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Control Algorithm of a Floating Wind Turbine for Reduction of Tower Loads and Power Fluctuation

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A new control algorithm for a MW class spar-type floating offshore wind turbine has been developed to improve its performance and to reduce its mechanical load. The new blade pitch control having two PI control loops applied for different wind speed regions were designed. The bandwidth of the controller at near above-rated wind speed region was made lower to keep the vibration mode of the floating platform from being driven, and the bandwidth of the controller at far above-rated wind speed region was made higher to improve the wind turbine performance. Also, a feedback control loop using the angular acceleration information of the nacelle in the fore-aft direction was designed additionally to reduce the tower vibration. To perform modeling and simulation, a commercial multi-dynamics simulation program widely used for wind turbine design and certification, DNV-GL Bladed was used. The DNV-GL Bladed simulation results for the proposed new control algorithm showed that the output performance is improved and the tower load is reduced in various wind speeds above the rated wind speed.

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NOMENCLATURE

$\Delta\theta^{cmd}_{Blade}$ = Difference in command and measured pitch angle
θ = Pitch angle
K_P = Proportional gain
K_I = Integral gain
$\omega(t)$ = Angular velocity of generator
ω_{ref} = Reference angular velocity of generator
x_{faft} = Displacement in fore-aft
m = Mass
c = Damping coefficient
k = Spring constant
F_{thrust} = Thrust force of wind turbine
τ = Time constant

1. Introduction

Wind turbines are divided into three different kinds such as onshore wind turbines, offshore wind turbines with fixed substructures, and floating offshore wind turbines for their installation locations and methods. So far onshore or offshore wind turbines with fixed sub structures in shallow sea have been mainly installed due to their cost effectiveness and mature technology. However interests on floating offshore wind turbines are getting larger and larger due to their superior wind power generation and less local acceptance issues. Floating offshore wind turbines inherently have more tower vibration compared to onshore wind turbines or offshore wind turbines with fixed sub structures. This undesirable situation results from the fact that wind turbines have negative damping characteristics with respect to the wind speed above the rated wind speed region because of the collective pitch control for power regulation.

Therefore increasing damping of floating offshore wind turbines to reduce the power fluctuations and loads of floating offshore wind turbines have been investigated by many researchers.[1-3] Larsen et al. proposed lowering the control frequency of the collective pitch control to increase the damping of the wind turbine, and successfully showed that the proposed method reduces the tower vibration and the loads. However lowering control frequency led to slower pitch control and ended up with more power fluctuation.[1,2] Matsunaga et al. kept the control frequency high similar to the control frequency of onshore wind

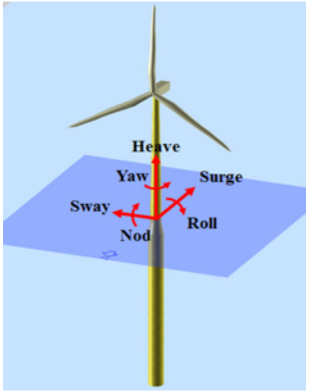

Fig. 1 Spar-Type floating offshore wind turbine

Table 1 Environmental conditions used in simulation

Simulation Time	600 s
Average wind speed & Turbulence intensity	16 m/s & 17.60 %
	22 m/s & 16.07 %
Significant wave height	3.66 m
Significant wave period	9.7 s
Wind & Wave directionality	co-directional

turbines and used additional feedback control loop using angular acceleration signal. Their method successfully improved power performance and tower loads, however, the results presented in their paper are limited to a single wind speed and no simulation results with other wind speeds are presented.[3] Therefore a complete performance of their controller cannot be evaluated over wide wind speeds.

The key idea of both methods is increasing damping of floating offshore wind turbines. However, it is hard to know which method is better or worse, and it is hard to know if the methods perform better or worse at different wind speeds. Also one might think that combining two methods could improve the performances better because more damping is available to the turbines. Although this issue is pretty important to control floating offshore wind turbines, the research on this is extremely limited.

Therefore, in this study, two methods in the literature are investigated further and also a new method based on combining both methods are proposed. The various control methods are compared by simulations.

2. Simulation Condition and Wind Turbine Model

To compare the performances of floating wind turbines with different control algorithms, a commercial simulation program widely used for wind turbine design and certification, DNV-GL Bladed, was used.[4] The program enables dynamic simulations of spar-type floating offshore wind turbines. The environmental and simulation conditions used in the simulation are listed in Table 1, and the wind and wave speeds used in the simulation with respect to time are shown in Fig. 2. [5-8]

The wind turbine used in the simulation is a spar-type 5MW paper wind turbine designed by NREL. The specification of the turbine is shown in Table 2.[5,6]

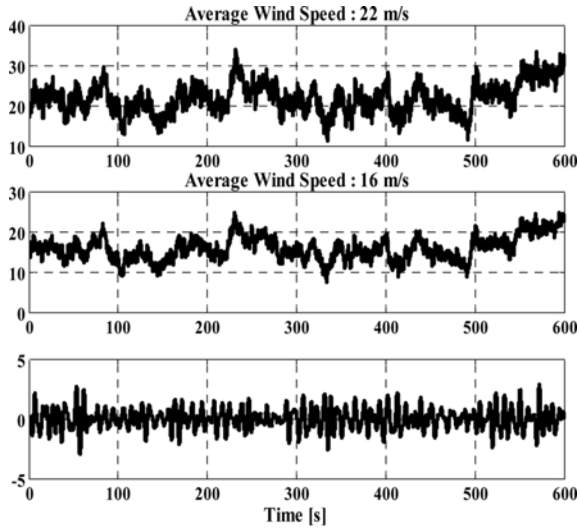

Fig. 2 Time series of wind speed and wave height used in simulation

Table 2 Specification of spar-type NREL 5MW wind turbine model used in simulation

Cut-in/out wind speed	3/25 m/s
Rated wind and rotor speed	11.3 m/s/12.1 rpm
Rated Generator Torque	43093.6 Nm
Rated Electrical Power	5 MW
Tower / Hub Height	86 / 90 m
Rotor/Nacelle/Tower Mass	110/240/250 Tons
Platform Mass, including ballast	7466330 kg
Number of Mooring Lines	3
Platform Depth	120 m
Water Depth	320 m
Control Type	VSVP (Variable-Speed Variable-Pitch)

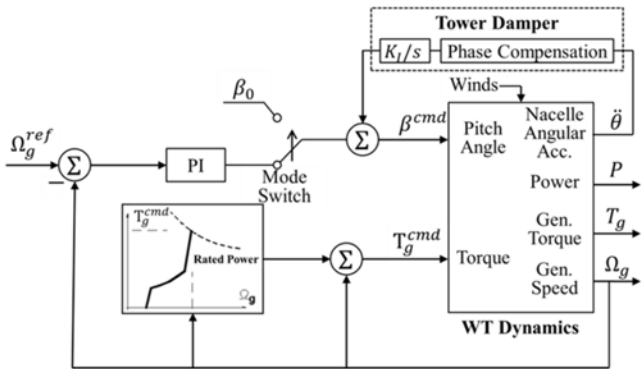

Fig. 3 Diagram of collective pitch control with a tower damper

3. Control Algorithm

Fig. 3 shows a general control scheme used for wind turbines.[9] As shown in Fig. 3, at wind speeds higher than rated wind speeds, wind turbines adjust blade pitch angles based on a suitable collective pitch control algorithm to produce the rated wind power.[1,2] The equation that

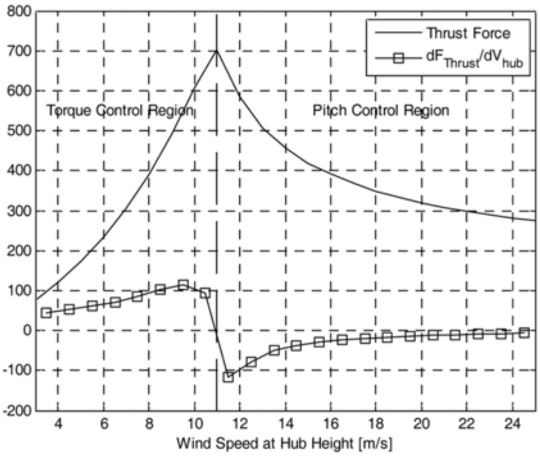

Fig. 4 Steady state thrust force with respect to wind speed. The unit of dF_{Thrust}/dV_{hub} is N·s/m

determines the command of the blade pitch angle is

$$\Delta\theta_{Blade}^{cmd} = K_P(\omega(t) - \omega_{ref}) + K_1\int(\omega(t) - \omega_{ref})dt \quad (1)$$

As the wind speed increases above the rated wind speed, wind turbines increase blade pitch angles to keep the rated power output and therefore the thrust force acting on the wind turbine rotor decreases. This means that the change in thrust force due to the change in wind speed has a negative slope as shown in Fig. 4. This "negative damping" characteristic causes more tower vibration for floating offshore wind turbines compared with onshore or fixed offshore wind turbines. Therefore a control algorithm to increase damping in floating offshore wind turbines is necessary.[1,2] This study used the same control scheme as shown in Fig. 2. More detailed information on the control scheme is available from the literature.[10,11]

3.1 HPC (High control frequency Pitch Control)

The method, HPC, is mainly used for onshore wind turbines or fixed offshore wind turbines. It uses a relatively high control frequency (cross-over frequency) about higher than 0.6 rad/s to extract energy in wind effectively. A higher control frequency leads to better electrical power generation because of faster pitching actions, but the load to the wind turbine increases because the control frequency approaches the tower vibration mode which is about 1~2 rad/s.[9]

3.2 LPC (Low control frequency Pitch Control)

LPC is a control method proposed by T. J. Larsen, T. D. Hanson. It's key idea is to lower the control frequency below the substructure or platform resonance mode existing only in floating offshore wind turbines and to increase damping. The resonance mode is about 0.1~0.6 rad/s depending on the substructure or platform used. The main advantage of the method is reducing wind turbine vibration and loads but lowering the control frequency makes blade pitching action slower and power performance worse.[1,2]

3.3 TFC (Tower acceleration Feedback Control)

TFC is different from HPC and LPC in that it is not adjusting the control frequency of collective pitch control but uses an additional feedback loop to increase damping of wind turbines. It uses the tower fore-aft motion speed by integrating the nacelle acceleration signal, $\ddot{x}_{faft}$, and forms a feedback loop to reduce the vibration of the wind turbine.[9]

The wind turbine fore-aft vibration can be approximated as the vibration of a simple cantilever system having a lumped mass on top, and this simple wind turbine vibration model can be expressed as a second order differential equation shown in Eq. (2).

$$m_t\ddot{x}_{faft} + c_t\dot{x}_{faft} + k_t x_{faft} = F_{thrust} + \delta u \quad (2)$$

In Eq. (2), du is an additional damping force (or negative thrust force) obtained from the feedback loop using the nacelle acceleration. du is given by

$$\delta uc = -c_a\int\ddot{x}_{faft}(\tau)d\tau \quad (3)$$

The wind turbine damping can be increased from c_t to c_t+c_a by the feedback loop. The relationship between δu and the pitch angle is given by

$$\delta u = (\delta\theta_{thrust}/\delta\theta_{blade})_0\delta\theta_{blade} \quad (4)$$

Therefore, Eq. (3) can be written in terms of blade pitch angle by

$$\delta\theta_{blade} = -C_a/(\delta\theta_{thrust}/\delta\theta_{blade})_0\int\ddot{x}_{faft}(\tau)d\tau \quad (5)$$

3.4 TAFC (Tower Angular acceleration Feedback Control)

TAFC is similar to TFC but has a feedback loop with respect to angular acceleration not nacelle acceleration. This is valid for floating

Table 3 Cases of different control algorithms used in simulation

Name	Control algorithm details
reference	HPC only
No 1	HPC with TFC
No 2	HPC with TAFC
No 3	LPC only
No 4	LPC with TFC
No 5	LPC with TAFC

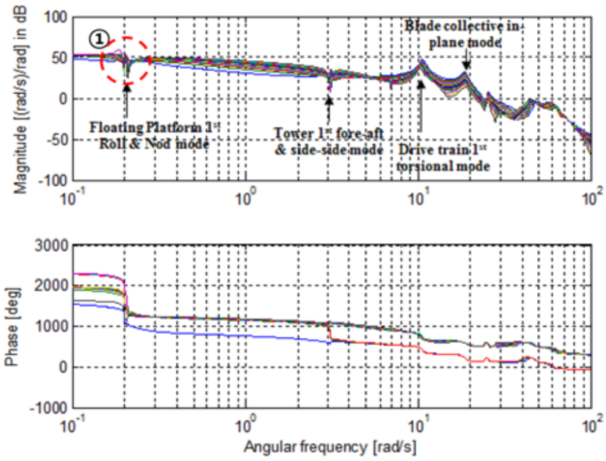

Fig. 5 Open loop frequency response of pitch control loop

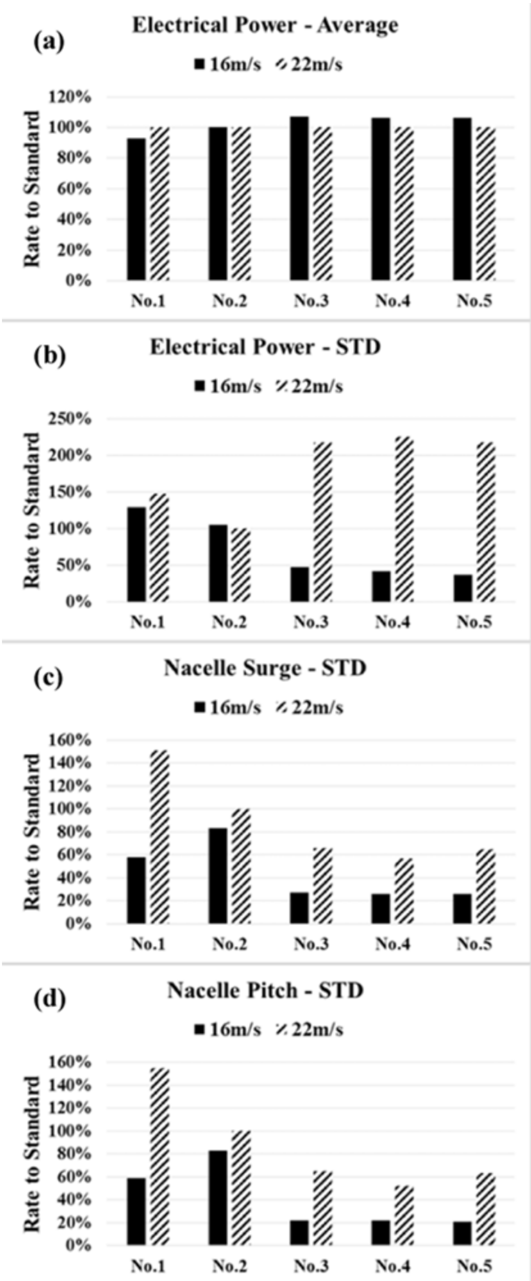

Fig. 6 Simulation results (performance) at two different turbulent wind speeds; (a) Average electrical power, (b) Standard deviation in electrical power, (c) Standard deviation in nacelle surge, (d) Standard deviation in nacelle pitch

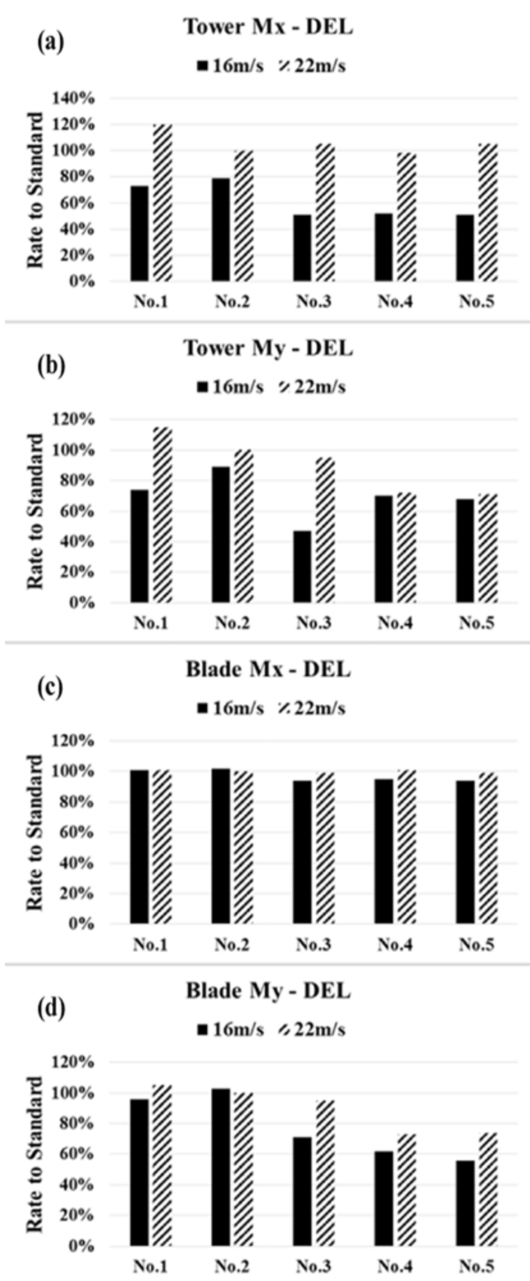

Fig. 7 Simulation results (damage equivalent load) at two different turbulent wind speeds; (a) Tower in-plane moment, (b) Tower out-of-plane moment, (c) Blade in-plane moment, (d) Blade out-of-plane moment

offshore wind turbines because they have surge motion and to find out the nacelle acceleration with respect to the tower root, the relative acceleration (angular acceleration) must be used.

The blade pitch angle for TAFC Control is determined by Eqs. (2) and (3) replacing x_{faft} with θ_{tower}.[3]

4. Simulation Methodology

To simulate various control algorithms and compare their performances, the commercial horizontal-axis wind-turbine design and analysis program, Bladed, developed by DNV-GL was used. The simulation cases with five different control algorithms listed in Table 3 were used in simulation.

The HPC used in onshore or fixed offshore wind turbines was chosen as a standard control algorithm and the results with different control algorithms were analyzed and compared with the results with the standard control algorithm. As shown in Table 1, two different wind conditions one relatively close to the rated wind speed and the other relatively close to the cut-out wind speed were used for simulation to check if the performances of the different cases vary with wind speed. The turbulence intensity was applied for Class A described in IEC

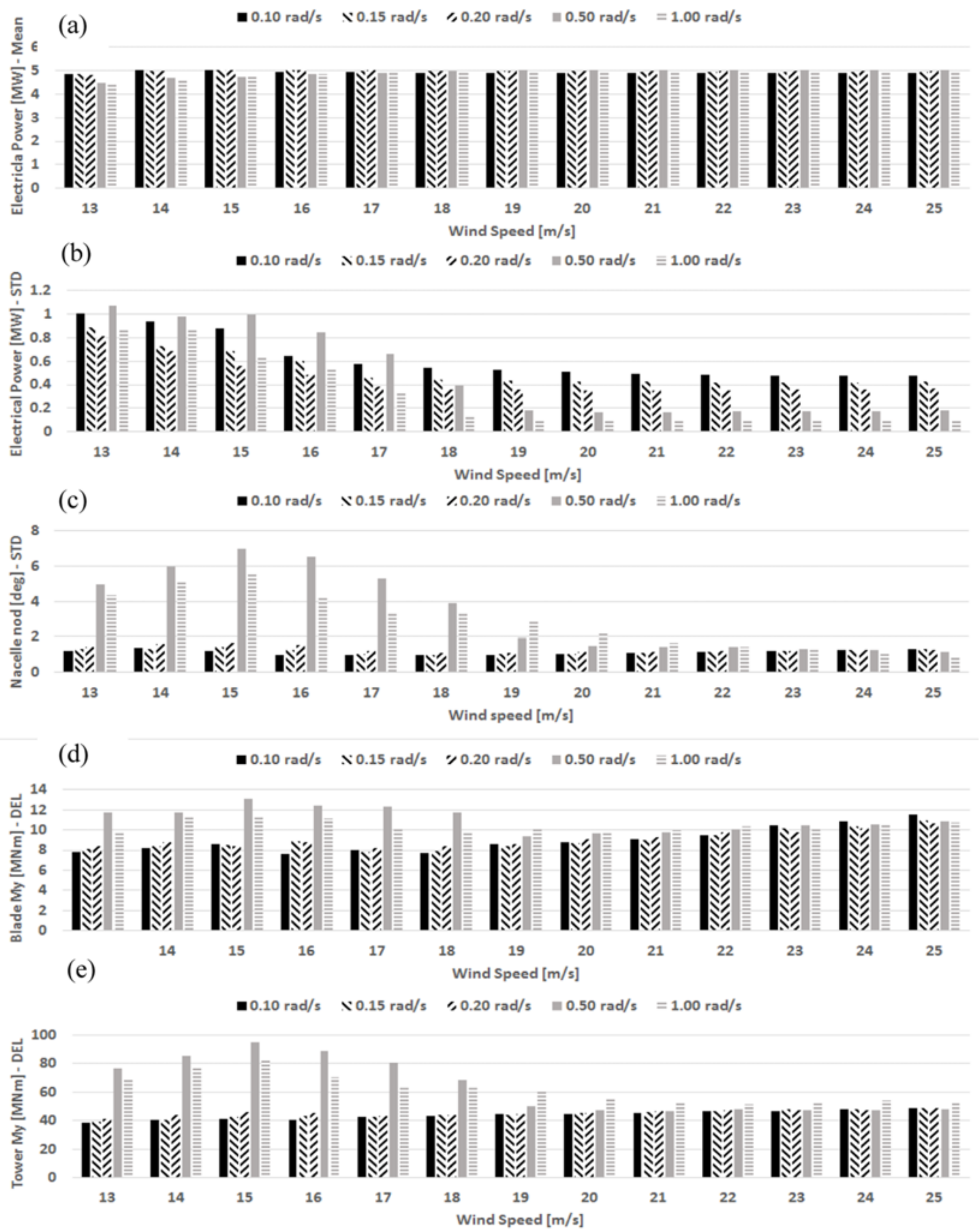

Fig. 8 Simulation results for various control frequencies with respect to wind speed; (a) Mean electrical power, (b) Standard deviation in electrical power, (c) Out-of-plane blade moment in DEL(damage equivalent load), (d) Out-of-plane tower moment in DEL (damage equivalent load)

61400-1 for simulation.[7] For floating offshore wind turbines, there is no international standard yet, therefore the simulation was performed based on IEC 61400-3 for fixed offshore wind turbines and the same wind and wave directions (COD: co-directional wind and waves) were used for simulation.[8]

Fig. 5 shows the open loop frequency response of the pitch control loop with various wind speeds from 13m/s to 25 m/s. As can be seen in the figure, the 1st floating platform(buoy) roll and nod mode occurs at 0.21 rad/s. Therefore the control frequency of LPC was chosen to be 0.2 rad/s in order not to drive the platform mode. Also, the control frequency of HPC was chosen to be 1 rad/s which is about the control frequency of onshore wind turbines.[9]

5. Simulation Results

The simulation results are shown in Figs. 6 and 7. Fig. 6 shows the performance related results including electrical power, Nacelle surge, and Nacelle pitch in both averages and standard deviations. Fig. 7 shows the load related results including tower and blade bending moments in DELs. As shown in figures all the results are presented with respect to the result with the standard control algorithm (HPC only) which is 100 %. The tower response is calculated at the center of the tower cross section above 10 m from the mean sea level.

Based on the figures, HPC cases (Case 1 and Case 2) show better performance in electrical power STD, and LPC cases (Case 3~Case 5) show better performance in tower vibration and load reduction. Also, in the figures, LPC cases (Case 3~Case 5) showed good performance even for both electrical power STD, and loads at 16 m/s, but they showed bad performance for electrical power STD at 22 m/s. The reason for this is that LPC lowers control frequency and therefore the blade pitching action becomes too slow to adjust pitch angles fast enough for changing wind speed.

The additional feedback loop by TFC and TAFC seems to effectively reduce loads. Specially, TAFC seems to reduce tower loads without affecting the power performance.

To find out the effect of LPC and HPC more clearly, simulations were performed with different control frequencies varying from 0.1 rad/s to 1.0 rad/s and different wind speeds, and the results are presented in Fig. 8. The case of control frequency of 1.0 rad/s is equivalent to the reference case (HPC only) and that of control frequency of 0.2 rad/s is equivalent to NO3 case (LPC only) in Figs. 6 and 7. Also three control frequencies including 0.1 rad/s, 0.15 rad/s, and 0.2 rad/s correspond to control frequencies lower than the platform(spar buoy)'s 1st roll and nod mode, and two control frequencies including 0.5 rad/s and 1.0 rad/s correspond to control frequencies higher than the platform's 1st roll and nod mode.

Fig. 8(a) shows the mean electrical power output. As shown in the figure, the rated power of the wind turbine is 5MW and the mean values don't exceed the rated power. For different control frequencies, the power outputs from the wind turbine vary. Fig. 8(b) shows the standard deviation in power output. The standard deviation decreases with increasing control frequency when the wind speed becomes higher than 18 m/s. The reason why the standard deviation decreases with increasing control frequency at high wind speed is due to faster pitching actions for power regulation.

However at low wind speed from 13m/s to 17 m/s, the standard deviation for high frequencies also increase because the pitching actions drive the nodding mode of the spar buoy. This is also noticed from the standard deviation in nacelle nod. At wind speeds lower than 18 m/s the nacelle nod significantly increases when the control frequency is higher than 0.2 rad/s. This is because the negative damping effect increases as the wind speed approaches the rated wind speed as shown in Fig. 4. Figs. 8(d) and 8(e) show the out-of-plane (fore-aft) blade and tower bending moments. For the cases of control frequencies lower than 0.5 rad/s, the loads are smaller than those of higher control frequency cases. This is because the platform (spar-buoy) roll and nod modes are not driven by the pitch actuation for low control frequency cases. However the loads of high control frequency cases are reduced for wind speeds far from the rated wind speed. The reason for this is that the negative damping effect increases as the wind speed approaches the rated wind speed and decreases as the wind speed gets higher as shown in Fig. 4.

6. New Control Algorithm

Based on the results in Section 5, it was found that a better result in performance and load could be obtained if the controller operates as the HPC at relatively low wind speed and as the LPC with TAFC at relatively high wind speed. Also from the results in Fig. 7, it can be found that the control frequency of 0.2 rad/s performed better than the other frequencies at wind speeds lower than 18 m/s and the control frequency of 0.5 rad/s performed better than the other frequencies at wind speeds higher than 18 m/s. Therefore a new control method using a region switch was considered.

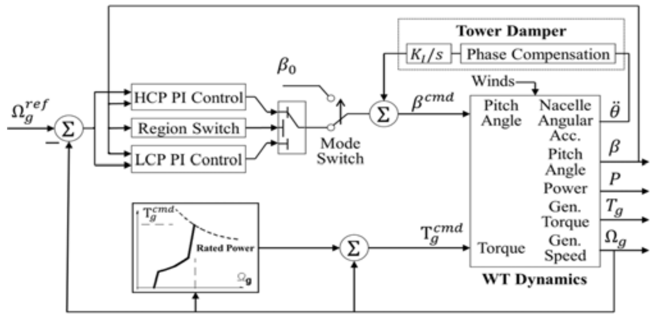

Fig. 9 New control algorithm using a region switch and a tower damper

Fig. 9 shows the schematic of the new control algorithm proposed in this study. It has a region switch in the pitch loop, and it decides more suitable control frequency at the current state and send pitch command based on the control frequency decided. The output of the region switch is connected to the mode switch which is used to select the torque or the pitch control based on the situation.

Fig. 10 shows the simulation results with the region switch of the control frequencies. It shows the results with and without the tower damper which is the additional feedback loop of Nacelle angular acceleration to increase tower damping using pitch motions.

First of all, without the tower damper, the simulation results show both characteristics of low and high control frequencies depending on the wind speed regions. That is all the figures show the same results as the results of the control frequency, 0.2 rad/s for the speeds between 13m/s and 18m/s and the same results as the results of the control frequency, 1.0 rad/s for the wind speeds higher than 18 m/s when the simulation results are compared with the results in Fig. 7. Therefore, the results show that the new control algorithm with the region switch works well as designed, and is better than the control scheme with the low or high control frequency alone.

Second of all, from Fig. 10, it can be found that the nacelle nod and the blade and tower bending moments are reduced with the tower damper but the electrical power is slightly degraded. Especially, the nacelle nod decreases significantly with the tower damper. Also the out-of-plane blade and tower bending moments were more or less reduced with the tower damper. Although the loads are reduced, the magnitudes are not that large. The reason for this is considered to be the fact that the damping of the system has been already increased by reducing the control frequency in the pitch loop and therefore adding more damping using the tower damper doesn't play a significant role in reducing the loads. However, it is not a trivial contribution.

In terms of electrical power, the tower damper slightly reduces the performance. The mean value of the electrical power is slightly lowered with the tower damper, and the standard deviation of the electrical power is slightly increased. The reason why this adverse effects occur in electrical power is considered to be the fact that the

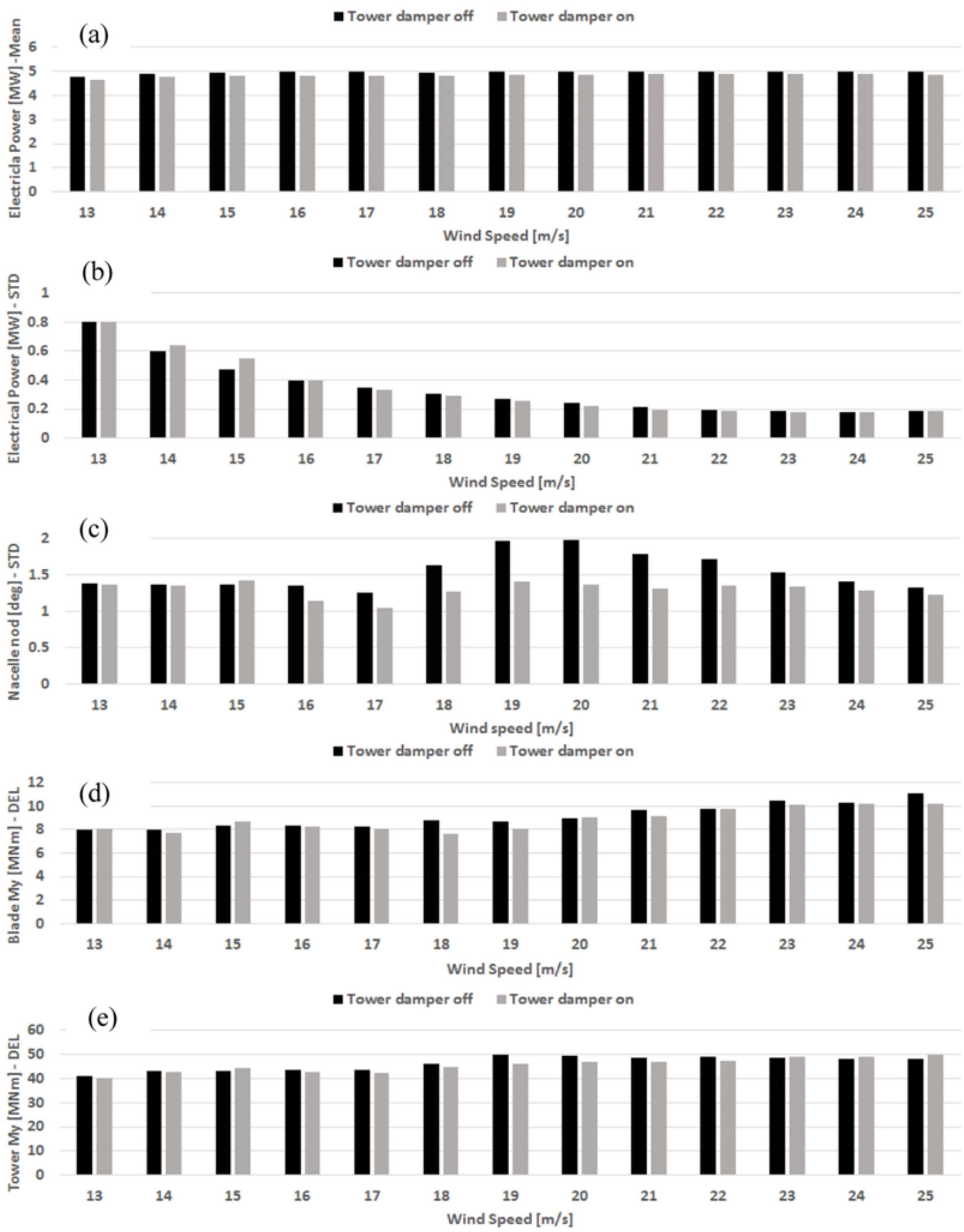

Fig. 10 Simulation results for various control frequencies with respect to wind speed; (a) Mean electrical power, (b) Standard deviation in electrical power, (c) Out-of-plane blade moment in DEL(damage equivalent load), (d) Out-of-plane tower moment in DEL (damage equivalent load)

additional loop of the nacelle angular acceleration feedback (tower damper) slightly interfere with the collective pitch control to increase damping. Similar slight performance degradation with tower dampers is known to exist in onshore wind turbines but advantages in terms of loading and nacelle nod are not trivial.[9]

7. Conclusion

In this study, a new wind turbine control algorithm for a spar-type floating offshore wind turbine was proposed. As a wind turbine, the NREL 5MW research wind turbine was used, and simulations with a commercial multi-body dynamics program was employed. The new control algorithm uses two different control frequencies in the pitch control loop with a region switch. The control algorithm uses a relatively low control frequency to increase the damping of the system at wind speeds lower than 18 m/s and uses a relatively high control frequency to increase the control response at wind speeds higher than 18 m/s. An additional feedback loop of the nacelle angular acceleration is also used to further increase the tower damping. From the simulation results it was found that the new method performs well and reduces blade and tower loads. A slight degradation in the performance in terms of average and standard deviation of the electrical power was also observed.

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REFERENCES

1. Hansen, M. H., Hansen, A., Larsen, T. J., Øye, S., Sørensen, P., and Fuglsang, P., "Control Design for a Pitch-Regulated, Variable Speed Wind Turbine," http://orbit.dtu.dk/fedora/objects/orbit:88301/datastreams/file_7710881/content (Accessed 29 MAY 2015)
2. Larsen, T. J. and Hanson, T. D., "A Method to Avoid Negative Damped Low Frequent Tower Vibrations for a Floating, Pitch Controlled Wind Turbine," Journal of Physics: Conference Series, Paper No. 012073, 2007.
3. Matsunaga, R., Tamagawa, Y., Lida, M., and Arakawa, C., "Development of Blade Pitch Control to Reduce Tower Motion of a 5MW Sapr-type Floating Offshore Wind Turbine," WWEC, 2014.
4. DNV, "Bladed: Bladed Wind Turbine Simulation Tool is Key for Optimizing Your Turbine at Every Phase of Its Design," https://www.dnvgl.com/services/bladed-3775 (Accessed 29 MAY 2015)
5. Jonkman, J. M., Butterfield, S., Musial, W., and Scott, G., "Definition of a 5-MW Reference Wind Turbine for Offshore System Development," National Renewable Energy Laboratory Golden, Technical Report NREL/TP-500-38060, 2009.
6. Jonkman, J. M., "Definition of the Floating System for Phase IV of OC3," National Renewable Energy Laboratory Golden, Technical Report NREL.TP-500-47535, 2010.
7. International Electrotechnical Commission, "Wind Turbines-Part 1: Design Requirements," IEC-61400-1, 2005.
8. International Electrotechnical Commission, "Wind Turbines – Part 3: Design Requirements for Offshore Wind Turbines," IEC-61400-3, 2009.
9. Nam, Y.-S., "Wind Turbine Control," GS InterVision, pp. 405-441, 2013.
10. Kim, K., Lim, C., Oh, Y.-O., Kwon, I., Yoo, N., and Paek, I., "Time-Domain Dynamic Simulation of a Wind Turbine Including Yaw Motion for Power Prediction," Int. J. Precis. Eng. Manuf., Vol. 15, No. 10, pp. 2199-2203, 2014.
11. Pham, T.-K., Nam, Y., Kim, H., and Son, J., "LQR Control for a Multi-MW Wind Turbine," World Academy of Science, Engineering and Technology, Vol. 6, No. 2, pp. 630-635, 2012.