Repetitive Individual Pitch Control for Load Alleviation at Variable Rotor Speed

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Abstract. In recent years, wind turbines have been growing in size and became more lightweight and thus more flexible. Spatial variation in the wind speed results in asymmetrical blade loads, which include a periodic component increasing with growing wind turbine size. Asymmetrical blade loads can be reduced by individual blade pitch control in general and repetitive control can reduce especially the periodical parts of the loads. We investigate, how a repetitive control based individual blade pitch controller as extension to an existing collective pitch controller can reduce periodical loads resulting from unsteady non-uniform wind conditions under consideration of variable rotor speeds. As plant, we use a simulation model of a 3 MW wind turbine, developed by W2E Wind to Energy GmbH, and control it with a model predictive collective pitch controller. This controller is extended with the proposed repetitive individual pitch control scheme. This study shows, that the presented repetitive controller reduces especially the tower yaw moments by up to 65% and higher harmonics of the blade root moments by up to 30% at the cost of increased pitch activity. Hence, for the use of this controller one has to balance the load reduction of blades and tower with increased loads of the pitch actuators.

1. Introduction

Due to expansion of wind energy, wind farms have already been built in the most favorable areas, so new wind turbines have to be installed in suboptimal locations. As wind energy must compete with other especially conventional energy producing technologies in terms of energy yield, production capacity and efficiency, wind turbines are steadily growing in size. The lighter and thus more flexible their mechanical structures become, their sensitivity toward mechanical load and load alteration increases [1]. Especially the spatial variation of the wind speed influences these altering loads [2, 3]. As another effect with large wind turbines, local gusts which only effect parts of the rotor plane area have increasing temporal stability the wider they are [4]. This causes multiple blades to pass through similar load conditions and therefore, especially the blade and tower loads show periodic behavior. Wind turbine controllers are not only designed for optimal power production, i.e. the wind turbine generates the most energy possible, but they also contribute significantly to load reduction.

In our former publications [1, 5], we investigated model predictive controllers (MPC) for power control and load alleviation of the tower in form of a collective blade pitch controller (CPC). In this study, we investigate how an already designed CPC can be extended by an
individual blade pitch controller (IPC) in combination with a repetitive control (RC) operating in parallel to the CPC, in order to reduce the loads of the individual blades.

1.1. Theory and research
Firstly, we outline related work in the context of load reduction in order to reduce asymmetrical blade loads. Subsequently, we present our objective to extend an existing MPC by an IPC to reduce loads of the wind turbine.

**Individual pitch control:** Most modern wind turbines offer individual blade pitch actuators. This offers IPC to reduce asymmetrical mechanical loads. Different types of IPCs are introduced in [3, 6, 7] which basically use the Coleman Transformation algorithm [8] to decouple the control tasks of reducing horizontal and vertical loads. These controllers basically reduce blade loads occurring at 1P (once per revolution) and tower loads at 3P. For instance, [7] proposed an additional control loop for every considered harmonic to reduce loads of higher harmonics.

**Gain scheduling:** The dynamic behavior of classical wind turbines cannot be modeled linear time invariant, but has to be considered as linear time variant (LTV). One can adjust linear behavior over a wide operational range by compensating the varying transmission factors with the wind turbine controller gains. This gain scheduling can create satisfying time invariant behavior of the wind turbine in most of the operation conditions [9].

**Repetitive control:** Wind characteristics in many wind turbine sites produce periodic loads which effect two or more blades after each other [4]. Classical IPC can only react towards those loads, with a certain phase, and thus only partly compensates those loads. With the periodic information the controller can act before the load affects the next blade. In turbulent wind, there are coherent structures of similar wind speeds, which effect the blades several times [3].

In [10], an RC has been used to harmonize the wind turbine loads through an MPC which itself operates as IPC. The design procedure of an MPC usually needs some experience. Also the commissioning of MPC is complicated. In [2] they use RC to control rotor blades with active flaps. The variation of the rotor speed is assumed small enough, that it hardly influences the RC. [11] adopts the sampling frequency of a controller for generators to the grid frequency in order to reduce grid effects to the generator. Thus, they need a controller operating at variable frequencies. In [12] a subspace predictive repetitive control is introduced. The dimensions of the RC formulation are reduced by sinusoidal basis functions. For every harmonic load frequency, they use a separate sinusoidal function. To take varying rotor speed into account, the cycle length of the RC which is related to the duration of the rotor revolution is adopted to the rotor speed. When loads occur at slightly different times in the repetitive cycles, the cycle length varies. Doing this, they accept possible effects to the controller performance.

To conclude, if variable rotor speed is considered in RC, this is done either by variable operating step size or with variable cycle length. As wind turbine controllers generally operate in fixed time steps, integration of these methods would require further adaptations.

1.2. Research context and objectives
Especially the blade root moments and the tower loads are cost drivers of wind turbines. In this paper, we investigate the fore-aft blade root loads which show great periodicity not only in the 1P-frequency, derived e.g. from wind shear, but also in higher harmonics. The aim of the suggested RC-based IPC is to reduce loads caused by unsteady non-uniform wind conditions.

The measured disturbances are filtered with a binomial filter, which can be adjusted to reduce many harmonics with few parameters. With the presented control concept, we are also able to
reduce higher harmonics of the blade loads. The asymmetrical loads act separately on the blades and have little effect on the power output which is controlled by the CPC. For simplification, we assume that the CPC and the IPC are loosely coupled, i.e. the controllers do not affect each other concerning the loads, which we aim to reduce. The presented RC deals with varying rotor speeds and uses a constant sampling time to prepare the control algorithm for practical use.

1.3. Research questions and hypotheses
Since the MPC already reduces loads, an open question is how effective RC-based IPC can additionally reduce the wind turbine’s loads. During the design process it is often assumed that IPC and CPC can be considered separately. Especially in combination with an MPC it is part of the investigation if this hypothesis is valid. Based on this, we formulate two research questions:

(i) Which loads can be reduced by the additional RC in IPC?
(ii) Does couplings between the MPC and the IPC influence the effectiveness of the control system?

For the testing setup, we compare the MPC separately with the combination of IPC and MPC. The minor modified MPC from [5] remains unchanged for the testing. To keep the IPC in its operational boundaries, the IPC gain is reduced when the RC is active. This gives the following hypotheses:

(i) The blade root loads of the 1P/2P frequency and the tower loads of the 3P/nP frequency can be reduced by the IPC/RC, whereas the pitch actuator activity is increased.
(ii) The cross coupling between the MPC and the IPC is negligible.

The paper is organized as follows. In Section 2 we give the simulation setup in which the controllers are validated. Section 3 presents the RC design which is analyzed in Section 4 and discussed in Section 5. Finally, in Section 6 we conclude this research.

2. Wind turbine model and simulation setup
The considered wind turbine is a 3 MW onshore wind turbine designed by W2E Wind to Energy GmbH (W2E) and shown in [13, 5].

![Control loop diagram](image)

Figure 1: Control loop consists of wind turbine and control system with parameters in Table 1.

| Name                        | Symbol          |
|-----------------------------|-----------------|
| Blade root moments          | $M_i, i \in \{1, 2, 3\}$ |
| Pitch angles                | $\theta_i$      |
| Rotor azimuth angle         | $\alpha$        |
| MPC-measurements            | $y_{MPC}$       |
| Desired individual pitch angle | $\theta_{i,ref}$ |
| Desired collective pitch    | $\theta_{ref}$  |
| Individual pitch offset     | $\Delta \theta_{i,ref}$ |
| Generator torque            | $T_{gen}$       |
| Wind speed                  | $v_{wind}$      |

Table 1: Variables of the control loop.
The wind turbine is used in wind farms as well as solitaire. For simulations, we consider turbulent wind of IEC-turbulence class A. We analyze simulations with three different hub height mean wind speed of $v_{Wind} = 12 \text{ m s}^{-1}$, $15 \text{ m s}^{-1}$ and $18 \text{ m s}^{-1}$.

We model the wind turbine in the FAST simulation tool\(^1\) and we designed and modeled the controller itself in Mathworks MATLAB SIMULINK (Simulink), where we include the FAST simulation via DLL for closed loop simulations.

The control scheme is given in Figure 1. The controller consists of two components: A power controller which already reduces mechanical loads of the tower and sets the generator torque and the collective pitch angle. It is designed for above rated wind speeds. The second component is an IPC, which operates in parallel to the MPC. This IPC consists of a baseline IPC realized as PI-Controller which is extended by the proposed RC.

3. Design of a repetitive controller
In the following section we present the structure of the IPC and describe the design of the RC. The asymmetrical loads have periodical and non-periodical components. To compensate control deviations from both parts, the presented IPC design combines the baseline IPC command $u_C$ with the RC command $u_{RC}$, as shown in Figure 2.

By using the Coleman Transformation $C$ for wind turbines in (1) and (2), it is possible to transform the measured rotating blade loads $M_i$ using the rotor azimuth angle $\alpha$ into non-rotating $d - q$ coordinates.

\[
(M_d \quad M_q) = \begin{bmatrix} 2 \cos(\alpha) & \cos(\alpha + 120^\circ) & \cos(\alpha + 240^\circ) \\ 3 \sin(\alpha) & \sin(\alpha + 120^\circ) & \sin(\alpha + 240^\circ) \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} \]

\[
(\theta_{ref,1} \quad \theta_{ref,2} \quad \theta_{ref,3}) = C\begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ \cos(\alpha + 120^\circ) & \sin(\alpha + 120^\circ) \\ \cos(\alpha + 240^\circ) & \sin(\alpha + 240^\circ) \end{bmatrix} \begin{bmatrix} u_{IPC,d} \\ u_{IPC,q} \end{bmatrix} \]

The non-rotating loads are controlled by the baseline IPC and its command $u_{IPC,d}$ is transformed to the actual commands $\theta_{ref,i}$ [3]. This way, it is possible to reduce the 1P loads of the blades and the 0P loads of the tower [7].

The proposed RC with its command $\pi_{RC}$ also operates in $d - q$ coordinates and thus we can integrate the commands of the baseline IPC $\pi_C$ directly, by adding both commands to the complete IPC command $\pi_{IPC}$ (3). Thus, the baseline IPC reacts to the actual control deviation and the RC command addition compensates the periodical loads,

\[
\pi_{IPC}(\alpha) = \pi_{RC}(\alpha) + \pi_C(\alpha).
\]

The RC uses the loads that occurred 120° before the current rotor azimuth angle. In (4), the RC combines the command of the former manipulated variable and the control error $e$, with the RC gain $\phi$. More specific, the transformed moments $M_{(d,q)}$ are $e$. The spatial variation of the wind speed changes in time, hence also the periodical parts of the blade’s moments vary. To consider this in the RC, the forgetting factor $\lambda$ with $0 \leq \lambda \leq 1$ is introduced:

\[
\pi_{RC}(\alpha) = \lambda \hat{u}_{IPC}(\alpha - 120^\circ) + \phi e(\alpha - 120^\circ).
\]

\(^1\) Fatigue, Aerodynamics, Structures and Turbulence simulation tool by the National Renewable Energy Laboratory
The forgetting factor $\lambda$ determines the amount of the measured last periods control command $\hat{u}_{IPC}$, which we keep for the next cycle.

As the wind turbine is modeled as LTV system with varying parameters in the stationary transmission behavior from pitch angle to blade loads, controller gain scheduling is applied with

$$\partial M_{\{d,q\}}/\partial \theta(\theta) \cdot \left( u_{IPC,\{d,q\}} - \hat{u}_{IPC,\{d,q\}} \right) = \left( \pi_{IPC,\{d,q\}} - \pi_{IPC,\{d,q\}} \right).$$

Here gain scheduling is analogously designed to gain scheduling for power control in [3], but using the thrust coefficient instead of the power coefficient. Therefore, the gain is chosen, such that the steady state transmission from $\pi_{IPC,\{d,q\}}$ to $M_{\{d,q\}}$ is equal to 1 for small deviations from an operating point $(\cdot)_0$.

### 3.1. Damping high frequencies

Studies of the duration of local gusts have revealed that the time it takes for most these gusts to pass through the rotor plane is the time it takes for the blades to pass through the affected plane area 3 and 5 times. The influence of a gust varies with time as it passes through the rotor plane. This variation is considered by the forgetting factor $\lambda$ in (4) so we only reuse a part of the former control command.

The proposed RC operates in fixed steps $\Delta \alpha$ with $\alpha = k \Delta \alpha$. Based on (4) the control law is formulated as

$$\pi_{RC}(k) = \lambda \pi_{RC}(k - p) + \sum_{i=1}^{i_f} f(i) \left( \lambda \pi_C \left( k - p - \frac{i - 1}{2} \right) \right) + \phi(i)e(k - p + \gamma + i).$$

### Table 2: Controller Symbols of the IPC

| Name                        | Symbol | Name                        | Symbol |
|-----------------------------|--------|-----------------------------|--------|
| Coleman Transformation      | $C$    | pitch angle                 | $\theta_i$ |
| inverse Coleman Transformation | $C^*$ | unscheduled command         | $\bar{u}$ |
and is given for discrete angular positions $k$ of the rotor. We compose the former RC command $\pi_{RC}(k-p)$, which was given $p$ steps ago, with the filtered former baseline IPC command $\pi_C$ and the filtered former control deviation $e$. The period length $p$ with $p \Delta \alpha = 120^\circ$ is chosen, that its length describes a third of a rotor revolution. Due to a delay e.g. from communication between the control command and its impact on the control error, the error is shifted by the number of delay steps $\gamma$. The phase of the system can be considered in the learning factor or RC gain $\phi(i)$ which also determine the learning rate.

We use the binomial filter $f(i)$ with the filter length $i_f$ to reduce the influence of noise and disturbances with high frequency (7). The local wind speed inside of gusts changes even slower, the smaller the spatial gradient of the wind speed is [4]. Vast gusts would lead to slow changes in the loads, as the blades take a long time to pass them. Hence, the periodical affect of a gust and its resulting moments is even less, the shorter it affected a blade, or the higher its frequency is.

We also want to damp the control error input and the command $u_C$ which monotonously increases with higher frequencies. Therefore, we use the binomial filter

$$f(i) = \binom{i_f}{i} 2^{-i_f}; \text{ e.g. for } i_f = 5: f = [0.0625 \ 0.25 \ 0.375 \ 0.25 \ 0.0625]. \quad (7)$$

3.2. Lifted system design and receding horizons

The formulation from (6) can be transformed into the lifted system domain form (8) and (9), where the whole RC command vector of a period $j$ is calculated.

$$U_{RC,j+1} = S \left(U_{RC,j} + F U_{C,j} + \Phi F E_j\right) \quad U_{RC} \in \mathbb{R}^p; \quad U_C, E \in \mathbb{R}^{p+i_f-1} \quad (8)$$

$$U_{RC,j+1} = \lambda \left(U_{RC,j} + \begin{bmatrix} f_1 & \cdots & f_n & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & f_1 & \cdots & f_n \end{bmatrix} U_{C,j}\right) + \phi \begin{bmatrix} f_1 & \cdots & f_n & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & f_1 & \cdots & f_n \end{bmatrix} E_j \quad (9)$$

The control command has to be calculated in every operation step. In practice, the command vector $U_{RC}$ with its elements $U_{RC}(\cdot)$ is updated with every new measurement at step $k$ to keep the calculation effort constant:

$$U_{RC,j+1}(k+1) = U_{RC,j+1}(k) + \lambda U_{RC,j} + \lambda F^{p \times 1, i} u_{C,j}(k) + [\Phi F]^{p \times 1, i} e_p(k) \quad (10)$$

After each calculation step, the last value of $U_{RC,j+1}(p)$ will be taken as control command. As the element $U_{RC,j+1}(p)$ of $U_{RC,j+1}$ now is the first element of $U_{RC,j}$, the vectors are shifted by one element, so the horizon recedes with every step.

3.3. Include Variable Rotor Speed

The variable rotational speed has an impact to the RC design process at two points.

Firstly, as the control system operates at fixed time steps $t_n = n \Delta T; n \in \mathbb{N}$, rotor azimuth angle and time are not equivalent. As the RC-periodicity is given in $\alpha$, we calculate the manipulated variables in fixed angular steps $\alpha_k = k \Delta \alpha$, but we cannot derive them directly from the measurements. Also, the control output has to be given at fixed time steps $t_n$ and the angle $\alpha(t_n) = \alpha_n$ may differ from $\alpha_k$.

Here, we choose the step width $\Delta \alpha$, so that the number of angular and time steps per revolution are similar. To ensure, that values of $u_C$ and $e$ are set on every step without a loss of information, we combine interpolation and weighted mean values for the calculation of $\alpha_n$ with
\[ \alpha_n = \alpha(n \Delta T) \] and \( \alpha_k \). This can be dealt with either by interpolation between the adjacent measured values, or by calculating a mean of the measured value inside an interval (11).

\[ x_k = \begin{cases} \frac{(\alpha_k - \alpha_n)(x_{n-1} - x_n)}{\alpha_{n-1} - \alpha_n} + x_n, & \alpha_{n-1} < \alpha_k < \alpha_n \\ x_i, & \alpha_k = \alpha_n \\ \frac{1}{n - n_0} \sum_{i=n_0}^{n} x_i, & \alpha_{n_0-1} < \alpha_{k-1} < \alpha_{n_0} < \alpha_n < \alpha_k \end{cases} \]

We calculate the mean value (bottom) from all the measured values \( x_i \) from the first time step in \( n_0 \) to the actual time step \( n \) inside an angular interval which is from angular step \( k - 1 \) to \( k \). Here, \( x \) represents the transformed measurements of the Pitch angles \( \theta_{d,q} \) and the Blade Moments \( M_{d,q} \). This way, the period length always correlates with the rotational speed and the measurements are fitted into the angular positions, if time steps and angular steps vary.

Secondly, the Dynamics of the wind turbine model are given in time or frequency domain. Especially the delays of the system now vary in the angular domain as well as the model dynamics change. This has an impact on how to choose the RC-gain \( \phi \). As the influence of the delay on the loads here is much smaller than the influence of drifting periods, the variety of the delay is neglected.

4. Simulation study
To show the benefit of this control concept, we simulate the wind turbine described in Section 2 in different turbulent wind speeds. We parameterized the RC with the RC-gain \( \phi = 0.5 \), the forgetting factor \( \lambda = 0.7 \), the binomial filter length \( i_f = 30 \), and the period length \( p = 120 \). The MPC used for CPC is designed for above rated speed only. The physical limits of the actuators were not been exceeded. For a detailed analysis, we exemplary start with detailed analysis of the load case with the wind speed \( v_{\text{Wind}} = 15 \, \text{m/s} \). Afterwards, we compare between all three considered load cases in general in Section 2.

To assess the improved control performance, we analyze the benefits as well as the costs of these benefits. Representative for the costs is the dynamical control effort. The benefit is supposed to be an extended lifetime of the wind turbine, which can be achieved by a reduction of the amplitudes or the number of the load cycles. As representative variables for the loads, we consider the blade root moments, the tower torsional and the tower bottom bending moments. The values are analyzed in frequency domain, to show characteristic differences between the baseline IPC and the RC. Furthermore, we extracted damage equivalent loads (DEL) for the different wind speeds shown in Section 2 to give an overview of the load variation for different wind speeds.

Figure 3 shows the frequency spectra (top, middle) and the load distribution (bottom) of the pitch angle, the blade root moments, the tower fore-aft moments and the tower torsional moments (left to right) for each of the three controller setups (colors). The frequencies are normalized to the 1P frequency and the amplitudes and load distributions are normalized to the maximum occurred amplitudes over all simulations.

The pitch activity in the 1P-frequency is increased with IPC for all frequencies. When using the RC, also the amplitudes in the 2P and 4P frequencies are increased compared to the baseline IPC. Also, the distribution of pitch positions shows for both IPC types, that the operational area is slightly increased and that especially the peak at 0.5 is reduced. This peak in the distribution is the optimal pitch angle for wind speed of \( v_{\text{Wind}} = 15 \, \text{m/s} \). Also, the distribution slightly shifted towards smaller pitch angles.

For the CPC, the blade root moments show a characteristic peak at the 1P frequency, which is reduced by both IPC’s. The RC also reduces the 2P loads by 30%, whereas the reduction of
Figure 3: Comparison of tower and blade loads normalized the maximum values reached in simulation. Frequency analysis and probability density for CPC (yellow), IPC without RC (green) and RC based IPC (blue). Frequency is normalized to 1P and histogram for $v_{Wind} = 15 \text{ m s}^{-1}$.

The 3P loads by the RC is negligible. As shown in the load distribution, the range, in which the blade root moments vary is decreased by the RC more than by the baseline IPC.

The effect of IPC on the towers fore-aft moments is assumed to be in the range of 3P. With the presented setup, the baseline IPC has nearly no effect in this frequency range, but the RC slightly reduces the amplitude here. Also the operational range of the tower bending moments is hardly reduced by both IPC’s.

The tower torsional moments have a mean value close to zero. For CPC the probability density is slightly shifted to negative moments whereas for IPC and RC this is slightly shifted to positive moments. Both IPC’s reduce those oscillations significantly compared to the CPC. In ranges of small frequencies the baseline IPC reduces the amplitudes more than the RC. IPC reduces low frequent torsional moments below 1P by up to 70 % (IPC) and 80 % (RC). For higher harmonics, the RC reduces torsional moments in the 3P range, but increases the amplitudes in the 1P range and for higher frequencies. The histogram shows that the range of torsional moments is decreased by both IPC’s, where the RC has the greater effect.

In Figure 4 the results for all simulated wind speeds are compared using DEL statistically. The DEL’s are a typical measure for fatigue damage. Here we take into account the fatigue
properties of steel and composite material with an S-N slope of 4 and 10 respectively. These loads are normalized to the maximum occurring load amplitudes during the simulations. For the pitch actuators, we determined the DEL indirectly by assuming the loads being proportional to the pitch rate. As representative value for the pitch load we also compare the absolute rotational pitch distance during the simulations.

The pitch angle fatigue is increased significantly by both IPC-variants especially for low wind speed. Although the pitch motion itself does not contain direct information about the fatigue damage, the fatigue is correlated to it. So the pitch actuators need to be more robust when using IPC especially with the presented RC. Also the covered pitch distance has increase by 50 % up to 80 % (IPC) and nearly doubled for RC.

On the other hand, IPC could reduce the fatigue of the blade root between 45 % and 80 % without RC and up to 85 % with RC. For the blade moments, the IPC is most effective with high wind speeds. As already seen in the frequency domain, the tower fore-aft fatigue is hardly affected by IPC. For wind speeds around $v_{\text{Wind}} = 15 \, \text{m s}^{-1}$ the DEL are slightly increased and for $v_{\text{Wind}} = 12 \, \text{m s}^{-1}$ and $v_{\text{Wind}} = 18 \, \text{m s}^{-1}$ they are slightly reduced. The tower torsional DEL are decreased by IPC. IPC without RC reduces the tower torsional DEL between 15 % and 30 %. Including RC, the DEL are reduced up to 65 % ($v_{\text{Wind}} = 15 \, \text{m s}^{-1}$).

With rising wind speed, the blade root fatigue and the tower fatigue resulting from torsional loads increase. With IPC this effect is reduced, so that IPC decreases the fatigue loads especially for higher wind speeds above rated wind speed.

5. Discussion
In this section, we discuss the results with respect to the research question and the hypothesis from Section 1.3. As expected in hypothesis (i), the pitch actuators are much more active when using IPC, than using CPC only, because the controller compensates more disturbances. These disturbances result from the spatial variation of the wind speed, which can only be reduced by IPC, but therefore, the pitch actuators need to be more mechanically robust.

Also, IPC reduced the 1P (baseline IPC) and 2P (RC) blade loads (hypothesis (i)) by up to 30 %. We expected this, since the IPC is designed to reduce especially loads in this frequency range. The 2P loads result from smaller spatial variation in the wind than the 1P loads and thus
these variation remains for shorter periods of time. As the RC which addresses the 2P loads is more powerful the longer disturbances affect the wind turbine, the RC reduces the 2P loads less than the 1P loads.

To answer research question (ii), we analyzed the tower bending moments. It was expected, that the IPC in general would reduce the 3P tower loads effectively, but the load reduction in these frequencies are minor. This can be explained with respect to the MPC design: The MPC reduces loads, that are estimated using the tower top acceleration [5, 1]. The asymmetrical loads, which are reduced by the IPC, also affect the tower top acceleration. As the MPC already reduced the loads onto the towers fore-aft motion and loads, the IPC has no additional effect here. That the median pitch angle in case of the IPC is slightly reduced, is interpreted as a result of these cross couplings. The IPC is designed to reduce the loads resulting from the thrust. By doing this, the power production is slightly reduced, which is compensated by the MPC with a smaller pitch angle. This shows, that hypothesis (ii) does not hold, because the MPC and the IPC influence each other.

Considering research question (i), both blade root DEL and tower torsional DEL could be reduced by up to 85 % and 65 % respectively. As the CPC does not have a direct effect onto these loads, IPC is the only control method to reduce those loads. The positive tower torsional moments result from an inclined rotor axis, which is typical for modern wind turbines. The IPC overcompensates this offset in the torsional moments. This can be explained by the IPC’s phase. Control actions which are supposed to reduce the tower bending moments also act onto the tower torsion.

With growing wind speed, the sensitivity of the loads towards the pitch system grows. Even though the turbulence changes faster, so that the pitch actors must act faster to reduce loads, IPC reduces especially the blade loads more effectively for higher wind speeds. But this leads to increasing pitch activities and fatigue, so that the advantages of the reduced loads must be weighted against the disadvantages of the increased fatigue of the pitch systems. A general statement cannot be given here, because this depends on the wind turbine, material costs and many others.

As the baseline IPC is combined with the Coleman Transformation, we already reduce the cross coupling between torsional and fore-aft load control. The Coleman Transformation also ensures, that the mean pitch angle demanded by the CPC is not changed through the IPC. Using gain scheduling, the proposed IPC can operate in a wide range of operation points and facilitates the inclusion of the RC, because the RC parameters could be held constant for the whole operational range.

6. Conclusion

The presented RC-based IPC can especially reduce loads of the blades, one of the cost driving elements of a wind turbine. Furthermore, certain higher harmonics of the blade loads are reduced up to 85 % by the RC. The tower torsional DEL are reduced by up to 30 % by IPC and up to 65 % by RC compared to the CPC. These loads are difficult to address solely using classical control schemes.

The presented controller can operate parallel to CPC, hence the RC can be used to extend an existing CPC. This controller can be applied as superimposed controller to different types of wind turbine controllers, especially those that act on a collective pitch angle. As this is shown here for above rated speed, in future work this will be done for partial load regions.

In the presented setup, the IPC controls the wind turbine loads, namely the out of plane blade root moments, by direct measurement. In future work, this can be done indirectly, by measuring the nacelle’s acceleration and angular velocity, as shown in [14]. The effects of different parameters inside the RC and the relation between the RC and IPC gain could be investigated for different wind turbines to give more general recommendations for the use of RC in wind
turbines. A comparison of sinusoidal basis functions with binomial filters will be investigated in future work. Also, the IPC could be directly included into the MPC, to investigate, if the MPC can operate in real time despite increasing model complexity and manipulated variables.

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