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A compensation scheme applied on wind turbine blade pitch control for the reduction of non-torque main shaft loads

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Abstract. It has been well established that non-torque main shaft loads influence the internal drive train loads. This paper proposes a scheme that compensates for non-torque loads in the blade pitch controller. The compensation scheme is implemented on a dynamic model developed in FAST/Simulink. Three wind conditions of 8, 11.4 and 20 m/s are examined. The dynamic analysis of the bending moment in the low-speed shaft showed a reduction in bending moment by 3 % for the rated wind speed (11.4 m/s) and 1.8 % for the above-rated wind speed (20 m/s), highlighting the effectiveness of the proposed scheme. However, a reduction in bending moment also slightly decreased the shaft's speed by 2.3 % and 0.5 %, respectively. Similarly, the turbine power was decreased by 9 % and 1 %, respectively. In comparison, further gain scheduling within the compensation scheme reduces the power loss to as low as 0.3 %. The 2 to 3 % reduction in the low-speed shaft bending moment can significantly influence the drive train loads and easily outweigh any loss resulting in the shaft rotational speed and turbine power. Thus, this paper shows that using bending moment error as feedback within the compensation scheme positively affects the low-speed shaft's bending moment with the eventual potential of reducing drivetrain loads.

1. Introduction

Wind energy is a key driving force in achieving the net-zero emissions target 2050 set forth by many countries, including Norway [1]. As more turbines are being built worldwide to achieve this target, it has become ever more equally essential to keep the cost of developing and servicing these turbines to a minimum. An essential aspect in keeping the cost low is ensuring wind turbines failure rates are minimized, as such failure can easily have extended downtime (varying from months to years) and heavily depends on the availability of the materials or manpower [2][3][4]. Furthermore, since some parts within the wind turbines are more susceptible to damages or are expensive to replace, it can significantly affect their base cost due to warranties. One such important example is the gearbox which makes up about 15 % of the cost involved in manufacturing a wind turbine, making it one of the more expensive components to service and replace during failure [3]. Even with better design and manufacturing processes, many gearboxes are still only commonly achieving lifespans of less than 20 years [4][5]. An estimate of about one gearbox failure occurs for every 145 wind turbines per year. Additionally, excessive loading also drives up the operations and maintenance costs for the manufacturers [3][4]. Therefore, uncertainty in failure rates within the gearbox naturally drives up the total cost of the turbines and the insurance cost involved in protecting them against damages [4].

The National Renewable Energy Laboratory (NREL) estimates that about 75 % and 15 % of gearboxes failures can be accredited to the bearing (abrasion and adhesion) or gear parts (bending fatigue

and corrosion), respectively. In addition, gearboxes experience different loads such as twisting moment or torque, transverse load, and axial load. Therefore, minimizing any of these loads will also vastly help reduce the total load acting on the gearbox. However, with very little room for better design improvements, today's research on the gearboxes focuses on better materials or reducing loads acting on the gearbox by modifying the control systems. Innovating the control systems focuses on improving its controls, and example includes varying shaft speed or individual blade pitch to reduce the loads acting on the turbine shaft connected to the gearbox.

It has been well established that non-torque main shaft loads influence the internal drive train loads. In Xing et al. [6], the authors showed that changes in floating wind turbine support led to a reduction in the non-torque main shaft loads, gear-teeth loads and bearing loads. While in three different papers [7][8][9], the authors confirmed that non-torque loads induced by overhang weight significantly influence the drive train loads and their response. The authors attempted to change the drive train design to reduce the effect of the load caused by the shaft. The authors also identified that both gravity and non-torque loads cause excitations within the carrier frame, leading to gearbox loading. In Link et al. [10], the authors confirmed that bending moment (BM) in the main shaft resulted in the planet-ring gear misalignment, which led to an increase in edge loading. Edge loading eventually led to an increase in contact stress which gave a shorter gear lifespan.

Wind turbines have long used active control to mitigate loads and increase power production under a wide variety of wind conditions. In Bossanyi [11][12][13][14], the author suggested that it is possible to further metamorphose controllers (limit pitch controllers), limiting certain types of mechanical loads. The author further discussed the possibility of using a control system and actuators to adjust the different pitch angles of each individual blade to reduce the loads on the systems. The authors illustrated a straightforward addition to the pitch control algorithm of each individual blade to reduce the peak load on some of the fixed components, which in turn led to a substantial amount of load reduction in the whole structure. At the same time, Henriksen [15], investigated the possibility of creating a model predictive controller (MPC) through gain scheduling or re-linearization. In this paper, the author only verified the ability of the MPC to control the turbines subjected to both physical and artificial constraints. However, the author did not focus on the effect the controllers had on the loads. While in the doctoral thesis written by Korber [5], the author found that a preview MPCs performed better in reducing both the mechanical extreme and fatigue loads than a non-preview MPCs and classical baseline controller. Much of this existing research did not focus on reducing non-torque main shaft loads.

This paper aims to focus on improving an existing control algorithm on the NREL 5 MW reference turbine which will reduce the bending moment in the low-speed shaft which will eventually lead to the reduction of the gearbox or drivetrain loads. This is performed via a simple but highly effective scheme that directly compensates the non-torque main shaft loads in the blade pitch control system.

2. NREL 5 MW reference turbine
The NREL 5 MW reference turbine [16] is used as the study object in this paper. It is a three-bladed, variable pitch-to-feather bladed, upwind, and variable-speed controlled megawatt wind turbine developed to study concepts surrounding wind technology. The following method applied on this turbine will help envisage the reduction in non-torque bending moment in the turbine's low-speed shaft. The NREL 5 MW reference turbine's control system algorithm [16] is executed in the Simulink/FAST framework [17] and is presented in Section 3.1.

3. The compensation scheme
The compensation scheme is presented in Figure 1 together with the original blade pitch controller. The original blade pitch controller corrects only for shaft speed error. In contrast, the compensation scheme adds the correction of the main shaft bending moment error. The scheme only modifies the blade pitch control, i.e., the generator control is not modified.
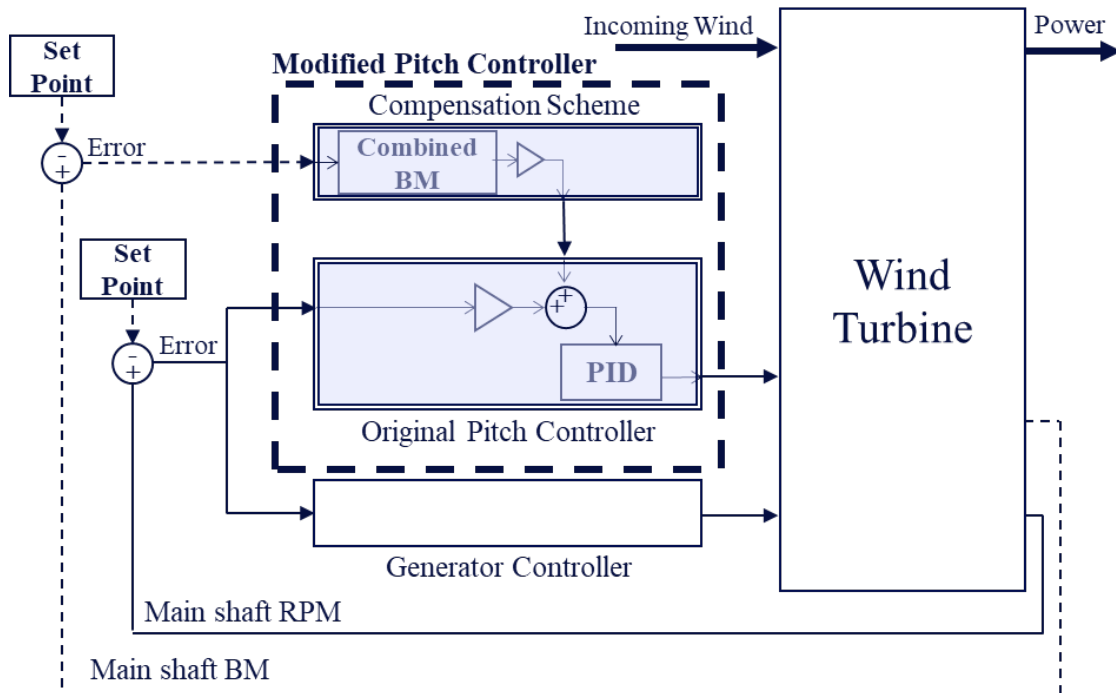
Figure 1. Modified pitch controller (Original controller with compensation scheme).

The collective blade pitch command, θ_{com} is calculated as:

$$\theta_{com} = k_p \cdot e_{tot} + k_p \cdot \int e_{tot}\, dt \qquad (1)$$

where e_{tot} is the total error, k_p is the proportional gain coefficient and k_i is the integral gain coefficient. The derivative gain is zero. There are saturation and rate limiter placed on the commanded pitch.

The total error, e_{tot} is calculated as:

$$e_{tot} = e_{RPM} + k_{BM} \cdot e_{BM} \qquad (2)$$

where e_{RPM} is the shaft speed error, e_{BM} is the bending moment error and k_{BM} is the compensation weight factor applied on e_{BM}. The values of k_{BM} studied are presented in Table 1. When k_{BM} is set to 0, the errors of the moment are not added to the PID controller. While when k_{BM} is set to 1, it hypothetically means that all the bending moment errors are sent into the PID controller.

The main shaft bending moment is the combined bending moment, M and is calculated as:

$$M = \sqrt{M_y^2 + M_z^2} \qquad (3)$$

where M is the combined bending moment, M_y and M_z are the non-rotating bending moments.

3.1. Simulink implementation
The compensation scheme is implemented in Simulink/FAST [17] and is presented in Figure 2. The NREL 5 MW blade pitch controller [16] is modified to include the compensation scheme (shaded in Figure 2).
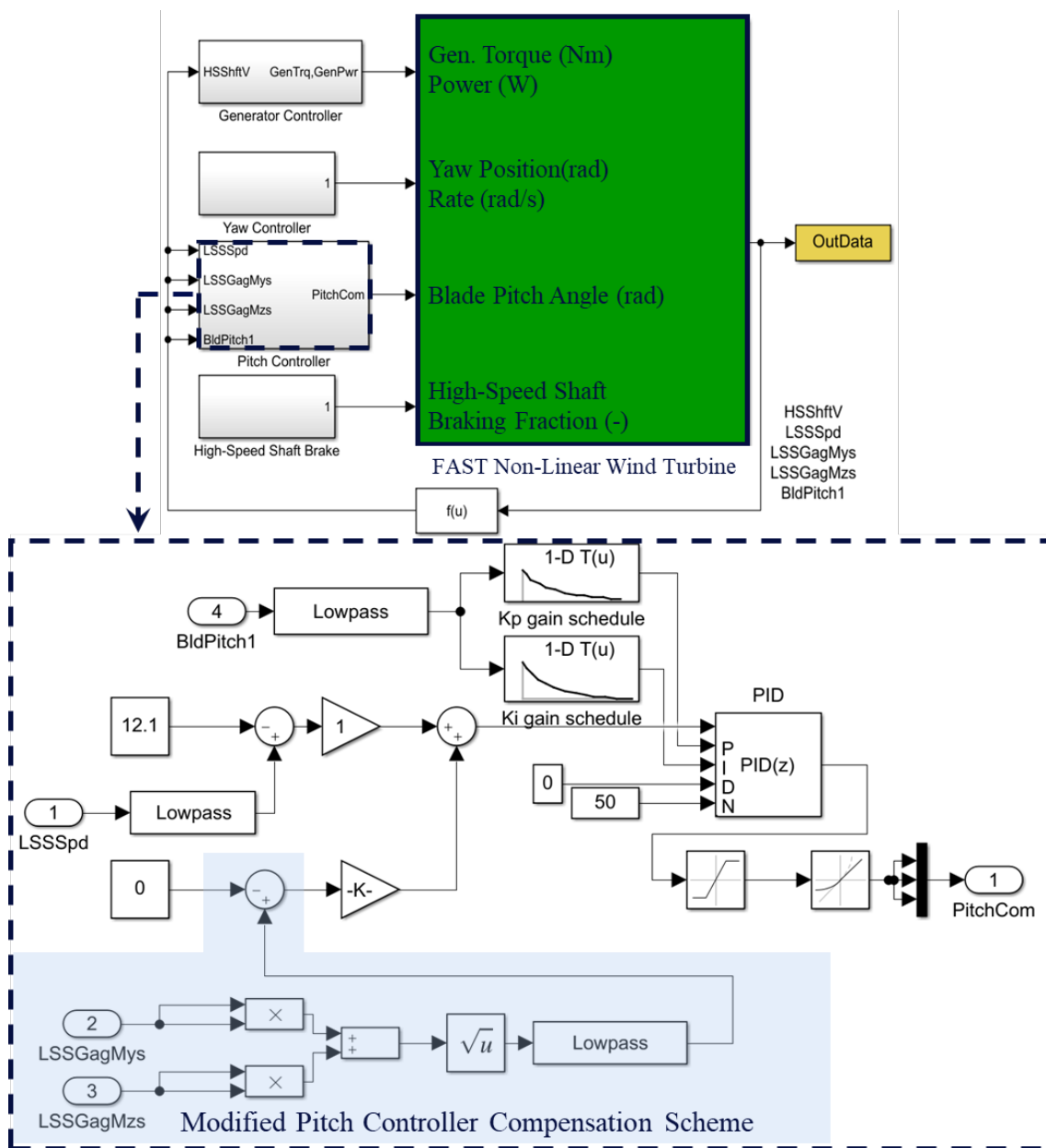
Figure 2. Simulink implementation.

In the implementation, the y and z directional low-speed-shaft bending moments are squared and added together. Next, the root of this summation vector is calculated using equation (3) before passing the signal through a low pass filter. The error of the moment is then calculated as a summation of the differences between the measured input moment and the ideal moment of 0. The signal is then multiplied by the compensation weight factor (K_{BM}). Finally, these two errors are added and then used as inputs into the PID controller.

4. Case studies
The cases studied in this paper are presented in Table 1. Three wind speeds corresponding to below-rated, rated and above-rated regions are studied for both steady wind and normal turbulent wind (NTM) conditions for a wide range of K_{BM} values. This gives a total of 72 simulation cases. The simulation times for each case are 300 s for both steady and NTM wind conditions.

Table 1. Case studies

Case no.	Values
Wind speed (m/s)	8, 11.4, 20
Wind condition	Steady, NTM
K_{BM}	0, 0.0001, 0.0002, 0.00032, 0.00064, 0.00072, 0.0001, 0.0002, 0.00032, 0.00064, 0.00072, 0.001

The variables studied are the non-torque bending moment (BM) (equation (3)), the low-speed shaft speed (RPM) and the generator power (Power). Percentage differences, i.e., %BM, %RPM and %Power are also calculated and investigated. As an example, the % difference in BM is calculated as:

$$\%BM = \frac{BM_{comp} - BM_{org}}{BM_{org}} \times 100\% \qquad (4)$$

where BM_{comp} is the bending moment obtained when the compensation scheme is applied and BM_{org} is the bending moment obtained with the original controller scheme with no modifications applied.

## 5. Results and discussions

5.1. Steady wind
The results of the steady wind cases are presented in Figure 3 and Figure 4. When calculating the shaft RPM, generator power and generator torque, their average values of the last 100 seconds were computed.
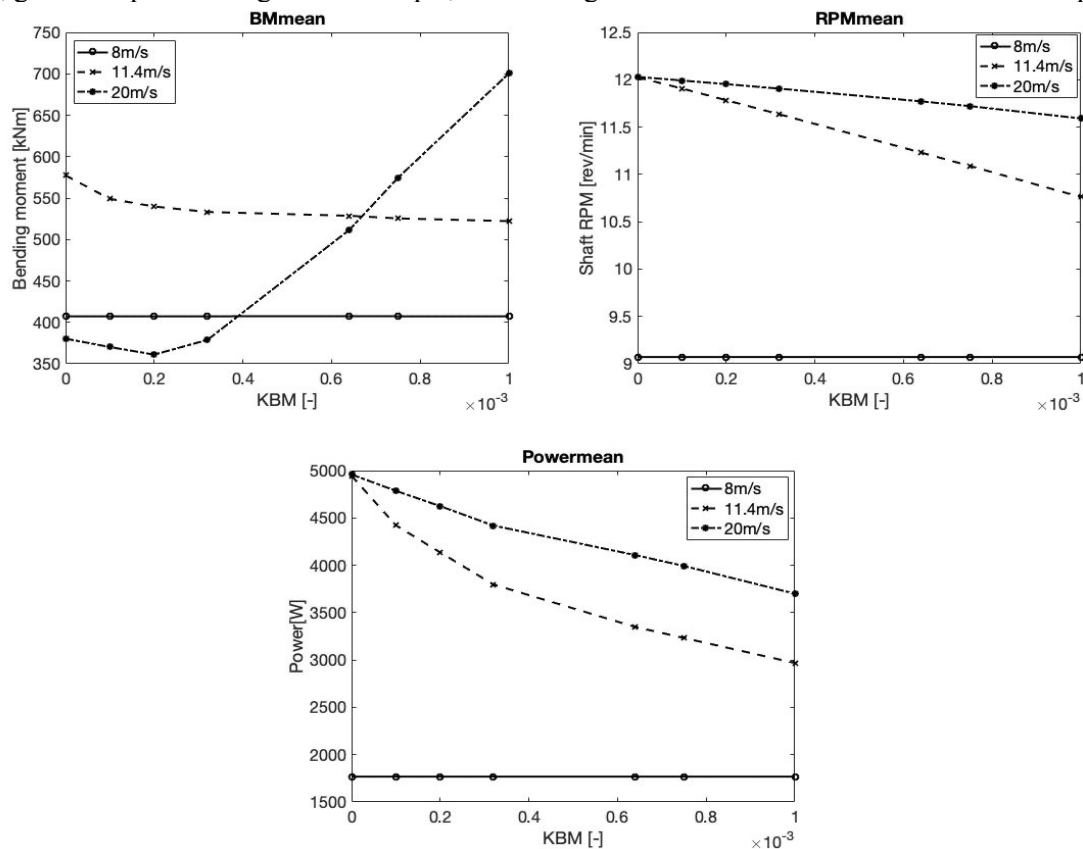
Figure 3. Steady state wind results at 3 different speeds with varying K_{BM}; a. BM (top-left), b. RPM (top-right) and c. Power (bottom).

At the underrated wind speed (8 m/s), the pitch controller is not activated, therefore there are no changes to the results for all values of K_{BM}. At the rated wind speed (11.4 m/s), the bending moment drops with increasing K_{BM} but plateau after it reaches 0.001. While at the above-rated speed (20 m/s), an interesting phenomenon is observed as the BM drops for the lower K_{BM} values and increases for the higher values. This phenomenon can be explained by the fact that as K_{BM} increases, the error is added to the PID from the bending moments that become significantly larger than the shaft RPM. This causes the system to start behaving erratically as errors are corrected incorrectly. Similar erratic behaviour can similarly be expected at other speeds in the above the rated speed ranges (e.g., 15 or 18 m/s) as the K_{BM} approaches 1). The bending moment drops with a negative gradient from 0 to 0.0002. This is as expected since the bending moments that is added at these K_{BM} suits their shaft error proportionally. Thus, a good proportionality allows the errors to be corrected more accurately. Further detailed analysis is conducted for K_{BM} values (between 0 and 0.0001) in the above-rated speed to garner improved efficiency of the bending moment values in that region. This detailed analysis is shown in Figure 4.

The shaft RPM values drop steadily for an increasing K_{BM} value for the rated and above-rated wind speeds. As these two lines decrease, in both cases, the shaft RPM error corrects the system to achieve its optimal shaft speed, which is the primary controller objective. The result shows a significant drop in power at the higher K_{BM} at both the rated and above-rated wind speeds. However, at the lower K_{BM} the power loss can be potentially better controlled and minimized.
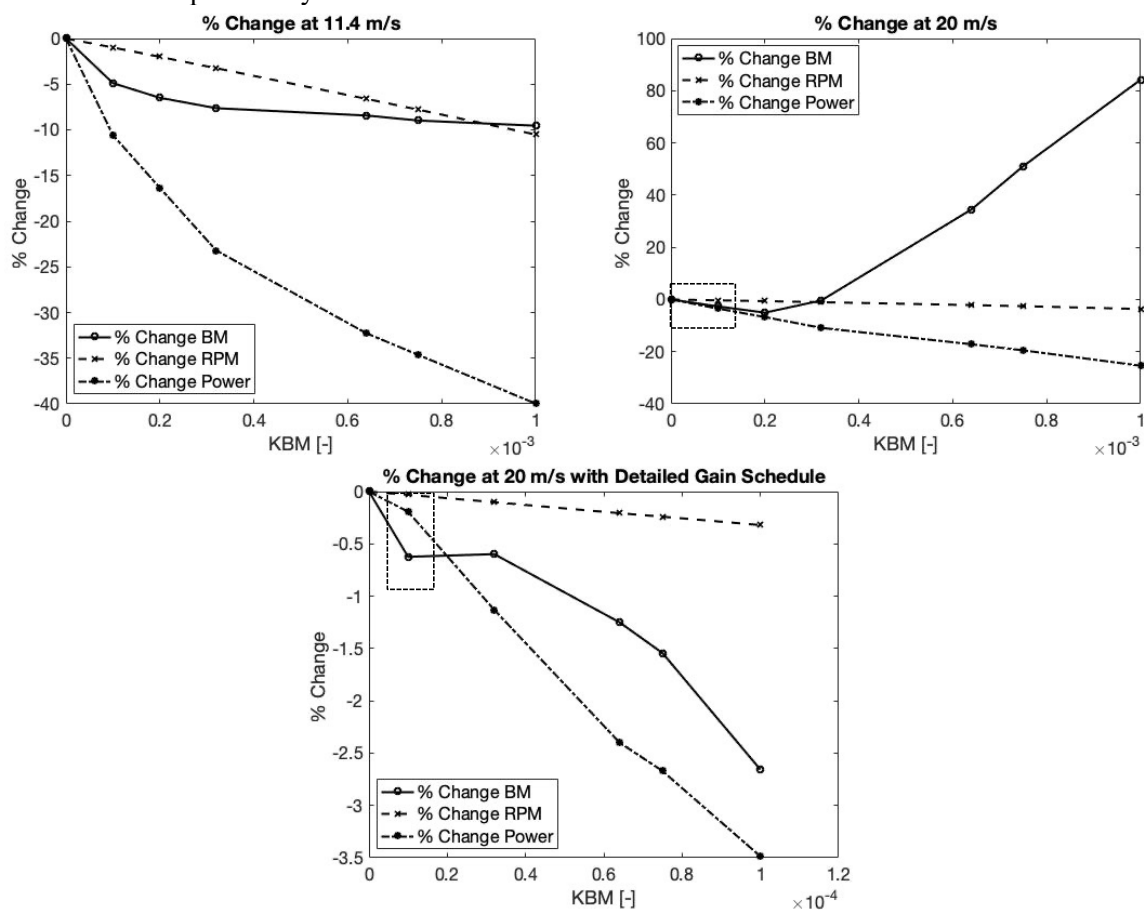

Figure 4. Steady state wind results (percentage (%) change for BM, RPM and Power) with varying K_{BM}; a. Rated (top), b. Above-rated (bottom-left) and c. Above-rated with K_{BM} scheduling(bottom-right).

The results from Figure *4* show that at rated speed (11.4 m/s) and above rated speed (20 m/s), all the percentage change of bending moments, shaft RPM and generator power are dropping with an increasing K_{BM}, except for the above rated speed (20 m/s) bending moment which reasoning was explained in the previous section. For the rated speed (11.4 m/s), Figure 4(a) indicates that 0.0001 gives the minimal proportion of losses between the percentage change of bending moments, shaft RPM and generator power. While for the above rated speed (20 m/s), a more detailed analysis was done in the ranges of 0.00001 to 0.00015 (boxed-up region: Figure 4(b)) to identify the best K_{BM} values. Figure 4(c) shows the results of the detailed gain scheduling of Figure 4(b). Figure 4(c) indicates that 0.00001 gives the minimal proportion of losses between the percentage change of bending moments, shaft RPM and generator power. More importantly, in Figure 4(c) at 0.00001, the bending moment loss is more significant than the power loss. Therefore, even though the percentage change might be small, it gives an ideal situation since the turbine reduction in bending moments is more than the loss in power

5.2. NTM wind

The results of the NTM wind cases are presented in Figure 5 and Figure 6. Like the steady wind cases presented in Section 5.1. , when calculating the shaft RPM, generator power and generator torque, their average values of the last 100 seconds were computed.
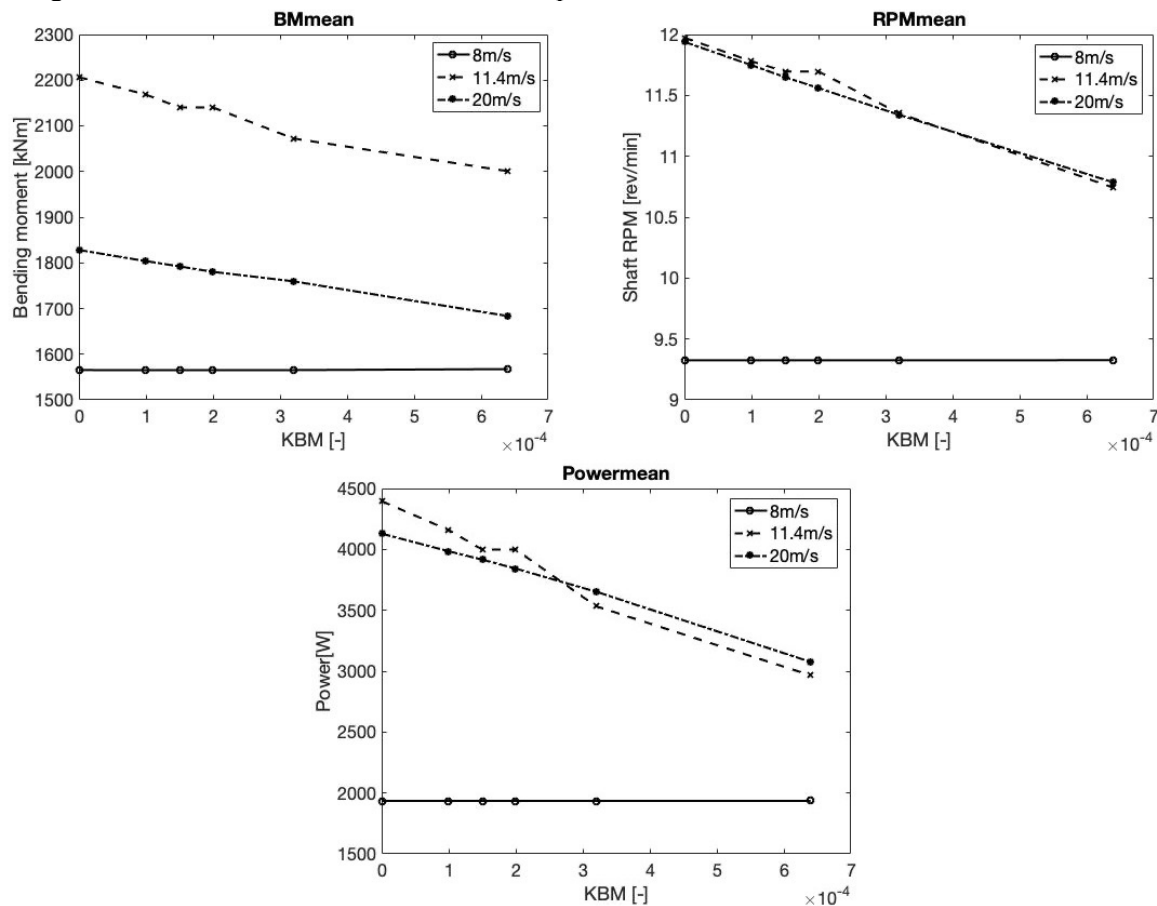

Figure 5. NTM wind results at 3 different speeds with varying K_{BM}; a. BM (top-left), b. RPM (top-right) and c. Power (bottom).

Similarly, for the NTM wind cases, at the under-rated wind speed (8 m/s), the bending moment, shaft RPM and generator power change are assumed to be zero due to the inactivation of the pitch controller. However, in the normal turbulent wind model the drop in the bending moments, shaft RPM and power seem to be relatively linear for both the rated and above-rated wind speeds. This is expected since with

the turbulent wind model the speed of the wind is varying at differently and averages out at the selected wind speed. The wind's net effect on the bending moment in this model clearly shows the steady dropped experienced with increasing K_{BM}.

The turbulent models' rated or above-rated speeds produce very similar shapes for the shaft RPM and power in all measured K_{BM} values. The bending moment values of the above rated speed is also lesser than the rated speed (using $K_{BM} = 0$ as reference). This is accounted for correctly by the fact that as the blades pitches at above the rated speed, the bending moment acting on the turbine body and shaft is reduced.
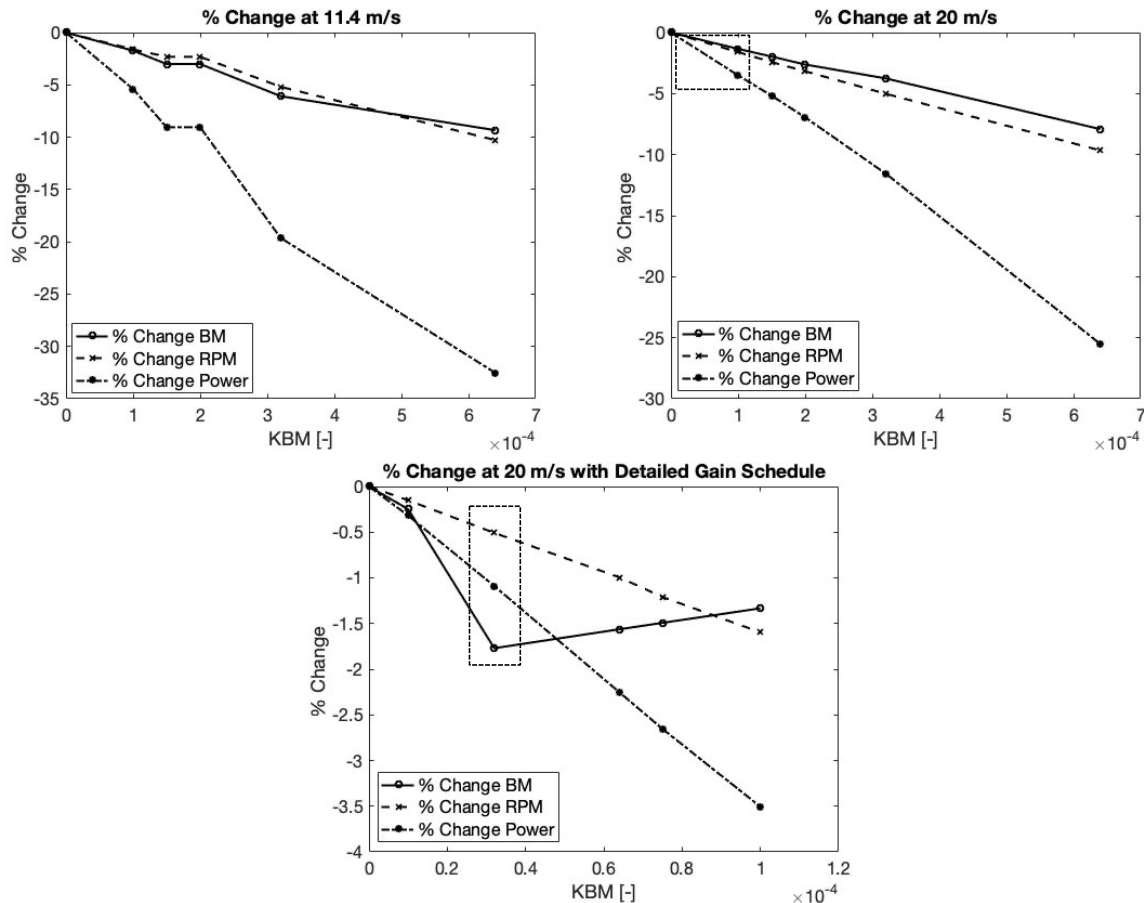
Figure 6. NTM wind results (percentage (%) change for BM, RPM and Power) with varying K_{BM}; a. Rated (top), b. Above-rated (bottom-left) and c. Above-rated with K_{BM} scheduling(bottom-right).

For the rated speed (11.4 m/s), in Figure 6(a), it can be seen clearly that the percentage change in bending moment and power decreases at the same rate while the power is more significantly affected with increasing K_{BM}. While for the above rated speed (20 m/s), in Figure 6(b), further investigation was done in the boxed-up region to find an appropriate K_{BM} value that can minimize the losses between the bending moments, RPM and power. These results are shown in Figure 6(c). In Figure 6(c), the best K_{BM} values are identified when there is more percentage loss of bending moment than power. A similar pattern was observed in the steady-state model. However, the K_{BM} value (0.000032) in the turbulent model is different from the steady-state model.

5.3. Best K_{BM} values
To estimate the best K_{BM} values for each wind speed, the best ratio for the percentage bending moment and percentage RPM is calculated. The higher the ratio would imply that the maximum decrease in

bending moment has been achieved with minimal change in RPM or power (P). The change is 0 at under rated wind speed (8 m/s) is insignificant and assumed to be zero. The results are presented in Table 2.

Table 2. Best K_{BM} values

Wind speed (m/s)	8	11.4	20
% difference, BM mean	0	-3.0041	-1.7701
% difference, RPM mean	0	-2.3144	-0.5079
Best ratio (%BM/%RPM)	0	1.29	3.48
Best ratio (%BM/%P)	0	0.33	1.62
K_{BM}	0	0.00015	0.000032

The percentage BM / percentage P ratio is less than 1 at the rated speed (11.4 m/s) and more than 1 at the above rated speed (11.4 m/s). Even though it might be questionable if the benefits are worthwhile at the rated speed, it is unquestionably beneficial at the above rated speed. The ability to minimize the bending moments acting on the shaft and eventually the gearbox will increase the gearbox's life span significantly as described by the S-N curve. Furthermore, the K_{BM} value can be scheduled to 0 at the rated speed if cost analysis research shows that it gives the most positive results.

Finally, it can be summarized that varying K_{BM} values and then adding the BM errors positively affect the reduction of the structural load oscillations. Furthermore, changing the K_{BM} values and thus the BM errors magnitudes seem to have a linear relationship within the examined ranges of 0.00001 to 0.001. However, it is essential to acknowledge that it does not necessarily mean that this relationship holds to different wind speeds or different ranges of K_{BM} values. Furthermore, it must be emphasized that the control algorithms used only considered the pitch angle controller for one blade and cumulated the results which were used for all three blades.

6. Conclusions

Control algorithms that can reduce the bending moment in the low-speed shaft will eventually reduce the internal drive train loads within the gearbox, thus extending its lifespan. This paper has shown that adding a bending moment error into the pitch controller can positively affect the bending moment acting on the low-speed shaft. The bending moment can be reduced by about 3 % for the rated wind speed (11.4 m/s) and 1.8 % for the above-rated wind speed (20 m/s) while only losing 2.3 % and 0.5 % of the shaft's rotational speed, respectively. Furthermore, a linear relationship was observed between the gain scheduled bending moment errors and the reduction of total bending moments if the K_{BM} values are scheduled in an appropriate range. However, further studies need to be done to ensure consistency of such reduction at different wind speeds. It is also vital to ensure that lifespan extension does not substantially reduce the turbine's power, torque, or rotational speed.

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