Optimised de-rated wind turbine response and loading through extended controller gain-scheduling

Galinos, Christos; Urbán, Albert M.; Lio, Wai Hou

Published in:
Proceedings of the WindEurope Conference and Exhibition 2019

Link to article, DOI:
10.1088/1742-6596/1222/1/012020

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Optimised de-rated wind turbine response and loading through extended controller gain-scheduling

To cite this article: Christos Galinos *et al* 2019 *J. Phys.: Conf. Ser.* **1222** 012020

IOP Conf. Series: Journal of Physics: Conf. Series **1222** (2019) 012020 doi:10.1088/1742-6596/1222/1/012020

Optimised de-rated wind turbine response and loading through extended controller gain-scheduling

Christos Galinos, Albert M. Urbán and Wai Hou Lio

Technical University of Denmark, Department of Wind Energy, Frederiksborgvej 399, 4000 Roskilde, Denmark

E-mail: cgal@dtu.dk

Abstract. An increasing number of wind turbines are expected to be able to participate in the ancillary services that would normally be provided by conventional power plants, as the penetration of the wind energy in the electricity grid is increasing. Specifically, the turbines are needed to be able to control their active power based on the operator command. Constraining the possible output power, i.e. decreasing the power to less than the maximum or rated power, is therefore important for the wind turbine control system. When a turbine is operating under a de-rating strategy, the operating points of the turbine, i.e. the steady-state blade pitch and the tip speed ratio, change compared to the normal case and this needs to be considered within the controller design. Thus, this paper is to study the influence of the de-rating on the turbine controller gain-scheduling and its effect to power output and fatigue damage of the key turbine components. The results show that the wind turbine response is refined through tuning under the different down-regulation operation points, that translate into less fatigue damage of the key turbine components. For a typical multi-megawatt turbine, it is found that the main component lifetime damage can be reduced substantially. In numerical terms, there are up to 6.5% for the tower BM in fore-aft direction and 2.7% for the blade root flapwise direction, which can lead in a prolonged operational lifetime of the wind turbine.

1. Introduction

Under normal Wind Turbine (WT) operation, the pitch controller, typically the proportional-integral (PI) controller, is responsible for governing the collective pitch of the blades in order to maintain the rated state, i.e. rated power, when the wind speed is above rated. A simple but commonly-used technique to tune the PI pitch controller is to exploit the aerodynamic gradients of the WT and the drive-train dynamics becomes a second-order closed-loop system [4]. Aerodynamic gradients with respect to the blades pitch and rotor speed are called aerodynamic gain and damping respectively. These aerodynamic gradients of the turbine depend on the operating points of the turbine. These operating point variables are the pitch angle, rotor speed and the wind speed. Consequently, the tuning of the PI pitch controller needs to be adjusted accordingly. This procedure is well-known in the wind turbine control community as the Gain-Scheduling (GS).

Traditionally, the WT gain-scheduling is only considered based on turbine's nominal operation, where the WT power output reaches the design rated power at designed wind speed. In recent years, turbines are required to de-rate or down-regulate for the purposes of providing ancillary services [1] or improving wind farm efficiency [3, 8]. However, when the WT is down-regulated, the tuning of the WT pitch controller and the GS parameters should be adjusted

since the operating points are different than the designed. In this paper, the main contribution is to study how de-rating WT operation states affects the tuning of the blade pitch controller and the WT response.

The layout of the reminder of the paper is as follows. In Section 2, the theoretical model of the extended PI pitch controller GS is introduced, while in Section 3 the developed method is applied on a reference turbine. Finally, in Section 4 conclusions of the study are summarized.

2. Modelling of the GS PI Pitch Controller

The turbine GS is necessary since the dynamics of the wind turbine change with wind speed. One of the most significant parameters is the aerodynamic gain, which determines the blade pitch angle - aerodynamic power relation. Essentially, the PI controller GS is needed even in nominal operations because the dynamics of the system change substantially the performance of the closed loop from the original design. In the worst case, without GS, the speed regulation loop would affect other turbines dynamics. As the operating point changes, the PI controller gains need to be adjusted/scheduled accordingly and this can be due to changes in the incoming wind speed and the rotor speed. Changes to the controller gains alter the turbine operating point and affect the speed regulation closed-loop response.

Under normal WT operation, the blade pitch and the rotor speed are following the changes of the wind speed. Therefore, the GS should be based on the wind speed since the wind speed is the exogenous input that affects the operating point of the WT. However, due to practical reasons, the GS is done based on the pitch angle of the blades. In order to compute the values for GS, we can look into the equation of motion of a single degree of freedom WT, i.e. a stiff turbine model with only a rotational degree of freedom (rotating shaft): φ, $I\ddot{\varphi} + D\dot{\varphi} + K\varphi = 0$ for more details see §4.5 [4]. Then, if the loop is closed with a PI pitch controller, the proportional and integral gains, K_p and K_i respectively, can be calculated as:

$$K_p = -\frac{2\zeta_\Omega \omega_\Omega I - \frac{\partial Q_g}{\partial \Omega} + \frac{\partial Q}{\partial \Omega}}{\frac{\partial Q}{\partial \theta}} \tag{1a}$$

$$K_i = -\frac{\omega_\Omega^2 I}{\frac{\partial Q}{\partial \theta}} \tag{1b}$$

where $\omega_\Omega = \sqrt{\frac{K}{I}}$ and $\zeta_\Omega = \frac{D}{2\sqrt{KI}}$ are the desired frequency and damping ratio of the mode associated with the rotor speed regulation, I is the rotor and drive-train inertia, K and D the 2nd order system damping and stiffness $\frac{\partial Q}{\partial \theta}$ is the derivative of the aerodynamic torque with respect to (w.r.t) the blade pitch angle or aerodynamic gain, $\frac{\partial Q}{\partial \Omega}$ is the derivative of the aerodynamic torque with respect to the rotational speed, here assumed to be negligible, and $\frac{\partial Q_g}{\partial \Omega}$ is the derivative of the generator torque with respect to the rotational speed that depends whether the turbine is regulated for constant torque ($\frac{\partial Q_g}{\partial \Omega} = 0$) or constant power ($\frac{\partial Q_g}{\partial \Omega} = -\frac{P_r}{\Omega^2}$), where P_r is the rated power.

In Figure 1, the gains K_p and K_i for the pitch controller as a function of blade pitch angle for nominal WT operation for the DTU 10MW reference wind turbine (rwt) [2] are shown.

The equations (1) depict how K_p and K_i depend on the derivative of the aerodynamic torque w.r.t. the blade pitch. Since the $\frac{\partial Q}{\partial \theta}$ changes as a function of the blade pitch i.e. $\frac{\partial Q}{\partial \theta}(\theta)$, K_p and K_i become functions of the pitch angle θ. Notice that such a function $\frac{\partial Q}{\partial \theta}(\theta)$ is typically non-linear. Nonetheless, traditionally, $\frac{\partial Q}{\partial \theta}$ is fitted with a 2nd order polynomial with constants K_1 and K_2 for a WT under nominal operation, i.e. WT power output is the designed rated at

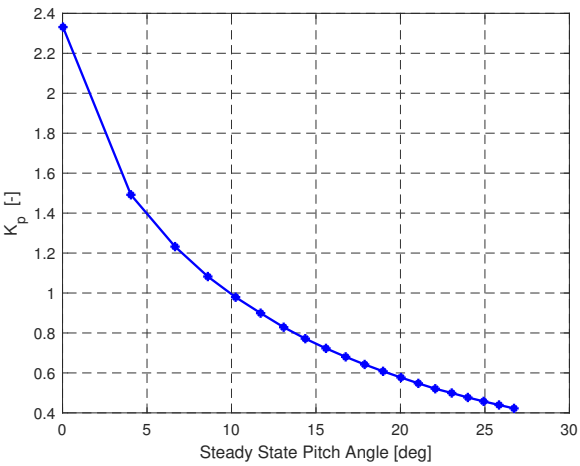

Figure 1. PI pitch controller gain K_p as a function of pitch angle under nominal WT operation.

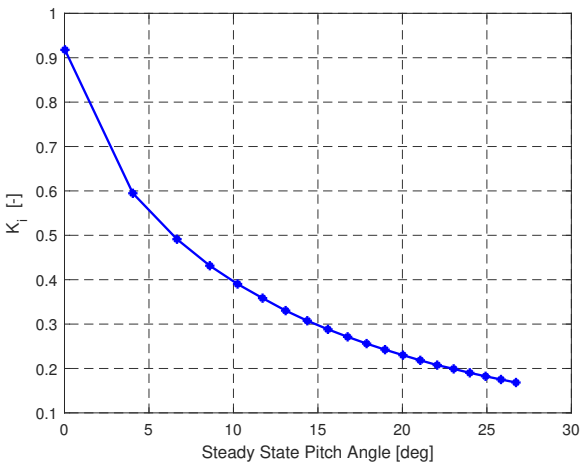

Figure 2. PI pitch controller gain K_i as a function of pitch angle under nominal WT operation

high wind speeds [10]:

$$\frac{\partial Q}{\partial \theta} = \frac{\partial Q}{\partial \theta} |_{\theta=0} \left(1 + \frac{\theta}{K_1} + \frac{\theta^2}{K_2}\right), \tag{2}$$

where $\frac{\partial Q}{\partial \theta} |_{\theta=0}$ is the gain at zero pitch. However, due to the demand of derating operation $\frac{\partial Q}{\partial \theta}$ or aerodynamic gain becomes a function of the desired power output P_r as well. Based on the de-rating percentage, the operating points of the WT can be different and therefore the aerodynamic gain which determines the value of the K_p and K_i for a specific wind speed varies.

In Figure 3, it is shown the aerodynamic gain values of the DTU 10MW rwt aero-servo-elastic model for nominal operation (power output is equal to P_r) and when the WT is forced to produce 25%, 50% and 75% of P_r. It can be observed that different constrains on power output lead to different aerodynamic gains. As a result the PI pitch controller should take these dependencies into account. The de-rating strategy followed here is the constant-Ω, for more details see [9]. The results have been obtained by using HAWCStab2 which transforms the non-linear finite beam WT aero-servo-elastic model to an analytical linearized one [5]. In the next paragraph, the developed extended GS approach is applied in the DTU reference WT aero-elastic model and its response is compared with the basic one (GS tuned only for nominal operation).

3. Application on the DTU 10MW RWT

The WT controller is the key instrument for stable and optimum WT operation under various conditions. The extended GS approach is evaluated below using the DTU 10MW rwt aero-elastic model and the open source DTU Wind Energy controller [10]. Its response and loading of main components under various simulation scenarios are compared using the basic GS approach versus the extended one. Simulations are conducted in time domain using HAWC2 aero-elastic code [7] and applying 50% down regulation.

HAWC2 performs time domain simulations of the system, where the dynamics are described by differential equations and solved using the Newmark numerical integration scheme. It is divided into modules which can be combined depending on what the user is studying. The main parts are:

- the structure where main WT components such as the blades, the tower, the rotor shaft and the substructure can be modelled by Timoschenko beam elements with Rayleigh damping

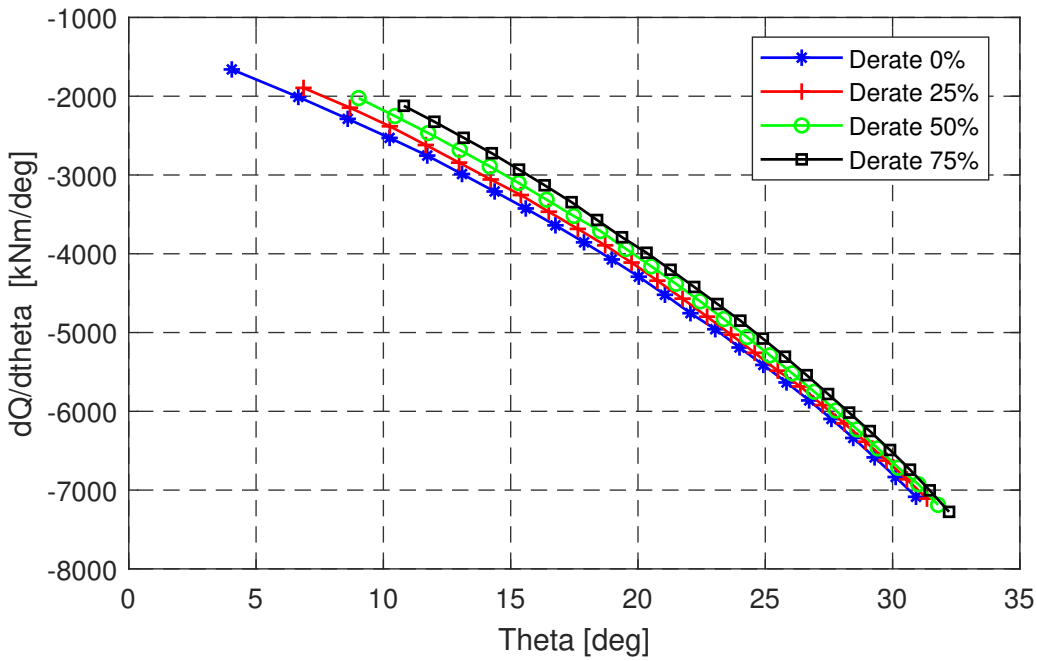

Figure 3. Aerodynamic gain as a function of blade pitch for different de-rating operation conditions.

or with super element models

- the aerodynamics which are based on the Blade Element Momentum and Actuator Cylinder models and the blade aerodynamic coefficients for computing the aerodynamic loads
- the wind field which can be deterministic, stochastic using the Veers and Mann models or custom
- the hydrodynamics which include regular, irregular waves with JONSWAP and Pierson-Moskowitz spectra, and the Morison approach for capturing the hydrodynamic loads on the components
- the soil module, where the soil-structure interaction is modelled using p-y curves
- the controller which is plugged in as a DLL file including the generator and the blade pitch system dynamics
- Finally, other special futures such as tower guy wires and nacelle lidar sensors can be implemented through custom external DLLs and link them with the code

3.1. Step response

The response of the WT is firstly evaluated by applying wind speed steps above rated wind speed where the PI pitch controller is active. The wind field is deterministic with a power law shear profile and exponent equal to 0.2 (see Figure 4). In Figures 5 and 6, the generator LSS torque, the rotor speed and the blade pitch response are plotted respectively. The results show that there is an improved response with the extended GS as the pitch angle changes more aggressively and the overshoot of the generator torque and rotor speed is smaller for each wind speed step. In Figure 7 the blade root flapwise and the tower base fore-aft Bending Moments (BM) are presented focused on a narrower time span for clarity reasons. It can be seen that due to the improved PI pitch controller response of the extended GS approach the blade load variation is smaller after each wind step while the tower fore-aft BM remains almost the same.

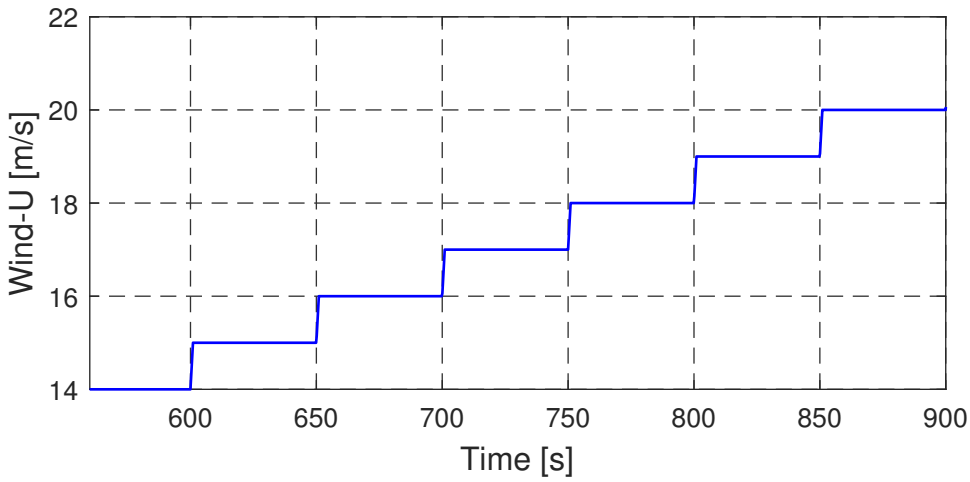

Figure 4. Applied wind steps.

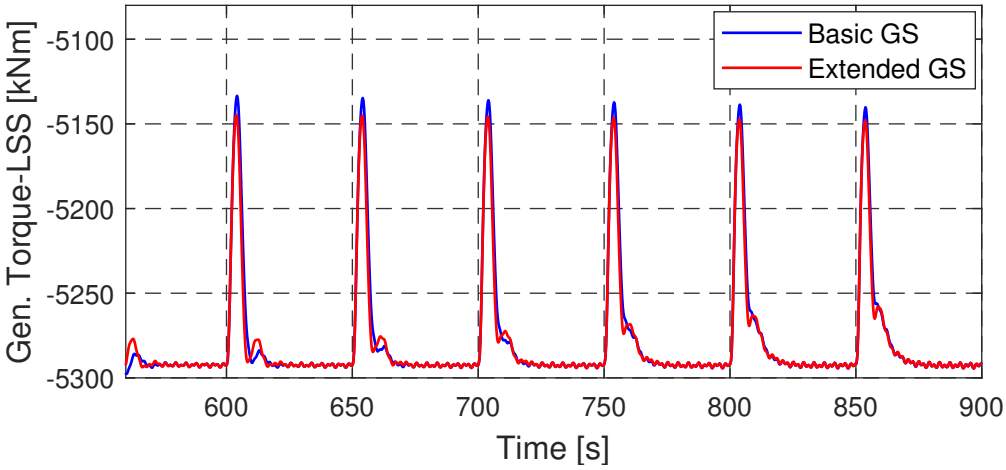

Figure 5. Generator torque expressed at LSS.

3.2. Turbulent Wind

Finally, a load comparison based on high fidelity aero-servo-elastic simulations is performed focusing on the lifetime fatigue damage of the WT main components such as the blade and the tower between the basic and the extended gain scheduling. The analysis is done following the IEC61400-1 ed.3 standard [6] and focusing only above rated where the PI pitch controller is mainly active. IEC turbulence and site conditions of Ib are assumed and eighteen 10 minute HAWC2 simulations are run per wind speed in order to capture the variations of the turbulence field. At table 1 the lifetime fatigue loads are compared after normalization with the basic GS simulation results. A Wöhler exponent of 4 and 12 are assumed for the tower and the blade respectively and a 20 year of design lifetime for the WT with 10 million cycles. The tower base fore-aft fatigue damage is reduced by 6.45% which is quite a lot and follows the blade root fatigue damage with a reduction of around 2%. The blade root edgewise damage is almost unchanged since the gravity field is the main contributor in this load direction. Finally, the tower base side-side damage is reduced slightly (around 1%). As a result, it can be concluded that even

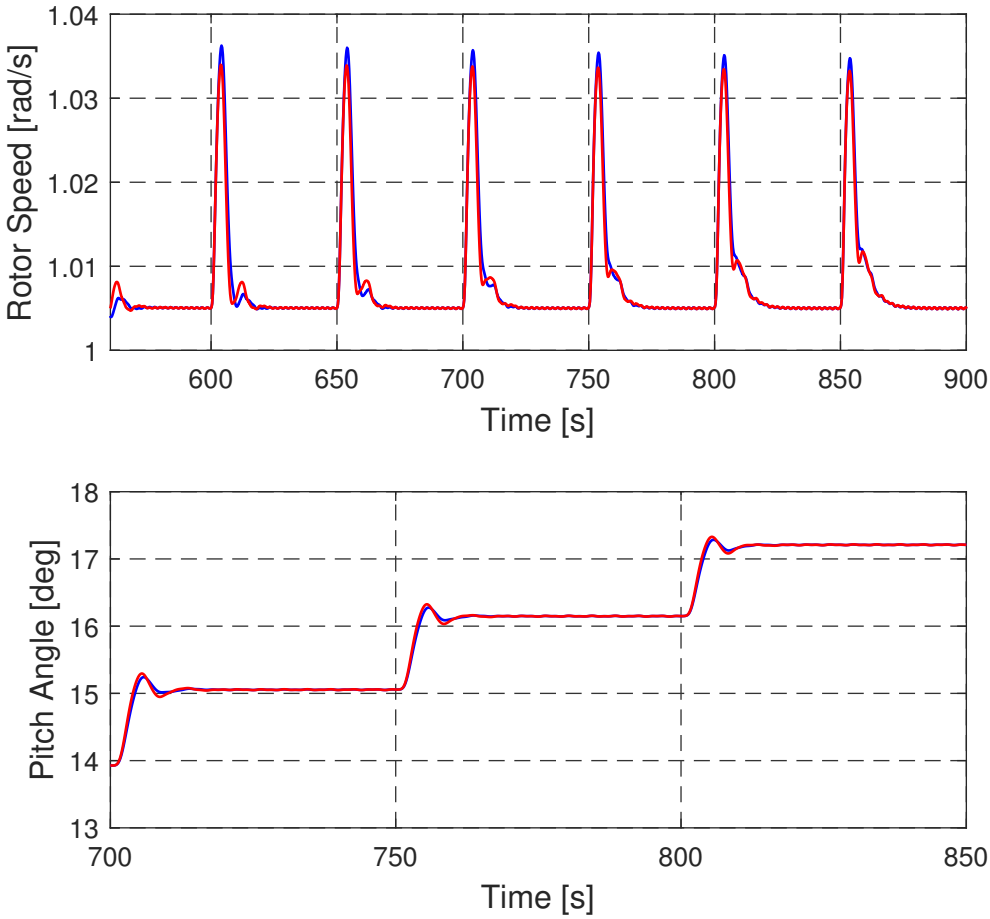

Figure 6. Rotor speed and blade pitch angle responses, upper and lower plots respectively.

Table 1. Normalized lifetime fatigue equivalent loads comparison.

Channel name	Baseline Operation [%]	Extended GS Operation [%]
Tower Base Fore-Aft BM	100	93.55
Tower Base Side-Side BM	100	98.78
Blade Root Flapwise BM	100	98.28
Blade Root Edgewise BM	100	99.99

though above rated both the basic and the extended GS approach WT simulations return the requested rated power output, the lifetime damage can be reduced substantially by extended tuning of the controller actions. This is especially important in large modern wind farms where turbines will be requested to operate in a lower rated power output more often.

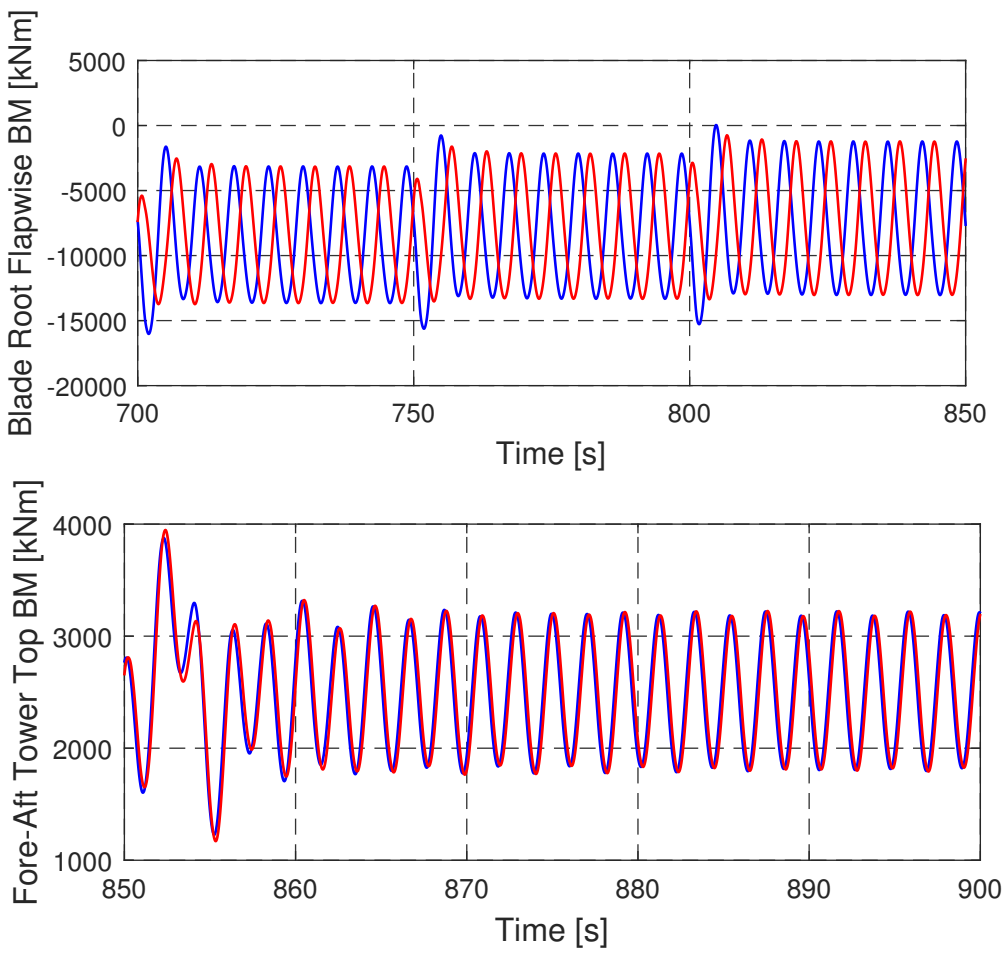

Figure 7. Blade root flapwise BM (upper plot), tower base fore-aft BM (lower plot).

4. Conclusions

In this paper is shown that de-rating WT operation affects the aerodynamic gradients of the turbine and in order to take these effects into account the PI pitch controller gain scheduling needs to be extended. In addition, is shown that the WT response is refined through tuning under the different down-regulation operation points. Finally, for a typical multi-megawatt turbine it was found that the main component lifetime damage can be reduced substantially. Up to 6.5% for the tower BM in fore-aft direction and 2.7% for the blade root flapwise direction, which can lead in a prolonged operational lifetime of the WT.

Acknowledgements

This work has been funded by the Danish Energy Technology Development and Demonstration Programme (EUDP) under project PowerKey - Enhanced WT control for Optimized WPP Operation, Grant No. 64017-0045. The support is greatly appreciated.

References

[1] Aho, J., Buckspan, A., Pao, L., and Fleming, P. An Active Power Control System for Wind Turbines Capable of Primary and Secondary Frequency Control for Supporting Grid Reliability. *AIAA/ASME Wind Symposium* (2013), 1–13.

[2] Bak, C., Zahle, F., Bitsche, R., Kim, T., Yde, A., Henriksen, L. C., Natarajan, A., and Hansen, M. Description of the DTU 10MW reference wind turbine. Tech. Rep. I-0092, Technical University of Denmark, Department of Wind Energy, 2013.

[3] Galinos, C., Larsen, T. J., and Mirzaei, M. Impact on wind turbine loads from different down regulation control strategies. In *DeepWind2018* (2018).

[4] Hansen, M. H., Larsen, T. J., Øye, S., Sørensen, P., and Fuglsang, P. Control design for a pitch-regulated, variable speed wind turbine. Tech. Rep. Risø-R-1500(EN), Risø National Laboratory, 2005.

[5] Henriksen, L. C., Tibaldi, C., and Bergami, L. HAWCStab2 User Manual. Tech. rep., Technical University of Denmark, Department of Wind Energy, 2015.

[6] IEC. International Standard IEC61400-1: Wind Turbines - Part 1: Design Guidelines, 2005.

[7] Larsen, T. J., and Hansen, A. M. How to HAWC2, the user's manual. Tech. Rep. R-1597(ver.4-7)(EN), Technical University of Denmark, Department of Wind Energy, 2018.

[8] Lio, W. H., Mirzaei, M., and Larsen, G. C. On wind turbine down-regulation control strategies and rotor speed set-point. *Journal of Physics: Conference Series 1037* (jun 2018), 032040.

[9] Mirzaei, M., Gocmen, T., Giebel, G., Sorensen, P. E., and Poulsen, N. K. Turbine control strategies for wind farm power optimization. *Proceedings of the American Control Conference* (2015), 1709–1714.

[10] Mirzaei, M., Hansen, M. H., Tibaldi, C., Henriksen, L. C., and Hanis, T. Basic DTU wind energy controller version 2. Tech. rep., Technical University of Denmark, Department of Wind Energy, 2015. `https://github.com/DTUWindEnergy/BasicDTUController`.