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Model Reference Adaptive Control for Load Mitigation in Floating Offshore Wind Turbines via Blade Pitch Regulation

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Abstract: Floating offshore wind turbines (FOWTs) face significant challenges in power regulation due to the inherent intermittency and fluctuations of wind resources. To address this issue, this study proposes a novel collective blade pitch controller based on Model Reference Adaptive Control (MRAC) with a constant modification term for precise generator speed regulation. Furthermore, an auxiliary feedback loop incorporating a PID controller is integrated to utilize floating platform pitch angle measurements, thereby enhancing overall system stability. Simulation results demonstrate that the proposed control strategy effectively mitigates load variations and improves power output quality, confirming its superior performance compared to conventional methods.

Keywords: FOWTs, MRAC, blade pitch regulation, load mitigation.

1. Introduction

The growing urgency to address fossil fuel depletion and climate change has markedly accelerated the global transition towards renewable energy. Among these sources, wind energy—with a long history of human utilization—has re-emerged as a pivotal technology in modern power systems. In particular, offshore wind energy has witnessed substantial recent growth. The distinction between offshore and onshore wind turbines extends beyond installation site to encompass fundamental structural differences, primarily in foundation design, which is critically influenced by water depth and seabed conditions. Floating offshore wind turbines (FOWTs), designed for deep-water deployment, present a promising solution for exploiting wind resources in extensive maritime areas. However, FOWTs inherit and exacerbate the challenge of power generation intermittency and variability common to wind turbines. While traditional gain-scheduled PI (GSPI) blade pitch controllers [1] offer partial mitigation of power fluctuations by adapting to varying wind speeds, the additional degrees of freedom introduced by the floating platform necessitate more advanced control strategies to ensure stability and performance.

The operating environment of Floating Offshore Wind Turbines (FOWTs) is highly dynamic and challenging, subject to continuous variations in wind and wave conditions. This necessitates a control system capable of maintaining robust performance under widely varying operational states. Adaptive control presents a fitting solution for this requirement, as it can automatically adjust control parameters in response to changing conditions while ensuring closed-loop stability and performance. In particular, the Model Reference Adaptive Control (MRAC) framework, pioneered by Narendra [2], employs a reference model to define the desired system response for the plant output to track. This inherent ability to enforce a prescribed performance standard makes the MRAC architecture a highly suitable candidate for generator speed regulation in FOWTs.

This paper presents the design of a collective blade pitch controller for operation in the above-rated wind speed region. The proposed control architecture, illustrated in Fig. 1, features a dual-loop structure. The primary control loop is designed based on a Model Reference Adaptive Control (MRAC) scheme, incorporating a constant-σ modification term to ensure robust generator speed regulation. The secondary loop employs a PID controller, where the gains are tuned using a P+quasi-I+D method [3,4], dedicated to suppressing pitch fluctuations of the floating platform.

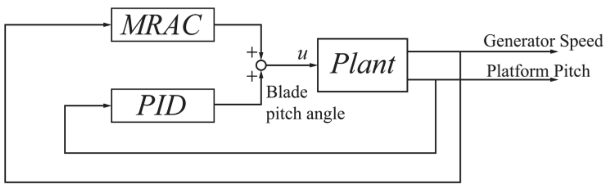

Figure 1. Overview of control system

2. Controller Design

2.1. Floating offshore wind turbine system

In this paper, we use the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) simulator that is a comprehensive aeroelastic simulator developed by the National Renewable Energy Laboratory (NREL) in the United States [5]. We consider the 5MW offshore wind turbine system with the floating platform. This is a typical three-bladed upwind turbine and has a semisubmersible substructure type platform in Table I.

Table 1. Floating Platform

Parameter	***Value***
Total Draft	20 m
Tower Base (Above water level)	10 m
Elevation to Tower Top (Above water level)	87.6 m

FAST is able to perform nonlinear simulations and has the ability to make periodic linear models for controller design. This FOWT's rated generator speed is 1173.7 rpm (12.1 rpm in the rotor speed); at above the rated wind speed region (region 3), the generator speed (rotor speed) needs to be regulated to its rated speed under disturbances. We can obtain a periodic linear state-space model at around the operating point corresponding to the wind speed 18 m/s (in region 3). We average the periodic model over one rotor revolution, which gives the time-invariant model:

$$\begin{aligned}\dot{x}_p(t)&=A_p x_p(t)+B_p u(t),\\ y_p(t)&=C_p x_p,\end{aligned} \tag{1}$$

Table 2. DOFs for linearization

q_1-q_3	*Platform translation*
q_4-q_6	*Platform rotation*
q_7-q_{10}	*1st and 2nd tower bending mode*
q_{11}	*Nacelle yaw*
q_{12}	*Variable speed generator*
q_{13}	*Drivetrain rotational-flexibility*
q_{14}-q_{16}	*1st flapwise bending-mode*
q_{17}-q_{19}	*1st edgewise bending-mode*
q_{20}-q_{22}	*2nd flapwise bending-mode*

where $x_p=[q^T,\dot{q}^T]^T \in R^{44}$ is the state and q is a vector consisting of the variables corresponding to the degrees of freedom (DOFs) shown in Table II. The measured output $y_p(t) \in R$ is the generator speed, and the input of the plant $u(t)$ is the blade pitch angle. A_p, B_p, and C_p have the compatible dimensions. The eigenvalues of A_p are in the left half of the complex plane.

We consider the reduced-order model containing the state variables $x_p=[q_{13},\dot{q}_{12},\dot{q}_{13}]^T$ and its transfer function is

$$G_p(s)=K_p \frac{Z_p(s)}{D_p(s)}, \tag{2}$$

where K_p is a constant gain, $Z_p(s)$ and $D_p(s)$ are monic polynomials with the degrees, m_p and n_p, respectively. The relative degree n^* of $G_p(s)$ is

$$n^*=n_p-m_p. \tag{3}$$

Our FOWT reduced-order model has the relative degree $n^*=1$ and this determines the structure of the reference model.

2.2. Reference Model and Adaptive Law

The basic premise of the model reference adaptive control (MRAC) system is to have the output of a plant follow a prescribed reference model through the online adjustment of control parameters. We thus need a reference model (see Fig. 2) which is given by the following transfer function:

$$G_m(s)=\frac{y_m(s)}{r(s)}=K_m \frac{Z_m(s)}{D_m(s)}, \tag{4}$$

where $y_m(s)$ is a reference output, $r(s)$ is a reference input signal, and $Z_m(s)$ and $D_m(s)$ are monic polynomials with the degrees m_m and n_m ($m_m \le m_p$), respectively. The reference model should have the same relative degree with Eq. (3) (=1). In model reference adaptive control, the plant $G_p(s)$ and the reference model $G_m(s)$ are assumed to satisfy the following conditions [6]:

The zeros of G_p are located in the left-half plane of the complex plane.

The degree n_p of D_p is known.

The relative degree n^* of $G_p(s)$ is known.

The sign of K_p is known.

G_m is strictly stable with the relative degree n^*.

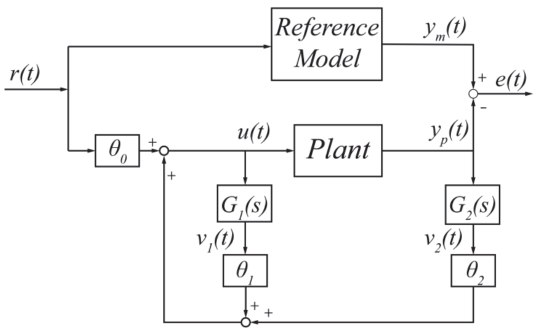

Figure 2. MRAC system

The first four conditions are for the plant and the fifth is for the structure of the reference model. The basic block diagram of MRAC system is shown in Fig. 2. An output error between the reference model output $y_m(t)$ and measured output $y_p(t)$ is

$$e(t)=y_m(t)-y_p(t). \tag{5}$$

We use the MRAC law with σ -modification for robustifying an original MRAC law that has a pure integral action [7,8]:

$$\dot{\Theta}(t)=\mathrm{sgn}(K_p)\Gamma\{\omega(t)e(t)-\sigma\Theta(t)\}(\sigma \ge 0), \tag{6}$$

where $\Theta(t)=[\theta_0(t),\theta_1(t)^T,\theta_2(t)^T]^T$ are controller parameters with $\theta_0 \in R$, $\theta_1 \in R^{m_p}$, $\theta_2 \in R^{m_p}$, $\omega(t)=[W(s)y_m(t),v_1(t)^T,v_2(t)^T]^T$. Here, $W(s)=s+0.0001$ and Γ is a real symmetrical matrix. The input of plant is written as

$$u(t)=\Theta(t)^T\omega(t). \tag{7}$$

As not all state variables are measurable in the FOWT, we apply filters to $u(t)$ and $y_p(t)$. The signals, v_1 and v_2, are the states of the n_p dimensional filters, G_1 and G_2:

$$\begin{aligned} G_1(s)&:\dot{v}_1(t)=F_1v_1(t)+g_1u(t),\\ G_2(s)&:\dot{v}_2(t)=F_2v_2(t)+g_2y_p(t), \end{aligned} \tag{8}$$

where F_i is an $n_p\times n_p$ stable matrix and each (F_i,g_i) is a controllable pair $(i=1,2)$.

2.3. Auxiliary Feedback Loop

For the FOWTs, the fluctuation of the platform pitch angle has an influence on the wind turbine system such as generator speed. We add an auxiliary blade pitch controller having the platform pitch angle as its measurement (Fig. 3).

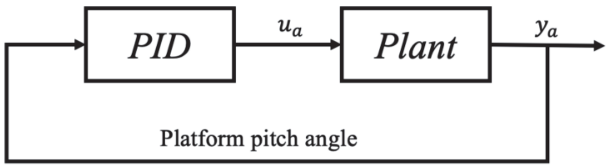

Figure 3. Auxiliary feedback loop

We use the linear time-invariant plant with full DOFs obtained from FAST,

$$\begin{aligned} \dot{x}_p(t)&=A_px_p(t)+B_pu_a(t)\\ y_a(t)&=C_ax_p(t) \end{aligned} \tag{9}$$

and consider a PID controller $K(s)$. In Eq. (9), $y_a(t)\in R$ is the platform pitch, and the system (A_p,B_p,C_a) is controllable and observable. We define $z(t)=\int_0^t y_a(\tau)-Dz(\tau)d\tau$, where $D\in R$ is a positive real parameter, and consider the PID law of the form,

$$u_a(t)=-K_py_a(t)-K_iz(t)-K_d\dot{y}_a(t) \tag{10}$$

where K_p, K_i, K_d are the gains of the PID controller. We design the PID gain parameters using the method described in [4].

In this study, the adaptive control system has two feedback loops. One is the model reference adaptive control loop with generator speed as feedback, which is the main loop of this study. The other is the PID control loop based on the floating platform pitch angle as the auxiliary loop.

2.4. Parameter Design

Using the FAST linearization tool with the full DOFs being activated, we get the linear time-invariant model Eq. (1) and reduced-order model Eq. (2).

The poles of the reduced-order model are P_p=[-1.7098+ 21.2287i,-1.7098-21.2287i,-0.1308], which lie in the left-half complex plane. We use a reference model with relative degree $n_m^*=1$,

$$G_m(s)=\frac{s^2+4.999s-0.005}{s^3+6s^2+11s+6} \tag{11}$$

The poles of the reference model are P_m=[-1,-2,-3]; obviously, all of them are negative, and the reference model is stable. For the parameter filters Eq. (8), we design F_1 so that it has the same poles as P_p but the different zeros. F_2 has the same poles as P_m. F_1, F_2, g_1 and g_2 are as follows:

$$F_1=\begin{bmatrix} -0.1038 & 0 & 0\\ -1.1038 & -3.4169 & -21.2974\\ 0 & 221.2974 & 0 \end{bmatrix} \tag{12}$$

$$F_2=\begin{bmatrix} -1 & 0 & 0\\ 0 & -2 & 0\\ 0 & 0 & -3 \end{bmatrix} \tag{13}$$

$$g_1=[1 \quad 1 \quad 0]^T, g_2=[1 \quad 2 \quad 1]^T \tag{14}$$

The pairs (F_1,g_1) and (F_2,g_2) are both controllable. Then, for this system we use the constant σ-modification, σ=0.001.

For the auxiliary feedback loop, the resulting PID gains are computed as K_p=-1.9364, K_i=0.03, and K_d=0.1016.

3. Simulation

In this section, we will present the simulation results by FAST nonlinear simulator. We compare the proposed MARC and MARC without auxiliary loop to the GSPI controller designed by Jonkman. We simulated under two different conditions. One simulation condition is under the uniform wind with step change as shown in Fig. 4, where the profile over an interval [250, 300] is plotted. Another condition is a turbulent wind having an average of 18 m/s. All simulations are under the same random waves shown in Fig. 5.

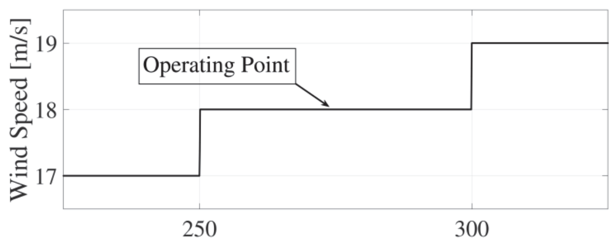

Figure 4. Wind speed

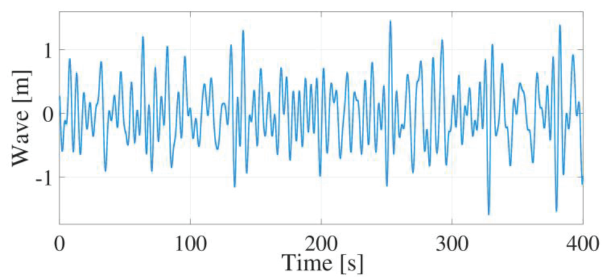

Figure 5. Wave

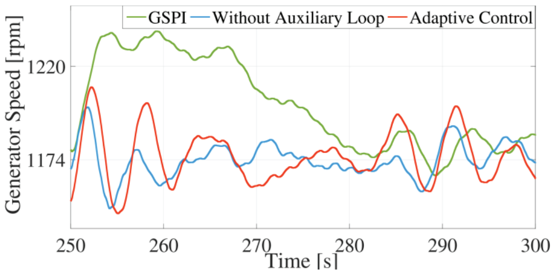

Figure 6. Generator speed

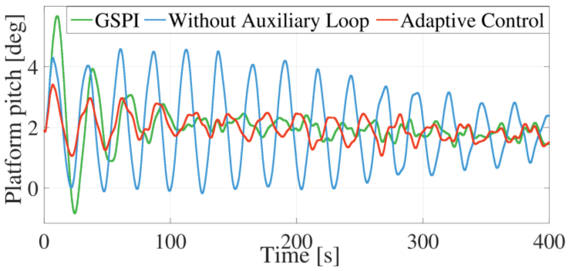

Figure 7. Platform pitch angle

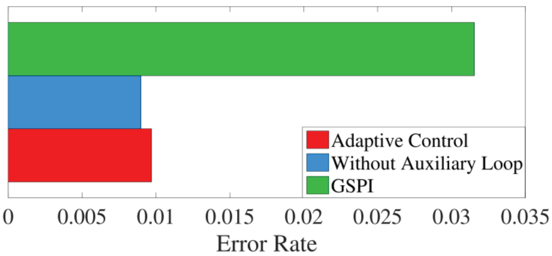

Figure 8. Generator speed error rate

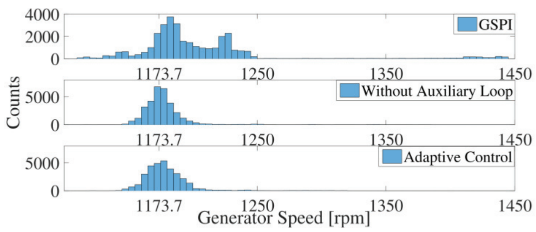

Figure 9. Generator speed distribution

Fig. 6 shows the results of generator speed. We can see that when the wind speed is stepped, the GSPI control (green line) shows a slower convergence to the rated value than other controls. Fig. 7 shows the floating platform pitch. The MRAC without auxiliary feedback loop (blue line) fluctuates significantly and the damping is weak. The proposed MARC (red line) has a better response.

In order to show the deviation of each control result from the rated value, sampling the continuous generator speed signal with a sampling time of 0.0125s, and we calculate error rate

$$E_{rate}=\frac{1}{N_s}\left(\sum_{t=0}^{Tmax}\frac{\left|y_{gen}(t)\text{-rated value}\right|}{\text{rated value}}\right), \qquad (15)$$

where $y_{gen}(t)$ denotes the generator speed and N_s is the number of sampling points; the result is shown in Fig. 8. For the entire simulation process, the generator speed deviation value of GSPI is the largest, while the generator speed deviation value of the proposed controller is better. To compare the performance among the three control laws, the distributions of the generator speeds are computed and shown in Fig. 9. The proposed MRAC shows the best regulation performance to the rated value. Only the MRAC controller with the auxiliary control loop has the same excellent control performance in terms of generator speed and floating platform pitch angle. Next, we carry out nonlinear simulation under the turbulent wind condition with an average speed of 18m/s (Fig. 10), and wave in Fig. 5.

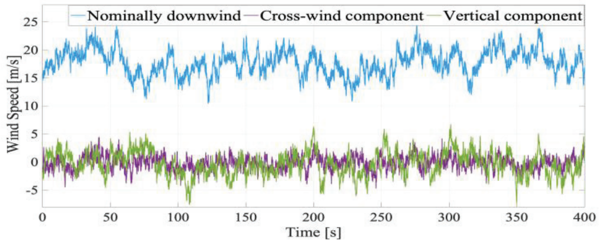

Figure 10. Wind speed

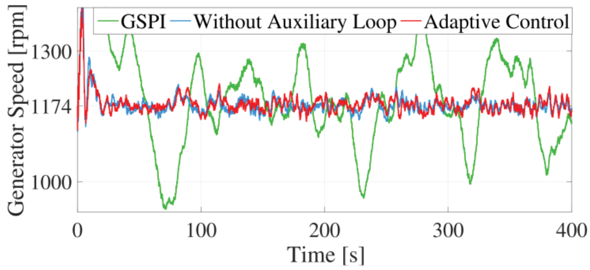

Figure 11. Generator speed

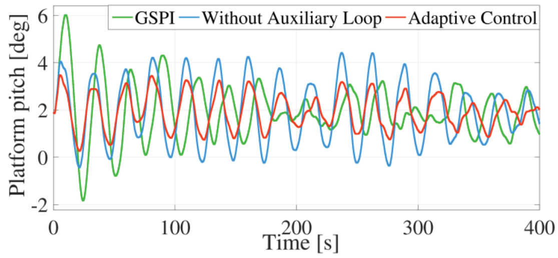

Figure 12. Platform pitch angle

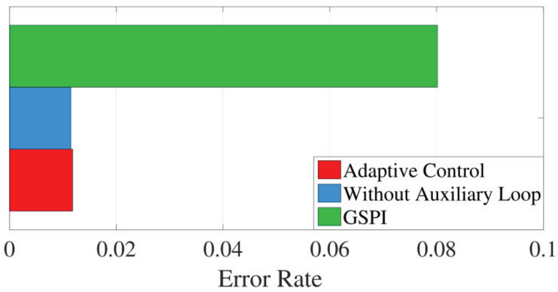

Figure 13. Generator speed error rate

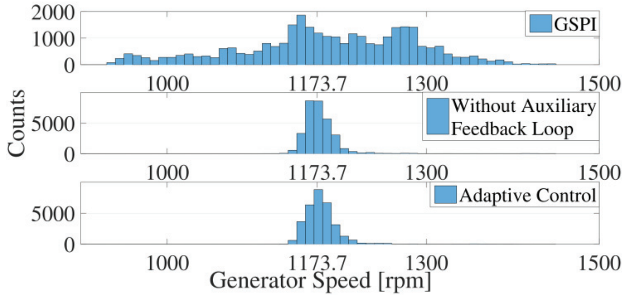

Figure 14. Generator speed distribution

We can see that the generator speed response of GSPI has a large fluctuation in Fig. 11; the proposed controller succeeds in regulating the response around the rated value. Fig. 12 shows that the platform pitch response of the proposed controller has an improved performance. It can be seen from Fig. 13 that generator speed error rate (MRAC) is far less than GSPI. The generator speed distribution around the rated value is investigated and shown in Fig. 14. The conducted nonlinear simulations show that the proposed MRAC law shows a good performance on the regulation of the generator speed and suppression of the platform pitch fluctuation.

4. Conclusions

This paper presented a Model Reference Adaptive Control (MRAC) law with "σ" -modification for collective pitch control of floating offshore wind turbines. The overall control architecture integrates the proposed adaptive law with an auxiliary feedback loop designed to stabilize platform pitch motion. Simulation studies validate the advantages of incorporating both the "σ" -modification term, which ensures bounded adaptation, and the auxiliary loop for enhanced structural damping. A comparative analysis with a conventional gain-scheduled PI (GSPI) controller demonstrates the superior performance of the proposed strategy, particularly in generator speed regulation and load mitigation. Future work will focus on replacing the constant "σ" -modification with a switching modification scheme to further improve the system's robustness against extreme and transient environmental conditions.

Acknowledgment

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