Effect of Pitch Control on the Performance of an Offshore Floating Multi-Wind-Turbine Platform

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Abstract. The extraction of wind energy from more reliable deep-water offshore wind resources can be advanced by using a multi-wind turbine platform that can reduce mooring and installation costs. This paper describes the results of research aimed at designing a novel semi-submersible platform for placing multiple wind turbines. The offshore floating multi-wind turbine platform (OFMWTP) hosts five 8 MW wind turbines which is proposed for installing on the gulf coast of the United States. The principal problems that have been addressed here include analyzing the effects of blade pitch control on the performance of the OFMWTP in the above-rated wind speed operating conditions. In this process, the adaptive control techniques vary the blade pitch angle for generating optimum power production and reduce platform motions. The coupled dynamics of the wind turbines with the platform are formulated considering the aerodynamic, hydrostatic, hydrodynamic, and mooring forces. In this study, the adaptive control algorithm designed in previous work is used for the blade pitch control. The wind speed distribution with 15% turbulence intensity and irregular waves with zero degrees incident wave angle is used for simulating the operating conditions. The performance of the adaptive control is compared to a baseline proportional-integral (PI) controller. Simulation results showed that the adaptive controller significantly improves the rotor speed regulation and reduces the fluctuations in generated output power under varying operating conditions.

1. Introduction
Currently, due to technological advancements, there are more offshore wind turbines considered and installed around the globe. When moving to farther water depths, the floating wind turbine platforms can enable the harness of abundant and reliable wind energy resources without any visual concerns or environmental impacts [1]. The installation and mooring costs can be reduced by employing multiple wind turbines on a single floating platform that can also increase stability [2]. The multi-floater concept can generate substantial amounts of wind energy at competitive prices with the current technological developments [3-5]. However, the coupled aerodynamic and hydrodynamic loads acting on the offshore floating multi-wind turbine platform (OFMWTP) can significantly affect power production hence reducing these loads is a challenging part of the design phase of the overall system. The control system is a key component for improving the wind turbine efficiency that can ensure rated power production as well as reduce the loads. The main idea of this research is to analyze the effects of blade pitch control on the performance of offshore floating multi-wind-turbine platform designed in the previous work [6-8].

This paper presents the results of the ongoing research at designing an offshore floating semi-submersible platform for arranging multiple wind turbines. The coupled dynamics of the OFMWTP is
formulated by considering all the forces acting on the system. The state-space representation of the dynamic equations is used to simulate the system in MATLAB Simulink. The adaptive control algorithm designed in the previous work [9] is summarized which is used for the blade pitch control in this study. The effect of the adaptive control of the blade pitch angle on the performance of the OFMWTP is analyzed for the wind speeds higher than the rated wind speed. The performance parameters considered for the analysis are generated output power, platform surge, heave, and pitch motion. The adaptive control is used in this study because of its effectiveness in dealing with the highly nonlinear model with unknown parameters and complicated operating conditions [10-12]. The control performance of the adaptive controller is compared to a baseline proportional-integral (PI) controller to validate its effectiveness.

The rest of the paper is organized as follows. The dynamics, state-space representation of the model, and the adaptive control algorithm are provided in section II. In section III, the simulation results of the OFMWTP are presented. Conclusions and suggestions for future work are provided in section VI.

2. Materials and Proposed Methodologies
The OFMWTP modeled in previous work [6-8] is used in this study. The platform has five 8MW wind turbines mounted on the cylindrical columns that are connected with the pontoon structures. The platform is designed to minimize the wake effects between the wind turbines and to generate power output approximately equal to the rated power. The overall properties of the platform can be summarized as given in Table 1.

| Property                    | Value       |
|-----------------------------|-------------|
| Wind turbine rated power    | 8 MW        |
| Rotor diameter              | 164 m       |
| Rated wind speed            | 12.5 m/s    |
| Nominal rotor speed         | 1.1 rad/s   |
| Water depth                 | 250 m       |
| Draft                       | 20 m        |
| System mass including ballast | 37,839,000 kg |
| Roll inertia                | 8.667 x 10^{11} kg.m² |
| Pitch inertia               | 4.452 x 10^{11} kg.m² |
| Yaw inertia                 | 1.209 x 10^{12} kg.m² |

2.1. Governing Equations
The dynamics of the structure is formulated using a 6 DOF rigid platform assumption. Based on Newton’s II law of motion, the equation of motion for the coupled platform and wind turbines can be written as

\[(M + A)\ddot{u} = \sum_{T=1}^{5} F_{AD}^T + F_{HS} + F_{HD} + F_M\]  

(1)

where \(M\) is a generalized inertia matrix containing mass and moment of inertia components, \(A\) is an added inertia matrix, \(\sum_{T=1}^{5} F_{AD}^T\) is the summation of the aerodynamic forces from the five wind turbines, \(F_{HS}\) is the hydrostatic force, \(F_{HD}\) is the hydrodynamic force, \(F_M\) is the mooring line forces and \(\ddot{u}\) is the acceleration vector.

The aerodynamic thrust force \((T)\) acting on the wind turbine rotor blades and the aerodynamic torque \((Q)\) that the wind exerts on the rotor of the wind turbine are expressed as

\[T = \frac{1}{2} \rho_{air} A_r C_T(\lambda, \beta) v^2 ; \quad Q = \frac{1}{2} \rho_{air} A R C_Q(\lambda, \beta) v^2\]  

(2)
where $\rho_{\text{air}}$ is the density of the air, $A_r$ is the rotor swept area, $R$ is the rotor radius, $v$ is the wind speed, $C_p$ and $C_q$ are the aerodynamic thrust and torque coefficients as a function of pitch angle, $\beta$, and tip speed ratio, $\lambda$, respectively. The thrust force is applied horizontally in the direction of the wind and the torque is applied as a horizontal torque vector in the direction of the wind by assuming that the rotor is aligned into the wind at all times [13].

The hydrostatic restoring forces can be expressed as follows

$$ F_{HS} = -K_h u(t) ; \quad K_h = [C_{ij}] \quad i,j = 1,2,\ldots,6 $$

where $u$ is the displacement vector and $K_h$ is the hydrostatic restoring coefficient matrix with $C_{33} = -\rho_s g A_0$, $C_{44} = -mg G M_X$, $C_{55} = -mg G M_Y$ and the remaining elements are zero. $A_0$ is the waterplane area, $m$ is the mass of the body, $\rho_s$ is the seawater density, $g$ is gravity, $G M_X$ and $G M_Y$ are the metacentric heights in the X and Y direction respectively [14,15].

The hydrodynamic force acting on the support platform is given by

$$ F_{HD} = F^\text{wave} - \int_0^t K_k(t - \tau) \dot{u}(\tau) d\tau $$

where the first term describes the total excitation load due to incident waves and the second term is the additional load contribution from the wave-radiation. $\dot{u}$ is the velocity vector, $t$ is a dummy variable, and $K_k$ is the wave-radiation-retardation kernel matrix [16]. The wave excitation force can be expressed as

$$ F^\text{wave}_{HD} = \sum_{n=1}^N A_{jn} A_n \cos(\omega_n t + k_n \bar{x} \cos \theta + k_n \bar{y} \sin \theta + \phi_{jn} + \phi_n) $$

where $A_n$ is the incident wave amplitude, $\omega_n$ is the wave frequency, $k_n$ is the wavenumber, $\theta$ is the wave incident angle, $(\bar{x}, \bar{y})$ is the mean horizontal offset of the structure, $\phi_n$ is the randomly generated phase, $A_{jn}$ and $\phi_{jn}$ are the amplitude and phase of the $n^{th}$ excitation harmonic in the $j^{th}$ DOF respectively.

A linearized model of the mooring system can be used to represent the mooring line restoring forces as follows

$$ F_M = -K_m u(t) $$

where $K_m$ is the mooring stiffness matrix and $u$ is the displacement vector.

2.2. State Space Representation

The equation of motion can be rewritten by rearranging the linear terms that depend on accelerations, velocities, and displacements together as follows:

$$ M \ddot{u} + D \dot{u} + K u = F $$

Equation (7) can be converted to a traditional state-space representation as follows

$$ \dot{x} = A x + B f_u $$

$$ y = C x $$

where

$$ A = \begin{bmatrix} -M^{-1}D & -M^{-1}K \\ I & 0 \end{bmatrix} ; \quad B = \begin{bmatrix} -M^{-1} \\ 0 \end{bmatrix} $$

$$ x = \begin{bmatrix} \ddot{u} \\ \dot{u} \end{bmatrix} ; \quad f_u = \begin{bmatrix} F \\ 0 \end{bmatrix} $$

In this system $x$ is the state vector, $f_u$ is the nonlinear input vector, $y$ is the output vector, $A$ is the system matrix, $B$ is the input matrix and $C$ is the output matrix.

2.3. Adaptive Control

The adaptive control algorithm developed in previous work [9] is used in this simulation. The main objective of this algorithm is to find a control input that follows the output of the reference model given by
\[ \dot{x}_m = A_m x_m + B_m u_m \]
\[ y_m = C_m x_m \]  
\[ (10) \]

where \( A_m \), \( B_m \), and \( C_m \) are the state, input, and output matrices of the reference model. The adaptive control signal \( (u_p) \) composed of the error in the feedback, the model states, and the model input in the feed-forward is given below as
\[ u_p(t) = K_e(t) e_y(t) + K_x(t) x_m(t) + K_u(t) u_m(t) \]  
\[ (11) \]

where \( K_e(t) \), \( K_x(t) \), and \( K_u(t) \) are adaptive gains on error, model state, and model input, respectively, and \( e_y(t) \) is the output error.

The state-space system described in the previous section is implemented in MATLAB Simulink to analyze the effects of adaptive blade pitch control on the performance of the OFMWTP operating under coupled wind-wave conditions. The adaptive control algorithm implemented on the floating platform is as shown in figure 1. The reference value of the nominal rotor speed is fed from the reference model into the adaptive pitch controller where the error value between the calculated rotor speed and the reference value is evaluated. The pitch angle is the adaptive control \( (u_p) \) signal given as input to the system plant where the output parameters are estimated by considering a constant generator torque value.

The baseline proportional-integral controller is used as the reference controller for performance comparison. The gain scheduling of the PI controller at above-rated wind speeds is done to drive the proportional and integral gains. The proportional gain is a function of the blade pitch angle, the gain scheduling function \([17-21]\).

3. Simulation

The focus of this study is on the OFMWTP operating in the above-rated wind speed region where the rotor speed is regulated to generate rated power by varying the blade pitch. Therefore, the primary objective of the adaptive controller is to minimize the power fluctuations of the floater and the secondary objective is to minimize the platform motions and maintain structural safety. The adaptive controller performances are evaluated for the mean stochastic wind speed of 18 m/s with 15% turbulence intensity and 2 m/s wind speed fluctuations. The wave data is generated with irregular waves of significant wave height equal to 4m and peak spectra period of incident waves equal to 9 seconds.

3.1. Results

The results of the performance parameters of the floater are presented in this section. The conventional PI control is used as a reference controller to compare the performance of the calculated parameters of the OFMWTP using an adaptive controller. The wind speed distribution and wave surface elevation used for the runtime simulation of 600 seconds are shown in figure 2 and figure 3 respectively.
In this paper, the main focus is on the effect of the blade pitch control on the generated power, platform surge, platform heave, and platform pitch motion respectively. The blade pitch angle variation of a selected wind turbine is depicted in figure 4. The pitch angle is varied by the adaptive controller based on the error value between the reference rotor speed and the calculated rotor speed. As the pitch angle is varied, the pressure on the lower surface of the blade and hence the torque force is varied which in turn varies the rotor speed to maintain the generated output power at its rated capacity. It can be observed that the pitch angle change rate in the adaptive control is smaller relative to the PI controller. The rotor speed regulation of the selected wind turbine in the above-rated wind speed region is shown in figure 5. The generated output power of a selected wind turbine is shown in figure 6. The power output follows the rotor speed due to the constant generator torque value in this operating region. These results show that there is a significant reduction in fluctuations of rotor speed and power output with the adaptive control implementation in comparison to the PI controller.

The maximum, mean, and minimum values of the rotor speed and generated power of a selected wind turbine are summarized in Table 2. The mean values of rotor speed for both the controllers are approximately the same as the nominal rotor speed value of 10.5 rpm which is also true for the generated power. The mean values of the generated power are approximately equal to the rated power capacity of 8 MW.
Figure 6. The power output of a selected wind turbine.

Table 2. Control performance comparison.

| Parameter        | PI Control | Adaptive |
|------------------|------------|----------|
| Rotor Speed      | Maximum    | 14.31 rpm| 12.62 rpm|
|                  | Mean       | 10.39 rpm| 10.42 rpm|
|                  | Minimum    | 8.02 rpm | 9.25 rpm |
|                  | Maximum    | 9.65 MW  | 8.88 MW  |
| Generated Power  | Mean       | 7.83 MW  | 7.84 MW  |
|                  | Minimum    | 6.81 MW  | 7.36 MW  |

The floating platform surge, heave, and pitch motions are depicted in figure 7, figure 8, and figure 9 respectively.

Figure 7. Surge motion of the platform.  
Figure 8. Heave motion of the platform.

The platform surge motion response shows that adaptive control reduces the peak amplitudes of the surge motion relative to the PI controller. The heave motion response in both the controllers follows the same profile. The platform pitch motion also has lower peak amplitudes with the adaptive control than the PI controller. The power output from the five wind turbines is summarized in Table 3. It shows that the power is equal to the rated capacity as expected in the region 3 operating conditions. In this study, the mean wind speed at hub height is 18 m/s which is higher than the rated wind speed of 12.5 m/s.
Figure 9. Pitch motion of the platform.

Table 3. The power output of wind turbines.

| Wind Turbine | Maximum | Minimum | Mean  |
|--------------|---------|---------|-------|
| Wind Turbine 1 | 8.879 MW | 7.361 MW | 7.837 MW |
| Wind Turbine 2 | 8.709 MW | 7.351 MW | 7.832 MW |
| Wind Turbine 3 | 8.461 MW | 7.343 MW | 7.816 MW |
| Wind Turbine 4 | 8.542 MW | 7.289 MW | 7.818 MW |
| Wind Turbine 5 | 8.215 MW | 7.096 MW | 7.671 MW |

It is important to note that turbine 5 which is in partial wake of the upstream turbines also generates reasonable power since the generation of power is not affected much at high wind speeds [3]. However, it is also important to note that the power generation can be affected when the wind turbines are operating at wind speeds near the rated conditions which are shown in the previous work [7]. The OFMWTP modeled in previous work based on the wake analysis between the turbines can be used to exploit the abundant offshore wind resources by employing the proposed adaptive pitch control strategy.

4. Conclusions
The controller is a key component of a wind turbine for regulating the power output and also reducing the loads. The coupled dynamics of the OFMWTP operating under turbulent wind and irregular wave conditions are formulated. The adaptive control designed in previous work is used for the blade pitch control of the wind turbine. The effect of the blade pitch control on the performance parameters like generated power and platform motions is studied. The control performance of the adaptive blade pitch control proved to be better than that of a baseline proportional-integral controller. The blade pitch change rate of the adaptive control is smaller than the PI controller. There is a significant reduction of fluctuations in the rotor speed and generated output power with the implementation of an adaptive controller. The platform motions also showed fewer peak amplitudes in case of surge and pitch motion responses. The heave motion response is similar for both the controllers. The generated power for all the five wind turbines showed to be approximately equal to the rated power capacity. The generated power for the turbine in the partial wake of upstream wind turbines is not affected much since the turbines are operating in high wind speed regions. The adaptive control can be employed for the OFMWTP when operating in wind speeds greater than rated wind speeds. This control strategy can also be tested for other operating regions near the rated wind speeds. In this study, the simulation is carried out by assuming the wind turbines facing the wind at all times. This can also be tested by designing a comprehensive yaw control of the platform to position the turbines in wind direction.
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