Design and performance analysis of control algorithm for a floating wind turbine on a large semi-submersible platform

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Abstract. A control algorithm for a floating wind turbine installed on a large semi-submersible platform is investigated in this study. The floating wind turbine is different from other typical semi-submersible floating wind turbines in that the platform is so large that the platform motion is not affected by the blade pitch control. For simulation, the hydrodynamic forces data were obtained from ANSYS/AQWA, and implemented to Bladed. For the basic pitch controller, the well-known technique to increase damping by reducing the bandwidth of the controller lower than the platform pitch mode was implemented. Also, to reduce the tower load in the pitch control region, a tower damper based on the nacelle angular acceleration signal was designed. Compared with the results obtained from an onshore wind turbine controller applied to the floating wind turbine, the floating wind turbine controller could reduce the tower moments effectively, however, the standard deviation in power increased significantly.

1. Introduction

It is a well-known technique in the control of floating offshore wind turbines to select the bandwidth of the blade pitch control lower than the platform pitching mode to avoid the platform pitching instability caused by collective pitch motions [1]. Also, to reduce the tower moments, an additional feedback on the pitch loop based on the nacelle acceleration or angular acceleration is used [2,3]. In this study, the well-known collective pitch control and the tower damper to reduce loads are designed for a floating wind turbine installed on a large semi-submersible platform. It is different for typical semi-submersible floating wind turbines in that it is installed on such a large floater that the platform motion affects the wind turbine but the blade pitching doesn't affect the platform motion. Therefore it is considered as a one-way aero-hydrodynamic coupling. The performance of the floating wind turbine control algorithms were compared with onshore wind turbine control algorithms by dynamic simulation for various wind speeds.

2. Approach and methods

2.1. Simulation Model

In this study, a wind turbine similar to the NREL 5MW paper wind turbine was used for simulations. It is a variable speed variable pitch upwind wind turbine and has a rated power of 3 MW. The specification of the wind turbine is shown in Table 1. Table 1 also includes the information of the platform. As shown in the table, the platform is square with a length of 158.5 m. The platform has twelve mooring lines. Wind turbines are installed at the corners of the platform, and therefore, four wind turbines are installed [4].

Table 1. Summary of wind turbine properties.

Rated Power	3 MW
Rotor Orientation	Upwind
Control	Variable Speed, Variable Pitch
Rotor Diameter	105 m
Hub Height	62 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 12 m/s, 25 m/s
Cut-In, Rated Rotor Speed	8 rpm, 17 rpm
Overhang, Tilt, Precone	5 m, 5 deg, -2.5 deg
Tower Mass	228,400 kg
Platform Size	158.5m x 158.5m x 25m
Platform Mass	21,740,000 kg
Platform Roll Inertia	81,027,611,028 kgm^2
Platform Pitch Inertia	80,917,761,712 kgm^2
Platform Yaw Inertia	146,723,078,754 kgm^2
Draft	-12.5 m
Water Depth	80 m
Number of Mooring Lines	12 EA
Anchors Depth	80 m
Chain Diameter	0.1365 m
Wet Weight	324.3 kg/m
MBL	16893 kN
Axial Stiffness	1496 MN
Mooring Line Length	600 m

For dynamic analysis of floating wind turbines with waves and winds, DNV GL's Bladed was used. Since the floating structure is large and complicated, hydrodynamic load from diffraction and radiation around the waves are highly important. Therefore, the wave load calculated by boundary element methods from ANSYS/AQWA was implemented to Bladed.

Also, Because Bladed can simulate only a single wind turbine, a single wind turbine was modeled on one corner of the platform, and the towers with concentrated masses equivalent to the nacelle mass including the rotor on the top were modeled in Bladed. The effect of a single wind turbine on the yaw of the platform was assumed to be small because of the large size of the platform and the one way aero-hydrodynamic coupling of the system. Figure 1 shows the bladed model for dynamic simulation with different wind turbine controllers and also the ANSYS/AQWA model to extract the radiation impulse response function of the system

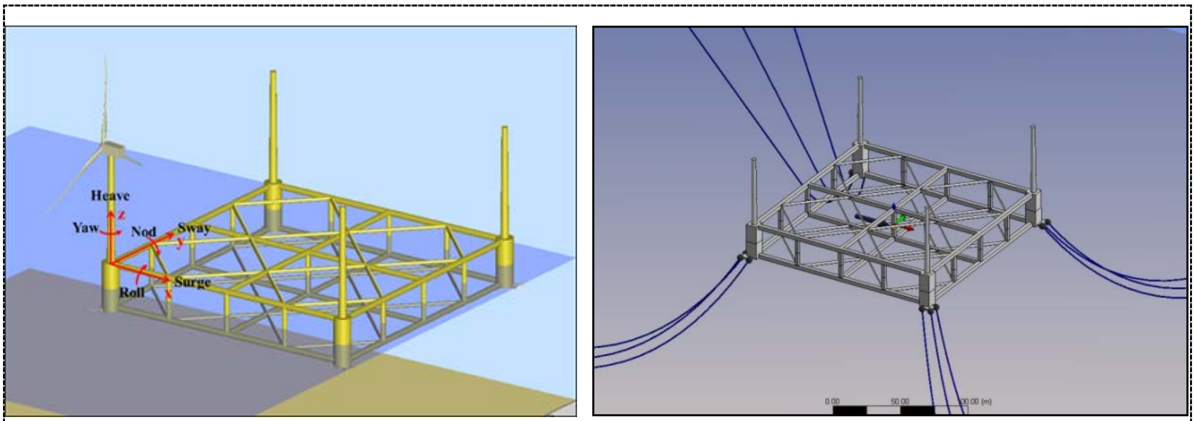

Figure 1. Wind Turbine Model (Left : Bladed, Right : ANSYS/AQWA)

To select the right proportional gain of the collective pitch controller to achieve the control frequency of the system lower than the platform pitch mode, the platform pitching mode was obtained from ANSYS/AQWA and found to be about 0.4rad/s. The platform pitch mode was double checked with the Campbell diagram obtained from Bladed. Figures 2 and 3 show the results on the modal frequencies obtained from both ANSYS/AQWA and Bladed, respectively. As shown in the Campbell diagram in Fig. 3, the 3P frequency line crosses the first mode of the tower vibration around 12 RPM and the tower can be resonated. Therefore, a control algorithm was applied not to keep the rotor speed in the vicinity of 12 RPM, and finally to avoid resonance.

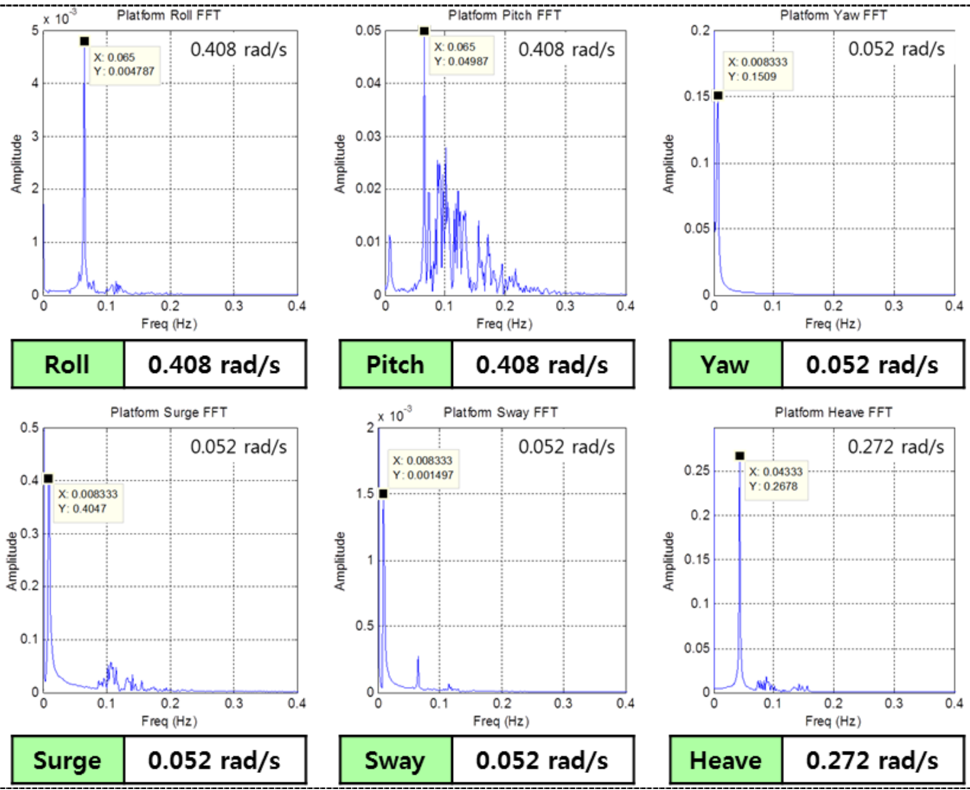

Figure 2. FFT analysis results

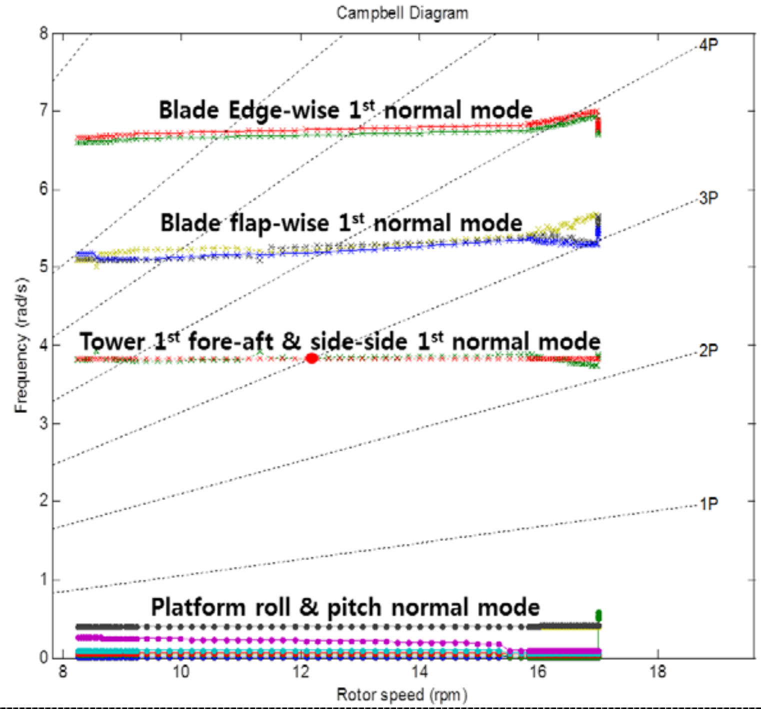

Figure 3. Campbell diagram

2.2. Simulation

The control scheme of the wind turbine is shown in Fig. 4. Based on Fig. 3, the wind turbine controller receives signals including the generator speed, pitch angle, electrical power, and nacelle angular speed from the wind turbine, and use them to calculate output commands. It is a basic torque and pitch control algorithm with a tower vibration damper. The gain scheduling was used for the pitch control to keep the sensitivities of the generator speed change by the pitch change for different wind speeds close. Also the controller included a power tracking algorithm to match the power demand from a higher-level wind farm controller. If the power demand from a wind farm controller is lower than the available power of the wind turbine, the generator torque is set to be the value which is the same as the generator torque at that power for max-Cp control, and the pitch angle is adjusted to achieve the rotating speed of the generator same as the value at that power for max-Cp control. For simulations, turbulent winds based on the normal turbulence model in IEC-61400-1 Ed3 normal turbulence model at the speeds of 12 m/s to 25m/s were used. Also for the wave, a JONSWAP spectrum which has a significant wave height of 3.5m, a period of 9 seconds, and a peak enhancement factor of 2.2 was used. All of the simulations were conducted in normal operation conditions for power production.

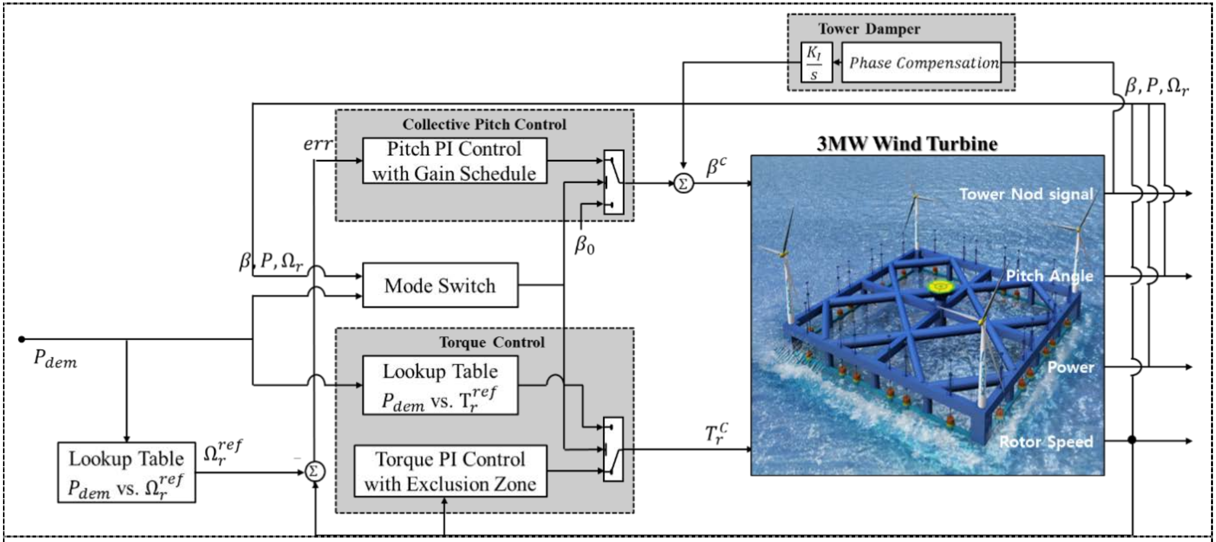

Figure 4. Schematic of Control Algorithm

3. Results

Figure 5 shows the simulation results on the mean power, power standard deviation, in-plane and out-of-plane bending moments at the tower root with respect to the wind speed. It also shows the results for three different cases. One is the case when the onshore wind turbine controller was applied to the onshore wind turbine (Onshore_1.0_damper, crossover frequency: 1.0), the other is the case when the onshore wind turbine controller was applied to the floating wind turbine without any gain changes of the controller (Semi_1.0_damper, crossover frequency: 1.0), and the third is the case when the floating wind turbine controller was applied to the floating wind turbine (Semi_0.3_sw, crossover frequency: 0.3).

When the onshore wind turbine controller was applied to the floating offshore wind turbine, the mean electrical power was slightly reduced with a maximum of 2 % compared to the electrical power obtained with the onshore wind turbine controller applied to the onshore wind turbine. Also, the standard deviation in power was increased by up to 72%, and the tower root bending moments were increased by up to 187% for the in-plane direction and by up to 61% for the out-of-plane direction.

When the floating wind turbine controller was applied to the floating offshore wind turbine, the standard deviation in power increased a lot by up to 501 % compared with the results obtained for the onshore wind turbine controller applied to the onshore wind turbine. However, the in-plane and out-of-plane bending moments at tower bottom decreased by 38.1% and 16.9%, respectively.

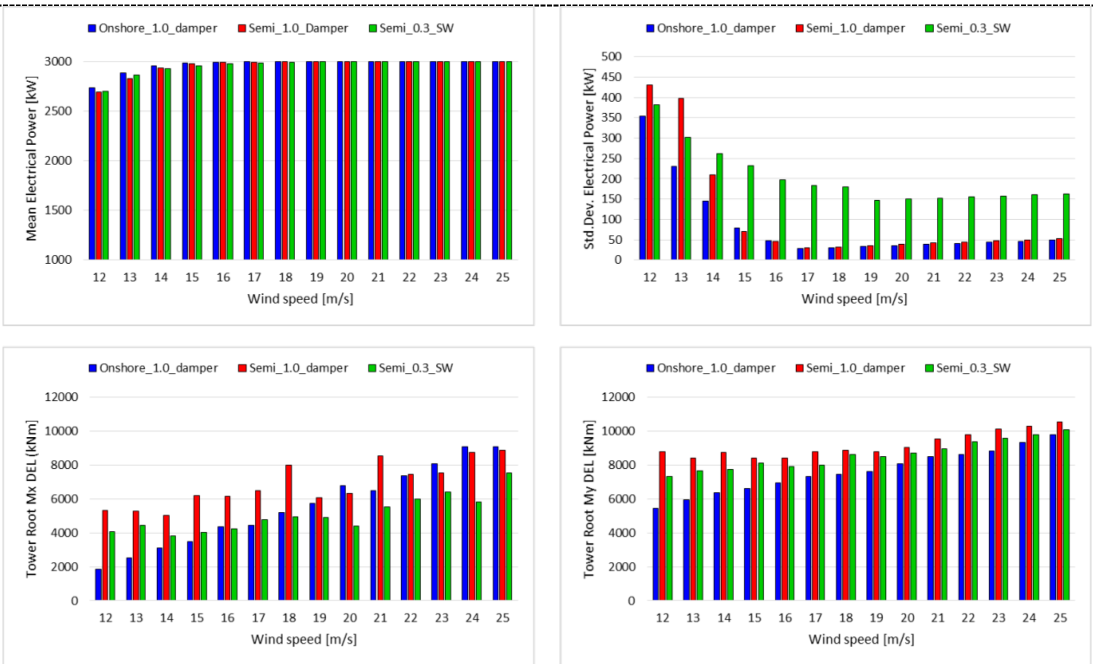

Figure 5. Results of Simulation for Bandwidth

Figure 6 shows the platform behaviour for different control frequencies of the collective pitch control. The average wind speed is 18 m/s. Based on the figure, the platform behaviour is found not to to be affected by the control frequency change. Therefore, the control frequency affects the power fluctuation and the tower load but doesn't affect the platform motion in the current setup. Based on the results, the wind turbine installed on the large semi-submersible platform seems to have a one-way coupling characteristic. That is, the platform motion created by the sea wave affects the wind turbine motion but the wind turbine motion created by the blade pitch control doesn't affect the platform motion. Therefore, although the bandwidth of the blade pitch control is higher than the platform pitch mode and drive the mode, the platform pitching motion doesn't become amplified and unstable.

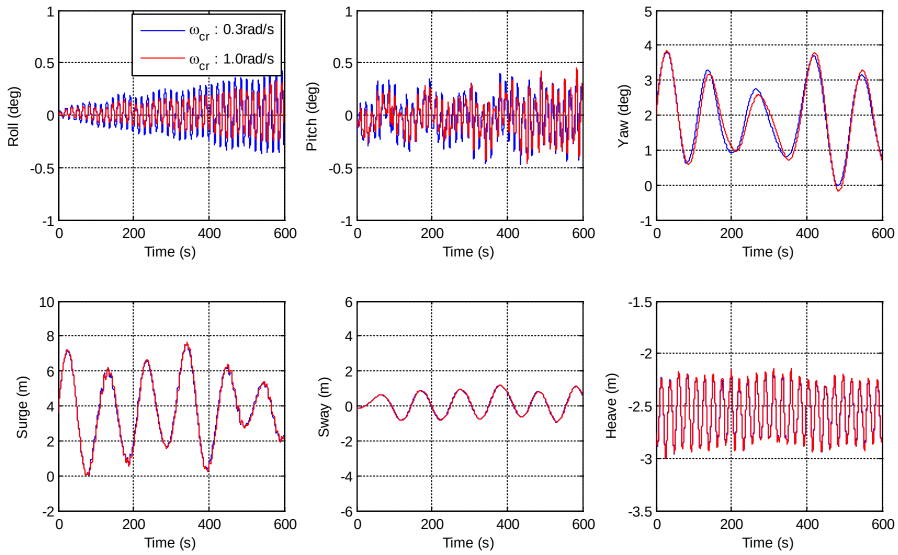

Figure 6. Platform Global Positions

Figure 7 shows the effect of the tower vibration damper on the onshore and floating cases. In the case of onshore, the tower root bending moment My was reduced by an average of 14%, while an average of 4% load reduction was found for the floating case. Thus, the effect of tower damper is not as good comparing to the onshore. Also the tower vibration damper made the power fluctuation slightly worse for the floating case.

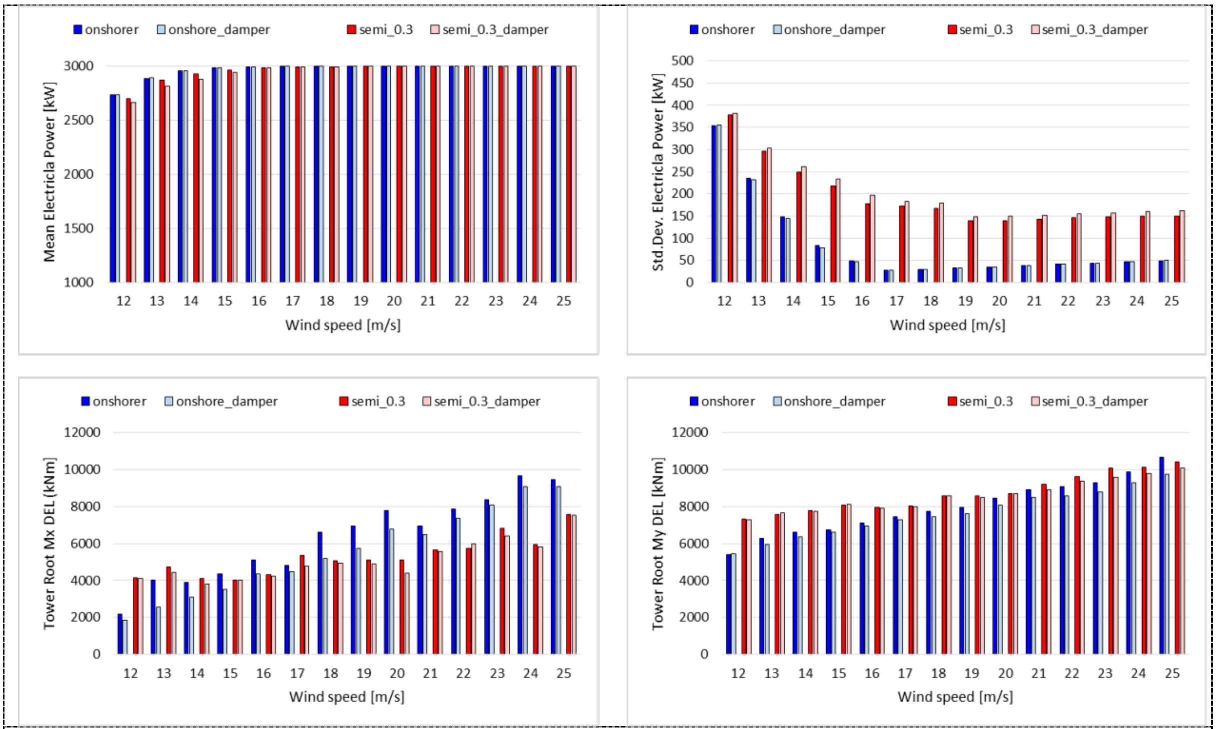

Figure 7. Results of Simulation for Tower Damper

4. Conclusions

In this study, a basic controller of a floating wind turbine installed on a large square semi-submersible platform was designed. The performance of the controller was verified using GL-DNV Bladed in conjunction with ANSYS/AWQA. The control algorithms were able to reduce the tower in-plane and out-of-plane bending moments by up to 38.1% and 16.9%, respectively. However, the standard deviation of the generated power significantly increased as a trade-off. When the onshore wind turbine controller was used for the floating wind turbine, the tower moments increased significantly but didn't make the platform motion unstable by driving the platform pitching mode. It is because the current floating wind turbine concept has a characteristic of one-way coupling of the platform-blade pitching motion. In addition, the effect of the tower vibration damper on the floating offshore wind turbine was not significant compared with that on the onshore wind turbine.

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