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Optimizing Wind Turbine Load Reduction: Trade-offs Including Blade Angle Deviation in PID Individual Pitch Control and MPC Collective Pitch Control

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1 Abstract

This study investigates trade-offs in Individual Pitch Control (IPC) for wind turbines by optimizing proportional-integral-derivative (PID) controllers, introducing blade pitch angle deviation as a performance objective that has received little attention so far. A drawback of IPC is the potential for higher loads during emergency shutdowns due to blades stopping at different angles. While often disregarded in proof-of-concept studies, this has to be addressed by keeping blade deviation as small as possible for implementation of IPC in production. By quantifying blade deviations alongside damage equivalent loads (DEL), power output, and actuator energy, a comprehensive IPC assessment is provided. Results reveal a trade-off between DEL reduction and blade deviation in IPC-PID controllers. A comparison with Model Predictive Control (MPC)-based Collective Pitch Control (CPC) highlights that wind information and advanced algorithms can improve this trade-off by shifting the Pareto front.

2 Introduction

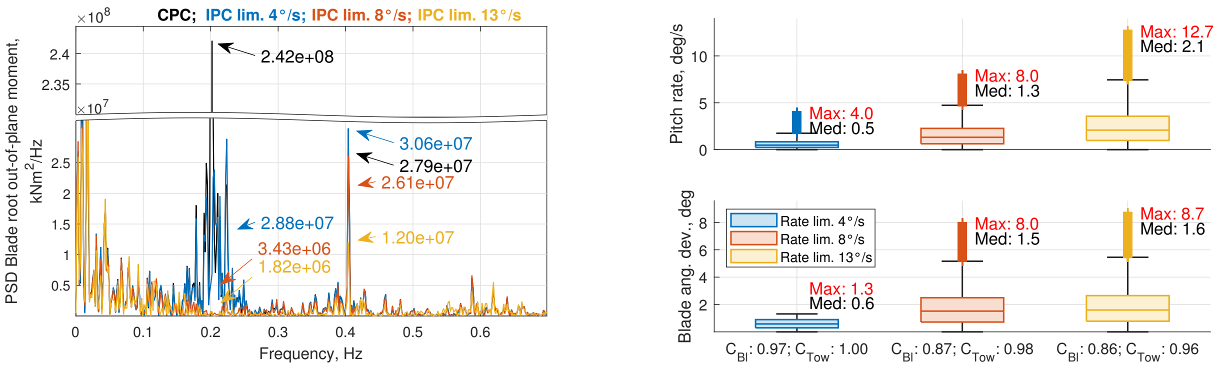
The growing importance of wind energy has driven the development of larger turbines with slender blade and tower designs, making fatigue load reduction critical for reliability and longevity. Individual pitch control (IPC) effectively reduces damage equivalent loads (DELs) at the blade root by mitigating aerodynamic imbalances from wind shear, turbulence, and other asymmetries. Various control strategies have been applied to IPC, including classical proportional-integral-derivative (PID) controllers and more advanced methods. While modern control techniques show superior performance, the advantage over PID-based IPC varies. Well-tuned PID controllers achieve performance comparable to linear quadratic Gaussian (LQG) controllers [1]. However, [2] highlights that LQG controllers reduce loads across a broader frequency range, up to three times the rotor frequency (3P), and [3] demonstrates that linear-parameter-varying (LPV) controllers outperform PID IPC in reducing fatigue loads. In [4], a feedback-feedforward H_∞ design outperforms an integrator-based feedback controller with inversion-based feed-forward. A field test in [5] confirms that H_∞ controllers slightly outperform PID controllers, achieving fatigue load reductions of 15% to 30% versus 10% to 30% for PID. A nonlinear PI IPC controller in [6] and a Neural Network trained via Reinforcement Learning in [7] both show similar load reduction at lower actuator duty cycles compared to a baseline linear PI IPC. In [8], the benefit of MPC for optimizing conflicting control objectives is demonstrated. Subspace predictive repetitive control (sPRC), implemented as an MPC with constraints on out-of-plane bending moments, increased the pitch actuator duty cycle by only 4%, compared to 10.8% for PID IPC, while achieving an average 25% moment reduction. However, this comparison used a single PID controller optimized for load reduction. This work explores the trade-off between load reduction and pitch actuator energy in PID controllers by optimizing parameters under three pitch rate limits, generating a Pareto front. Blade pitch deviation, a previously unconsidered criterion, is examined. The PID-based IPC is compared to a published MPC design, suggesting potential future combinations for improved performance.

3 Simulation Model and Controller Design

The IPC PID parameters are optimized with our simulation environment from [9], in which the NREL 5MW turbine model is integrated into Simulink as an S-Function and the baseline power controller from FASTTool is used. The IPC is tuned with the Nelder-Mead simplex algorithm to minimize the maximum blade root out-of-plane DEL among the three blades. For this proof-of-concept study, one wind test case with turbulence class A at 16 m/s mean wind speed was selected. Three controller parameter configurations, obtained at different pitch rate limits, are evaluated based on six performance criteria, including the five from [9]: blade root and tower DELs C_{Bl} and C_{Tow}, the mean and standard deviation of generated power C_P and $C_{\delta P}$, and additional pitch actuator power demands C_{Act}. IPC primarily reduces blade DEL, mitigating fatigue by decreasing the power spectral density (PSD) at 1P. Although tower DEL is not explicitly optimized, PSD reduction at 2P lowers it. The mean and standard deviation of generated power ensure minimal impact on production and variability. For 16 m/s mean wind speed, IPC's effect on power production and variance is negligible. Actuator power unavoidably increases due to continuous blade adjustments. The sixth criterion, previously unused, is the maximum blade angle deviation Δ_{Bl}, the relative difference between pitch angles. Excessive deviations can amplify vibrations and fatigue loads at the hub, leading to long-term damage to the hub assembly. Another disadvantage of IPC using large blade anlge deviation is the risk of increased loads during emergency shutdowns, as the blades may stop at different angles.

4 Results

Figure 1(a) shows the PSD of the blade root out-of-plane moment. The black line represents the baseline CPC. The blue line, representing IPC with a 4°/s rate limit, reduces the 1P peak by 87%, while the red line, representing IPC with an 8°/s rate limit, further lowers it, achieving a significant 98% reduction. At the 2P frequency, the blue line shows a slight increase compared to the baseline, while the red line effectively lowers the 2P peak. As expected, the 8°/s rate limit offers better load reduction across both 1P and 2P frequencies. The controller tuned with the rate limit set to 13°/s, depicted as a yellow line, decreases the 1P and 2P peaks even more. Figure 1(b) shows the pitch rate and deviation distributions of the three PID controllers optimized at different pitch rate limits and their respective blade and tower DELs. This visualizes the trade-offs of allowing higher pitch rates. The controller optimized with an 8°/s rate limit, depicted again in red, has a blade DEL reduction of 13% and a tower DEL reduction of 2% at a maximum pitch deviation of 8°. The maximum pitch deviation for the IPC with a 4°/s rate limit is only 1.3°, but its reduction in blade DEL is limited to 3%, and it actually increases the tower DEL slightly by 1% due to the amplification at the 2P frequency. The load reduction of the PID with a 13°/s rate limit, shown in yellow, is the highest, but so are its median and maximum pitch rate and blade angle deviation.



(a) Power spectral density

(b) Pitch rates and blade angle deviations

Figure 1: PSD, pitch rate and blade angle deviation distributions for PID IPC with controller parameters optimized with different rate limits

Figure 2 shows the evaluation criteria for the PID IPC and an MPC CPC from [10] under varying pitch rate limits, with the objectives achieved by PID-based CPC as the baseline. The PID IPC, depicted on the left side of the plot, achieves reductions in C_{Bl} (14% at 13°/s) and C_{Tow} (4%), but these reductions come at the cost of significantly higher actuator energy consumption and blade pitch deviations. At a pitch rate limit of 13°/s, the maximum blade pitch deviation reaches 8.7°, which may violate practical operational limits if restrictions on blade pitch deviation exist. The very low rate limit of 4°/s requires a blade pitch deviation of only 1.3°, but reduces C_{Bl} by just 3%. On the right side of the plot, the MPC CPC, as published in [10], achieves more substantial reductions in blade and tower DELs at the same pitch rate limits than the PID IPC. Specifically, at a pitch rate limit of 13°/s, the blade DEL is reduced by 60% compared to the baseline, and the tower DEL is reduced by 76%. Additionally, the actuator energy required by the MPC CPC at 13°/s is only 3.53, significantly lower than the 5.81 of the PID IPC.

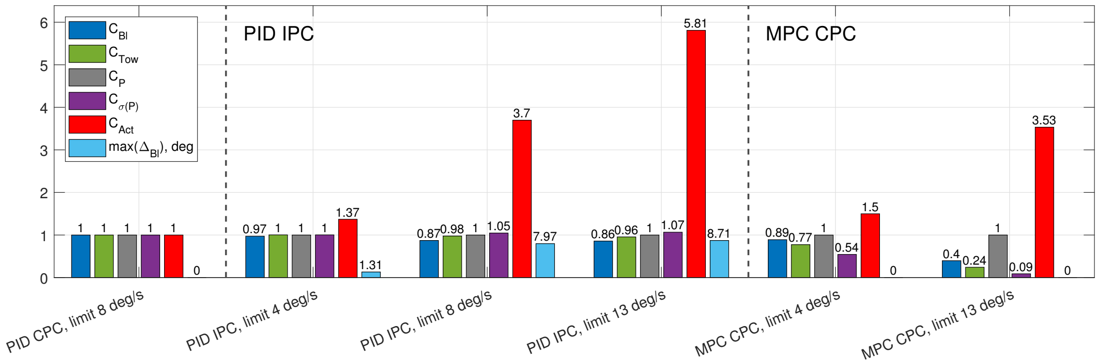


Figure 2: Power criteria, actuator energy, blade and tower DEL of PID CPC, PID IPC, and MPC CPC controllers

These results suggest that if limiting blade deviation is a critical requirement, using an MPC CPC could be a more effective alternative to the current PID-based IPC approach. However, unlike the PID IPC, the performance of the MPC requires accurate wind information. Hence, one future research direction is replacing the PID IPC with a more advanced controller that allows addressing blade deviation constraint in the design, e.g., MPC or LPV controller. Alternatively, the two presented control concepts could be combined, using MPC CPC for power control and PID IPC for further load reductions at small blade deviations.

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