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Robust Model-Free Control of a Floating Offshore Wind Turbine under High Wind & Wave Conditions

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Abstract—Offshore wind energy can provide a substantial amount of the world’s current electricity demand. Yet, harvesting this energy poses additional technical and economic challenges to the design and control of Floating Offshore Wind Turbines (FOWT). Different control strategies have been used to mitigate these challenges to increase the efficiency of the FOWTs and stabilize their power output. This paper presents a model-free adaptive control using Generalized Proportional Integral Control (GPIC) based on integral reconstruction in the form of robust Classical Compensation Networks (CCN) to control the collective pitch angle of a FOWT operating above rated wind speed (Region 3). The control is validated on a nonlinear model of a 5 MW FOWT with a semi-submersible platform and compared to the basic Gain Scheduling PI (GSPI) controller with Anti-Windup. Results show a more robust performance of the proposed controller under various wind and wave conditions.

Keywords—Floating Offshore Wind Turbine (FOWT); Pitch Control; Model-Free Control (MFC); Generalized PI Control (GPIC); Gain Scheduling PI (GSPI); Classical Compensation Networks (CCN)

I. INTRODUCTION

Following the COVID-19 pandemic, rapid economic recovery in most markets worldwide, along with wars and changing weather conditions, caused a sharp increase in energy costs. Record high prices for fossil fuels (oil and natural gas) instigated high inflation, rise in poverty levels, interruption in energy supplies, and, in many countries, severe recessions [1]. In the same context, greenhouse gas emissions continue to increase, aggravating global warming and dramatic changes in the weather worldwide [2]. Consequently, the demand for renewable energy, such as solar and wind, has been increasing to answer the need to reduce emissions, secure energy supplies, and meet energy needs [3].

Wind energy is one of the most promising renewable sources, as it can be produced onshore and offshore. According to [1], the best offshore wind sites could supply more than the total electricity consumed worldwide today. Yet, harvesting offshore wind energy is challenging since most of the energy lies in water deeper than 60 m [4]. Fixed-bottom offshore wind turbines are used in shallow and transitional waters (0-60 m). They are similar to their onshore counterparts. However, in deep waters (more than 60 m deep), floating platforms support

the wind turbine, adding complexity to the system [5]. Significant improvement in the cost-effectiveness, i.e., efficiency and reliability, of FOWTs is the key to unleashing the potential of clean and abundant offshore wind energy [1].

The FOWT (Fig. 1) is a highly complex system with multiple sub-systems that are dynamically coupled (Blades aerodynamics, rotor, drivetrain, electric generator, power electronics, structure – Nacelle and Tower, floating platform, and mooring), exhibiting nonlinear behavior, uncertainty in the modeling, and subject to several stochastic disturbances (wind, waves, currents, electrical load, ice, etc.) that significantly affect its operation. Different control systems are used with most sub-systems to ensure the FOWT generates the most efficient electric power, reducing their cost [4]. Different types of platforms are used in FOWT. The most common four are Barge, Tension Leg Platform (TLP), Spar, and Semi-submersible [5].

The FOWT converts wind energy into electrical energy depending on the wind speed. Fig. 2 shows the ideal power curve versus the wind speed. There are four regions of operation for the FOWT, depending on the wind speed. No power is generated in regions 1 and 4.

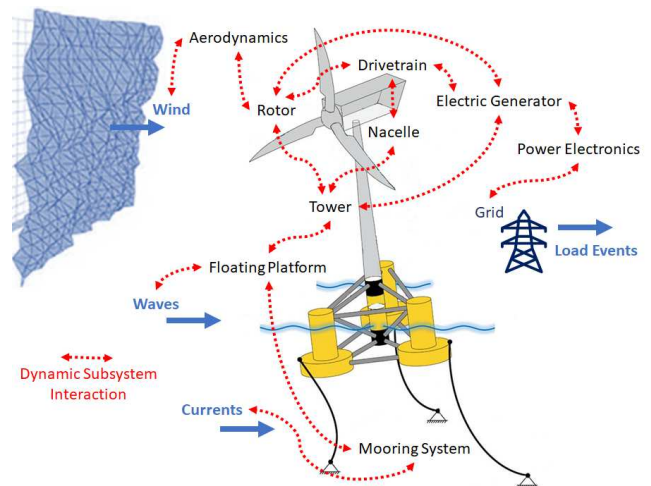


Fig. 1. Floating Offshore Wind Turbine (FOWT) system overview.

In region 2 ($V_{\text{cut-in}} \leq \text{wind speed} < V_{\text{rated}}$), the control objectives are to generate the maximum power, usually using Maximum Power Point Tracking (MPPT) techniques. The power in this region is always below the rated FOWT power since there is not enough wind. The pitch angles of the blades are set to zero to capture the maximum aerodynamic energy. When the wind speed is above V_{rated} but below $V_{\text{cut-out}}$, we are in region 3. In this region, the control objectives are to maintain the nominal turbine power through blade pitch control. Because the wind energy is high, the pitch angles of the turbine blades are changed so that the power captured remains constant. Transitional regions (Region 1½ and Region 2½) exist in some turbines to assure smooth transitions between the regions [6], [7].

Because of the nature of the FOWT complex system, which is highly nonlinear and subject to various disturbances, the goal in region 3 is to maintain the speed of the generator at the rated speed by adjusting the blades' pitch angles. Traditional Proportional Integral (PI) control does not work in this case because the aerodynamic power captured by the blades varies nonlinearly with the pitch angle and wind speed.

To address this, Wright and Fingersh [8] designed a Gain Scheduling PI (GSPI) controller based on the idea that the power generated is sensitive to changes in the pitch angle. Therefore, they used a single degree-of-freedom (DOF) model of the turbine to design a PI controller whose gains are adjusted depending on the pitch angle. This GSPI controller now serves as the baseline for blade pitch control in above-rated wind speed, though its performance is not the best.

Several control methods have been investigated to mitigate the problems with the GSPI. Gambier et al. [9] used a nonlinear PID approach with active tower damping. They obtained promising results but did not include gain scheduling, and the tests need to be real turbulent wind scenarios. Wang et al. [10] used fractional-order PID control with rate-limited anti-windup. Their results are satisfactory compared to the standard PID control. The authors treated the individual pitch control of a large wind turbine using a fractional order nonlinear PI approach with an anti-windup strategy [11]. Compared to the standard PI, the results were satisfactory but showed an increase in pitch activity. Other works include Fuzzy Logic Control, which exhibits an improvement over the basic PID control [12], [13], [14]. These controllers have one common disadvantage, which is having an accurate model of the wind turbine.

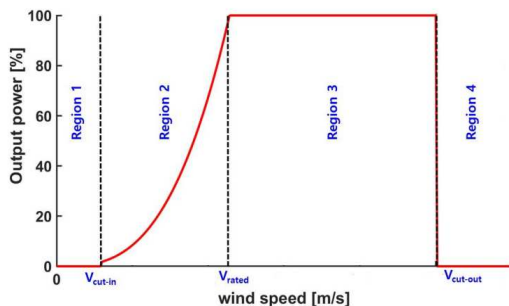


Fig. 2. Power curve versus wind speed.

Neural Networks of different types (Multi-Layer Perceptron (MLP) networks, Radial Basis Function (RBF) networks, Deep Extreme Learning Machine (DELm) networks, and many others) were used to control the pitch angles of wind turbines above-rated wind speed. Most showed improvements over the classical PID control and the GSPI control [15], [16], [17], [18], [19], [20]. These control methods are computationally expensive and, most of the time, impractical.

Robust control strategies are also used to control wind turbines in Region 3. Anjun et al. [21] used Active Disturbance Rejection Control (ADRC), which uses an Extended State Observer (ESO) to reject the disturbances and nonlinearities in the system. Results showed a faster response, smaller overshoot, and better robustness than the baseline PI controller. Jin et al. [22] used a linear ADRC to reduce the fatigue load of the turbine by 9%. However, ADRC requires the use of ESOs to achieve its control objectives.

In this paper, we tackle the collective pitch angle control of a FOWT in region 3, using model-free adaptive control using Generalized Proportional Integral Control (GPIC) based on integral reconstruction in the form of robust Classical Compensation Networks (CCN).

This paper is organized as follows: Section II presents the 5-MW FOWT mathematical model, the definitions of the turbine and the platform, and the OpenFAST (National Renewable Energy Laboratory (NREL), Denver, CO, USA) software used in simulating the system. Section III details the proposed model-free adaptive control using GPIC based on integral reconstruction in the form of robust CCNs. Section IV presents the results and compares the proposed control scheme with the baseline GSPI with Anti-windup. Section V presents the conclusions and future works.

II. NREL 5-MW FOWT MODEL

The NREL 5-MW FOWT is a representative utility-scale multimegawatt turbine with a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine [23]. The floating platform chosen for this work is the OC4 (Offshore Code Comparison Collaboration Continuation) semi-submersible floating platform [24]. Table I presents the detailed parameters of the wind turbine, its drivetrain, and the platform. Fig. 3 depicts the FOWT with its semi-submersible platform.

A. Mathematical Model

The mechanical power extracted by the wind turbine is proportional to the cube of the wind speed, and it can be expressed as:

$$P_{\text{mech}} = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3 [W] \quad (1)$$

Where $C_p(\lambda, \beta)$ is the power coefficient, λ is the tip speed ratio ($\lambda = \frac{\Omega R}{v}$), β is the pitch angle [rad], A is the area swept by the blades [m²], ρ is the air density [kg.m⁻³], v is the wind velocity [m/s], Ω is the rotor speed [rad/s], and R is the rotor-plane radius [m].

TABLE I. PROPERTIES OF THE 5-MW WIND TURBINE, DRIVETRAIN, AND FLOATING PLATFORM

System	Properties	
	Description	Value
5-MW Turbine	Rating	5 MW
	Rotor Orientation Configuration	Upwind 3 Blades
	Rotor, Hub Diameter	126 m, 3 m
	Hub Height	90 m
	Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
	Rated Tip Speed	80 m/s
	Overhang, Shaft Tilt, Precone	5 m, 5°, 2.5°
	Rotor Mass	110,000 kg
	Nacelle Mass	240,000 kg
	Tower Mass	347,460 kg
Drivetrain	Rated Rotor Speed	12.1 rpm
	Rated Generator Speed	1173.7 rpm
	Gearbox Ratio	97 :1
	Electrical Generator Efficiency	94.4 %
	Generator Inertia about High-Speed Shaft	534.116 kg.m ²
	Equivalent Drive-Shaft Torsional-Spring Constant	867,637,000 N.m/rad
Floating Platform	Equivalent Drive-Shaft Torsional-Damping Constant	6,215,000 N.m/(rad/s)
	Depth of platform base below SWL ^a	20 m
	Elevation of the main column above SWL	10 m
	Elevation of offset columns above SWL	12 m
	Spacing between offset columns	50 m
	Length of upper columns	26 m
	Length of base columns	6 m
	Depth to top of base columns below SWL	14 m
Diameter of main column	6.5 m	
Diameter of offset (upper) columns	12 m	
Diameter of base columns	24 m	
Diameter of pontoons and cross braces	1.6 m	

^a. Sea Water Level

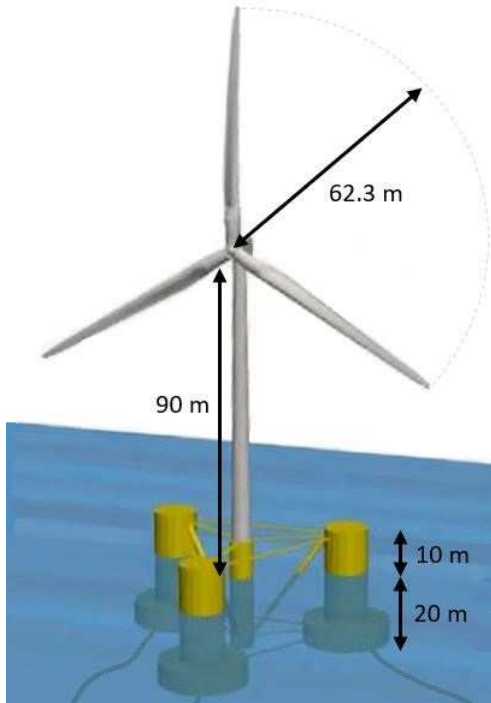


Fig. 3. NREL 5-MW FOWT with the OC4 Semi-submersible Platform [24].

The power coefficient, $C_p(\lambda, \beta)$, is a nonlinear function of the tip speed ratio and the pitch angle. According to [22], it can be approximated as:

$$C_p(\lambda, \beta) = 0.5176 \left(116 \frac{1}{\lambda_1} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_1}} + 0.0068\lambda \quad (2)$$

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

In Region 3, the electric power of the turbine must be maintained at its nominal value. Thus, the blades' pitch angle is changed to maintain the rotor speed at its nominal value. Using a single degree of freedom (DOF), the angular rotation of the shaft can be expressed using the equation of motion:

$$T_{Aero} - N_{Gear}T_{Gen} = (J_{Rotor} + N_{Gear}^2 J_{Gen}) \frac{d}{dt}(\Omega_0 + \Delta\Omega) \quad (4)$$

Where T_{Aero} is the low-speed shaft aerodynamic torque [N.m], T_{Gen} is the high-speed shaft generator torque [N.m], N_{Gear} is the high-speed to low-speed gearbox ratio, J_{Rotor} is the rotor inertia [kg.m²], J_{Gen} is the generator inertia relative to the high-speed shaft [kg.m²], Ω_0 is the rated low-speed shaft rotational speed [rad/s], $\Delta\Omega$ is the small perturbation of low-speed shaft rotational speed about the rated speed [rad/s]. Equation (4) can be simplified to:

$$T_{Aero} - N_{Gear}T_{Gen} = J_{Drivetrain}\Delta\dot{\Omega} \quad (5)$$

Where $J_{Drivetrain}$ is the drivetrain inertia cast to the low-speed shaft [kg.m²], and $\Delta\dot{\Omega}$ is the low-speed shaft rotational acceleration [rad/s²].

Because the generator-torque controller maintains constant generator power in Region 3, the generator torque in Region 3 is inversely proportional to the generator speed:

$$T_{Gen}(N_{Gear} \cdot \Omega) = \frac{P_0}{N_{Gear} \cdot \Omega} \quad (6)$$

Where P_0 is the rated mechanical power [W], similarly, assuming negligible variation of aerodynamic torque with rotor speed, the aerodynamic torque in Region 3 is expressed as:

$$T_{Aero}(\beta) = \frac{P(\beta, \Omega_0)}{\Omega_0} \quad (7)$$

B. OpenFAST and Simulink for the Simulation

Since the FOWT is a highly complex and nonlinear system, including not only the aerodynamic, drivetrain, and electric generator systems (Fig. 1), the model used in this study is a grey box. NREL OpenFAST, a multi-physics, high-fidelity tool for simulating the coupled dynamics of FOWT, is used to model 5-MW FOWT. The model is an S-Function compiled for Simulink[®] (MathWorks, Inc., Natick, MA, USA) and MATLAB[®] (MathWorks, Inc., Natick, MA, USA).

III. GPIC BASED ON INTEGRAL RECONSTRUCTION USING CCN

Before the synthesis of the controller, the control objectives must be reiterated. In region 3, i.e., above-rated wind speed, the objective is for the turbine to maintain rated power even though the wind speed is higher than the rated wind speed. Therefore, wind energy is greater than what is needed by the wind turbine, and this will cause the generator speed to increase to a dangerous level, compromising the structural safety of the turbine. Thus, collective blade pitch control controls the amount of aerodynamic energy the turbine absorbs, thus regulating the rotor/generator speed to the nominal value. Therefore, the control objectives in Region 3 are to regulate the rotor's speed to a nominal value in order to maintain the power output at rated power.

Model-free control (MFC) is a type of robust control that replaces the original system with an "ultra model" with the same response with the help of the control law. In this regard, it does not require ESO as in ADRC. Fliess and Join developed the GPIC based on integral reconstruction of the form of CCNs [25]. This type of controller provided good results for output feedback stabilization and output reference trajectory tracking tasks. Therefore, it can be used to control significantly perturbed nonlinear systems affected by unknown endogenous nonlinearities in the presence of exogenous disturbances and un-modeled dynamics [26].

Simplifying the FOWT collective pitch control system as a pure integral second-order system that is unperturbed:

$$\ddot{y} = u \quad (8)$$

Where y is the system output or controlled variable (the rotor speed), and u is the input or control law (the collective blade pitch angle). It is desired to asymptotically track the smooth output reference signal $y^*(t)$ (in our case, it is the constant nominal rotor speed of 12.1 rpm). The nominal control input (pitch angle), $u^*(t)$, is given by $u^*(t) = \ddot{y}(t)$. The output tracking error dynamics is given by:

$$\dot{e}_y = e_u, \quad e_y = y - y^*(t), \quad e_u = u - u^*(t)$$

The GPIC of this second-order system via integral reconstructor is shown in Fig. 4.

GPIC uses integral reconstructions of \dot{e}_y , which is off by an unknown constant initial condition as $\dot{e}_y = \widehat{e}_y + e_y(0)$, where:

$$\widehat{e}_y = \int_0^t e_u(\sigma) d\sigma \quad (9)$$

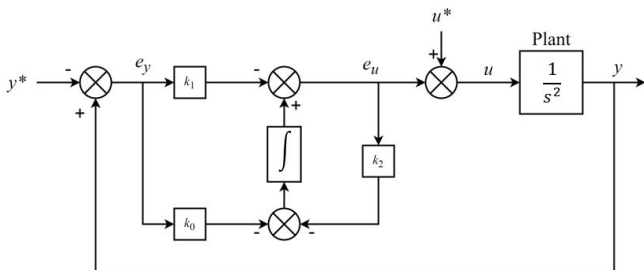


Fig. 4. GPIC of a second-order system via integral reconstructor.

A linear feedback controller is suggested as follows: considering an output integral compensation term to asymptotically eliminate the constant error in estimating the tracking error derivate.

$$e_u = -k_2 \widehat{e}_y - k_1 e_y - k_0 \int_0^t e_y(\sigma) d\sigma \quad (10)$$

Where k_0 , k_1 , and k_2 are constants designed to guarantee the tracking error's asymptotic stability. Thus, the closed-loop system tracking error dynamics is given by:

$$\dot{e}_y = -k_2 \dot{e}_y - k_1 e_y - k_0 \int_0^t e_y(\sigma) d\sigma + k_2 e_y(0) \quad (11)$$

Taking $z = \int_0^t e_y(\sigma) d\sigma + (k_2/k_1)e_y(0)$, the system's dynamics become:

$$\begin{aligned} \dot{e}_y &= -k_2 \dot{e}_y - k_1 e_y - k_0 z \\ \dot{z} &= e_y \end{aligned} \quad (12)$$

The Laplace transform of (12), along with some simplifications and rearrangements, gives the following:

$$u = u^* - \left[\frac{k_1 s + k_0}{s + k_2} \right] (y - y^*) \quad (13)$$

Which is equivalent to a lead compensation network (Fig. 5).

The characteristic polynomial of (12), or the denominator of the closed-loop system in Fig. 5, is written as:

$$p(s) = s^3 + k_2 s^2 + k_1 s + k_0$$

For stability, $k_0 > 0$, $k_2 > 0$, and $k_2 > k_0/k_1$. Using the pole placement technique, the desired system response is obtained by comparing it to $p(s) = (s + p_1)(s^2 + 2\xi\omega_n s + \omega_n^2)$. We get $k_0 = p_1 \xi \omega_n^2$; $k_1 = 2\xi\omega_n p_1 + \omega_n^2$; and $k_2 = 2\xi\omega_n + p_1$.

The proposed GPIC system's block diagram is presented in Fig. 6. Wind and waves are considered disturbances affecting the nonlinear FOWT system. The proposed controller used a Lagrangian lookup table to calculate the nominal pitch angle value depending on the wind speed measured by the turbine. Several simulations were conducted to create this lookup table by eliminating waves and fixing the wind speed at constant values from 12 m/s to 25 m/s. Then, a constant pitch angle is applied and varied for the nominal generator speed. Table II summarizes the recorded values.

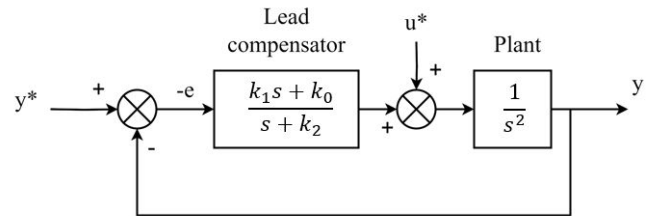


Fig. 5. Lead compensator realization of GPIC for second-order system.

IV. TESTING AND RESULTS

The proposed GPIC controller was tested on the nonlinear FOWT OpenFAST model in Simulink®, MATLAB® with a realistic scenario of turbulent wind and waves. It is compared with the baseline GSPI controller with added Anti-windup.

First, the turbulent wind profile is generated using TurbSim version 1.50 (NREL, Denver, CO, USA), a stochastic, full-field, turbulent-wind simulator. The wind data is generated over 200 s with a means of 17.037 m/s, 0.2461 m/s, and -0.1394 m/s in the x , y , and z directions, respectively (x is the upwind direction of the turbine). At the same time, the wave profile is chosen using the Beaufort scale corresponding to a wave height of 5 m with a JONSWAP/Pierson-Moskowitz spectrum. Fig. 7 shows the turbulent wind profile and the corresponding wave profile.

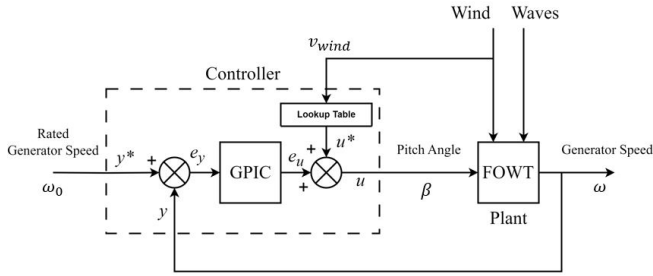


Fig. 6. The overall control system block diagram.

TABLE II. NOMINAL PITCH ANGLE LOOKUP TABLE

Wind Speed (m/s)	Nominal Pitch Angle (degrees)
12	2.10
13	5.50
14	7.78
15	9.70
16	11.40
17	12.96
18	14.35
19	15.70
20	16.95
21	18.18
22	19.36
23	20.60
24	21.74
25	22.90

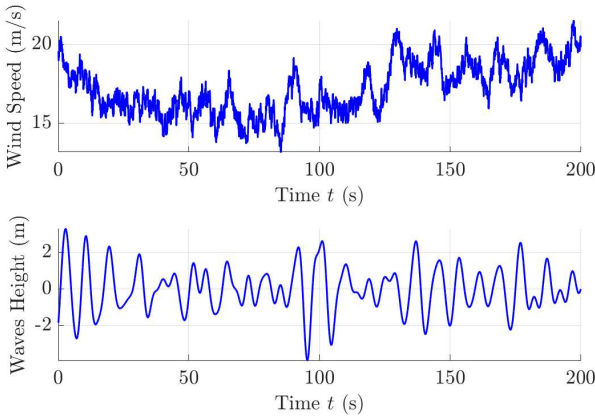


Fig. 7. Turbulent wind and wave profiles.

The baseline controller, i.e., the GSPI, was modified to include an anti-windup scheme to mitigate pitch angle saturation and prevent overshoot and oscillations. The parameters used with the GSPI are $K_P = 0.006275604$, $K_I = 0.0008965149$, and the gain correction factor $K_K = 0.109996$ [23]. The anti-windup scheme used is the back calculation with a gain of 80 (the inverse of the sampling time).

The GPIC with integral reconstruction using CCN is implemented as proposed in Fig. 6 using both the configuration of Fig. 4 and the lead compensation network in Fig. 5. The parameters of the GPIC are calculated using the pole placement technique to meet the desired dynamic response while satisfying the asymptotic stability criteria. The parameters are: $k_0 = 0.5$, $k_1 = 0.1$, and $k_2 = 80$.

The proposed GPIC was able to maintain the generator speed close to the rated speed better than the GSPI baseline controller, as seen in Fig. 8. At the same time, the generator torque varies less; therefore the electric power generated by the GPIC is more stable than that generated by the GSPI (Fig. 9). However, the pitch angle activity of the GPIC controller is much higher than the GSPI, but still within the saturation and rate limits of the pitch angle specifications (Fig. 9). Table III summarizes the comparison between both controllers. In fact, the GPIC had a Root-Mean Square Error (RMSE) of 3.6685 compared to 13.5748 to GSPI with anti-windup regarding the generator speed.

TABLE III. CAMPARISON RESULTS OF GPIC AND GSPI

Results	Control Scheme	
	GSPI with Anti-Windup	GPIC for 2 nd -Order System
Mean Generator Speed	127.5215	122.3788
Rated Gen. Speed (122.9 rad/s)		
Gen. Speed Deviation	12.7678	3.63
Minimum Gen. Speed	108.6375	110.6064
Maximum Gen. Speed	170.6754	131.8332
Gen. Speed RMSE	13.5748	3.6685
Mean Gen. Torque (kN.m)		
Rated Gen. Torque (43.1 kN.m)	41.606	42.996
Gen. Torque Deviation (kN.m)	4.6807	3.3256

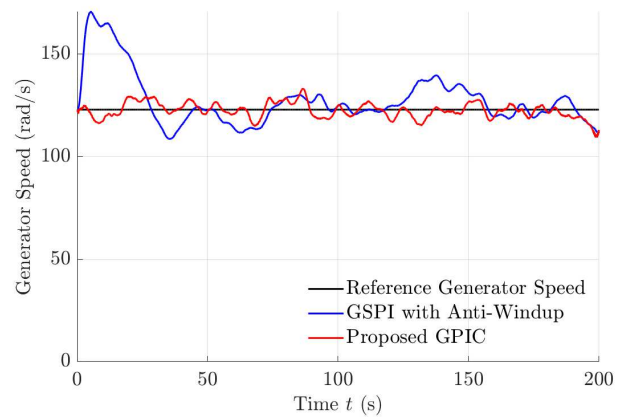


Fig. 8. Comparison of the generator speed for the GSPI with anti-windup and the proposed GPIC.

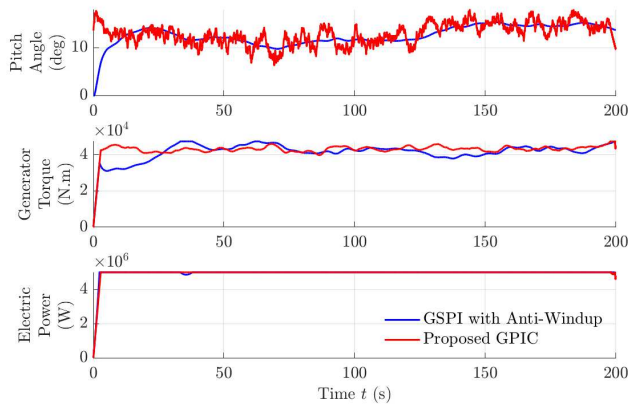


Fig. 9. Pitch angle, Generator Torque, and electric power.

V. CONCLUSIONS AND FUTURE WORK

In this paper, a model-free adaptive control using GPIC based on integral reconstruction in the form of robust CCN to control the collective pitch angle of a FOWT operating above rated wind speed (Region 3) was presented. The proposed control system was synthesized and simulated on the 5-MW NREL FOWT with OC4 Semi-submersible platform using a high-fidelity nonlinear OpenFAST model in MATLAB® Simulink®. It is then compared with an improved version of the baseline controller, the GSPI, with anti-windup under turbulent wind and waves. Results showed that the proposed controller outperforms the baseline controller in regulating the generator speed, the stability of generated electric power, and the generator torque fluctuations at the cost of more activity in the pitch angle.

Further work can be done regarding the replacement of the lookup table with an RBF (Radial Basis Function) Neural Network, as well as the investigation of higher-order controllers GPIC (third or fourth-order system), or the use of a reinterpretation of the GPIC using Flat Filters. Also, optimization work can be done on the controller parameters. In addition, the platform pitch angle should be controlled to reduce the fatigue load of the FOWT.

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