see, the deviation in generator speed is almost less than $25rpm$ (2% deviation[3]) which is satisfactory. Moreover, the sliding controller has improved the regulation drastically compared to the input/ output controller.

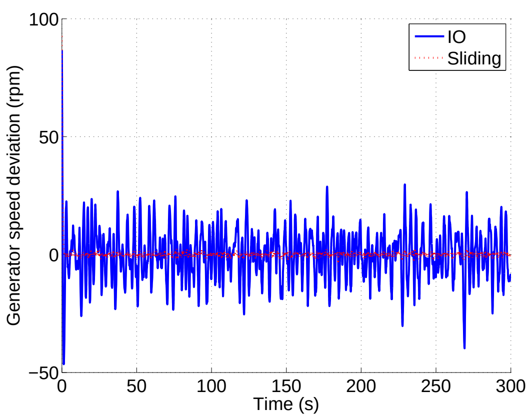
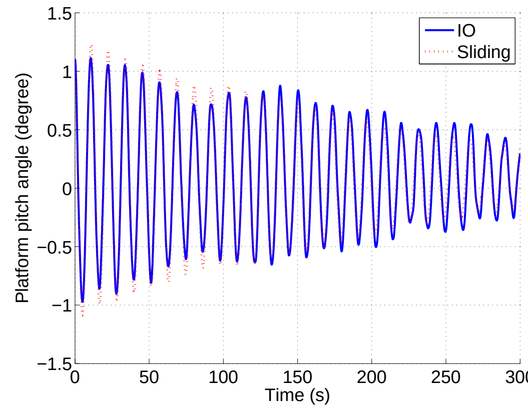
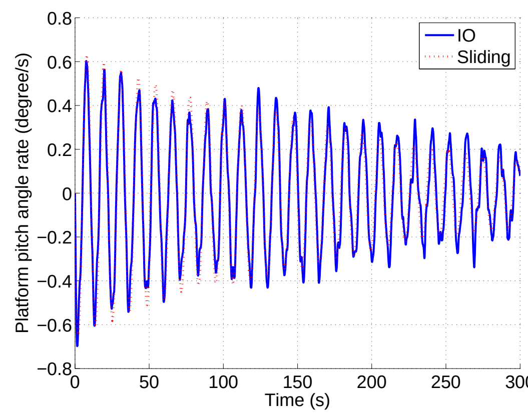


Figure 3. The regulation of generator speed for both input/ output and sliding control for the simplified model (The absolute value of desired generator speed is $1173.7rpm$)

The platform pitch movement, the movement in the direction of wind, is the most critical platform movement. This movement is shown in Figure 4. The regulation of this platform movement is not considered in the controller design and simulation results show that both of the controllers achieve almost the same movement.



(a) Platform pitch angle



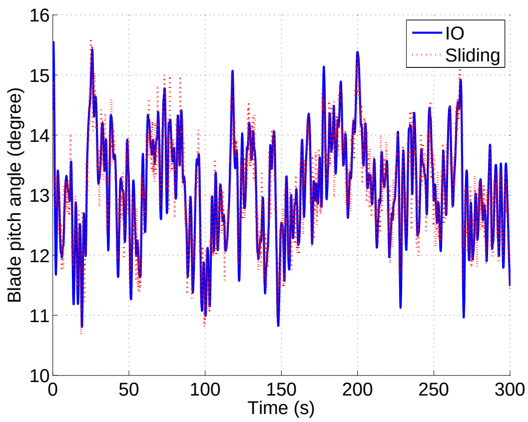
(b) Platform pitch angle rate

Figure 4. Platform response for the simplified model

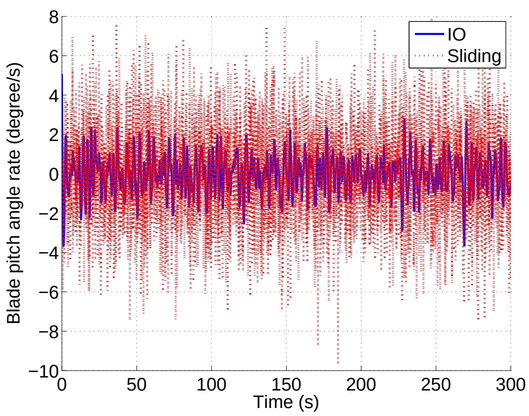
The actuator in this problem is the one which adjusts blade pitch angle. The constraint on this actuator limits the absolute value of blade pitch angle rate by 8 $degree/s$. The blade pitch angle and its rate are shown in Figure 5. As one can see, both controllers will satisfy performance limitations of the actuator. However, this constraint is violated at few points and it can be prevented using a saturation block.

The Lyapunov function is given in (25). Based on the theory of sliding control [14], this controller is designed in such a way that the term $S\dot{S}$ becomes negative outside the boundary layer. Therefore, the sliding surface is forced to move inside the boundary layer ϕ. Figure 6 shows that the sliding surface S has moved and stayed inside the boundary layer $[-\phi, \phi]$.

[3]The absolute value of desired generator speed is $1173.7rpm$.



(a) Blade pitch angle



(b) Blade pitch angle rate

Figure 5. Blade pitch activity for the simplified model

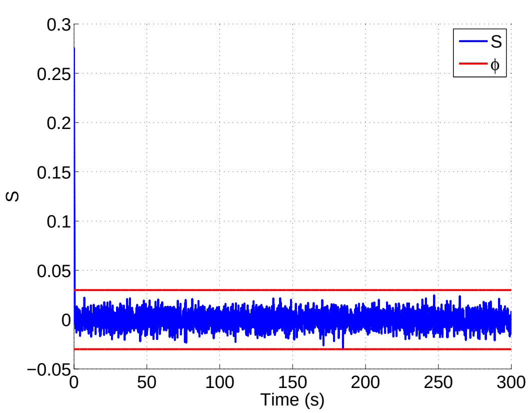


Figure 6. Sliding surface (S) for the simplified model

More Complex Model in the Software *FAST* with Six Degrees of Freedom for the Platform

The controllers designed based on the simplified model have relatively satisfactory performance. However, the performance of these controllers should be investigated when they are applied to the more realistic floating wind turbine model which its platform can move in six directions. If the performance of these controllers is not satisfactory, more complex model should be considered in the design stage. In this section, the designed controllers are applied to the nonlinear model inside software *FAST*. Also, their performance is compared to the baseline controller (PI gain-scheduling controller) [1].

The deviation of generator speed from its desired value is shown in Figure 7. As one can see, the nonlinear controllers improve the generator speed regulation compared to the baseline controller, and this improvement is more significant for the sliding mode controller. Although the generator speed deviation is relatively larger than the simulation results for the simplified model, the performance of these nonlinear controllers on the more complex model is still satisfactory; because they have improved generator speed regulation drastically compared to the baseline controller. The reasons for the larger generator speed deviation of more complex model can be ignored platform degrees of freedom (except pitch angle) in the design and also modeling errors in obtaining the simplified model of the system due to not considering the dependency of model on the azimuth angle of blades.

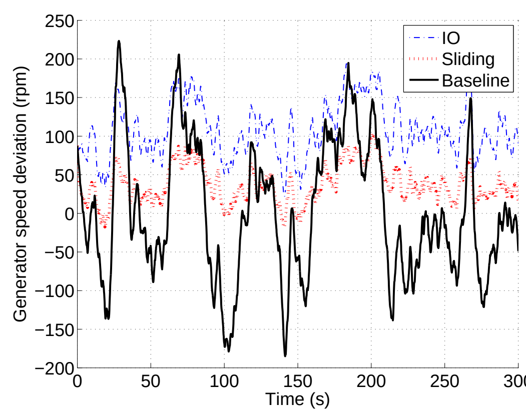
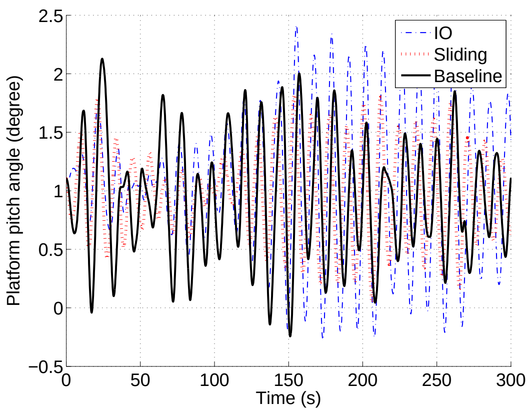
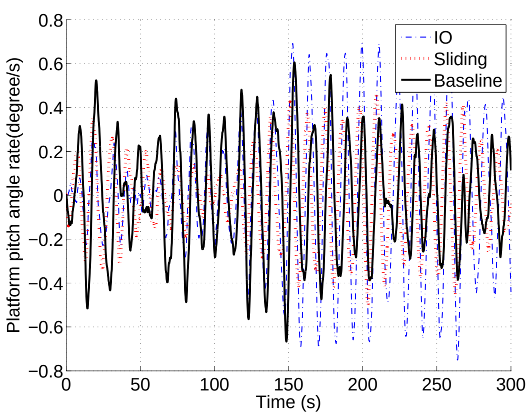


Figure 7. The regulation of generator speed for both input/ output and sliding control for the more complex model (the absolute value of generator speed is $1173.7rpm$)

The platform pitch response is shown in Figure 8. The sliding mode controller has achieved almost the same platform pitch movement as the baseline controller and the input/ output controller has the largest movements. Figure 9 shows the smoother change in blade pitch angle for the baseline controller. The control activity is more aggressive for both sliding and input/ output controllers. However, Figure 9 shows that the constraints for the blade pitch actuator are not violated (The absolute value of blade pitch angle rate is less than 8 $degree/s$)[4]

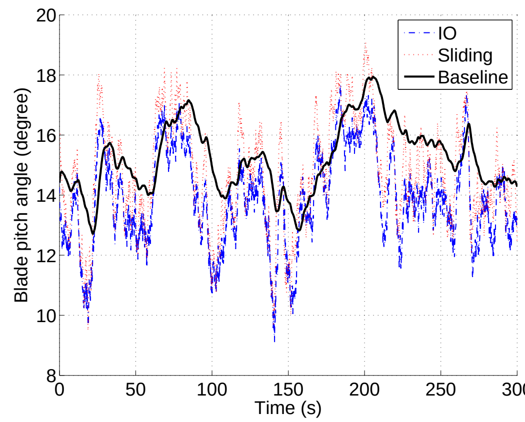


(a) Platform pitch angle

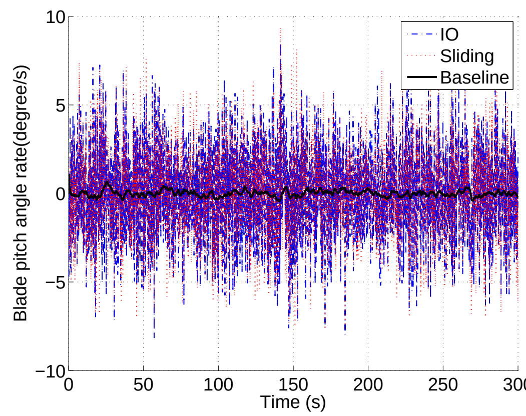


(b) Platform pitch angle rate

Figure 8. Platform response for the more complex model



(a) Blade pitch angle



(b) Blade pitch angle rate

Figure 9. Blade pitch activity for the more complex model

CONCLUSION

Two nonlinear control approach, input/ output feedback linearization and sliding control, have been applied to a floating offshore wind turbine. These controllers are designed using a simplified model of the turbine with lower degrees of freedom for the platform. Then simulations have been conducted using both the simplified and more complex nonlinear model. The control objective, which is the regulation of generator speed, has been improved using both sliding control and the input/ output control; this improvement is more significant using sliding mode control. The better performance of sliding mode control is expected, since the effects of worst case wind speed disturbance is considered in its design. Also, the input/ output controller needs the derivative of disturbance signal which is noisy and not always available. On the other hand, since the platform pitch reduction is not considered as a control objective, it is analyzed after simulating the designed controllers. The sliding controller could keep almost the same platform pitch movement as the baseline controller, while improving generator speed regulation. But, the input/ output controller has not improved platform pitch movement compared to the baseline controller.

The control input for the nonlinear controllers is not as smooth as the baseline controller, however, they are designed such that the control input rate does not violate its constraint. Also, the control action can be made smoother at the cost of having more generator speed fluctuation.

It's worth mentioning that the performance of both nonlinear controllers have been degraded by applying them to the more complex model. The main reason is that these controllers are designed for the simplified model, while they have been applied to the more complex model. The performance can be improved

[4]As explained for Figure 5, the few violation of constraints for the input/ output controller can be accommodated using saturation block.

at the cost of having a more complicated model in the controller design stage. however, the performance achieved by these nonlinear controllers is still satisfactory, since they have improved the generator speed regulation drastically compared to the baseline controller.

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