COMPARISON AND OPTIMIZING WIND TURBINE LOAD REDUCTION: TRADE-OFFS INCLUDING BLADE ANGLE DEVIATION IN PID INDIVIDUAL PITCH CONTROL AND MPC COLLECTIVE PITCH CONTROL

ANTJE DITTMER

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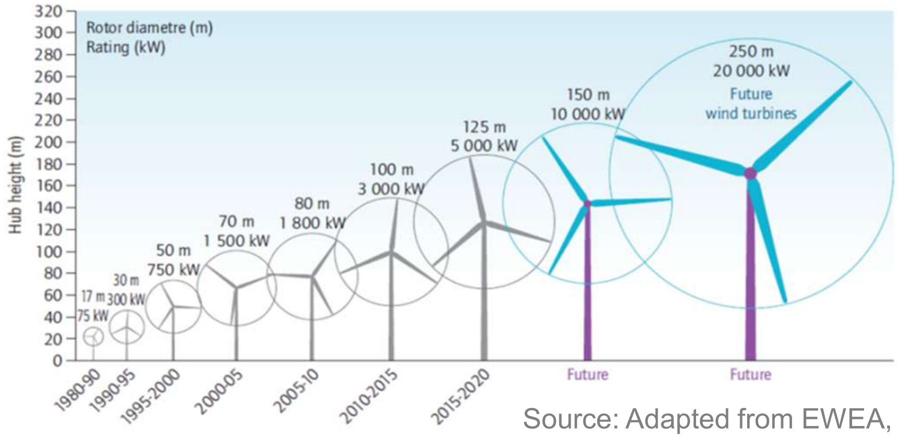
Motivation: Wind Turbine Control

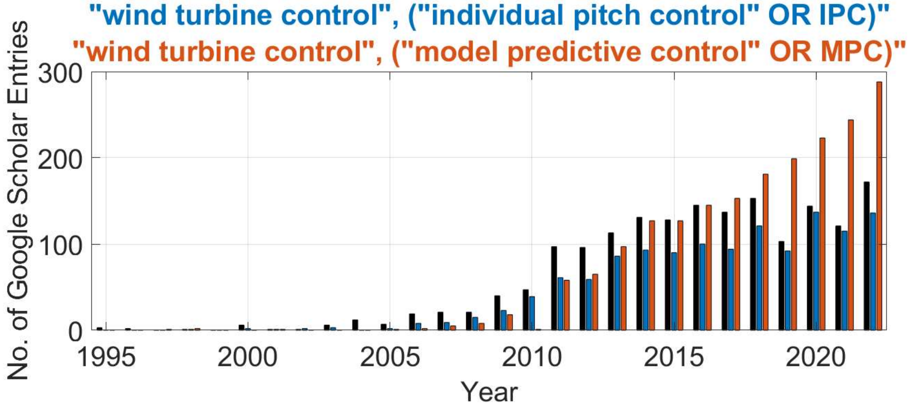
- Wind turbine control
  - Maximize generated power
  - Minimize damage equivalent loads (DEL) and minimize actuator activity
  - Modern control algorithm: Decrease DEL tower and blade roots, often increase in pitch actuator activity

- Individual Pitch Control (IPC)
  - Multi-objective PI [Hoffmann and Weiß 2016], LQG [Selvam et al. 2009], H-inf [Ossmann et al. 2021], RL for controller tuning [Coquelet et al. 2022]
- Model Predictive Control (MPC)
  - Collective Pitch Control (CPC) [Schlipf et al. 2013], CPC vs IPC [Sinner et al. 2018], constrained IPC-MPC [Petrovic et al. 2020], economic MPC [Pamososuryo et al. 2022b]

- Very active research area, but little literature on constraints for blade angle deviations → limits in angle deviation result in robust designs with regards to sensor errors

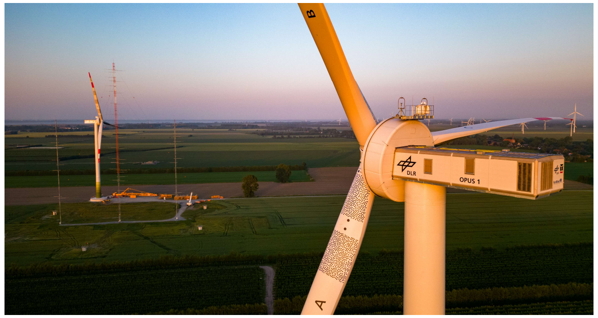


Source: Adapted from EWEA, 2009



Motivation: Constraint on Blade Pitch Deviation

- Work on wind turbine and farm control at German Aerospace Center
  - Proof-of-Concept FAST NREL 5MW and WFSim wind farm simulations
  - Actuation limited control in preparation for field tests in WiVaIdi: https://windenergy-researchfarm.com/



- Previous work on wind turbine control:
  - Investigation of Pareto front for different rate limits (4°/s, 8°/s, and 13°/s): DEL reduction vs actuator power, for IPC and MPC (Dittmer, WESC presentation 2021)
  - Power variance and tower DEL decrease with velocity-based quasi Linear Parameter Varying MPC (qLMPC) [Dittmer et al. 2021]

- Current work:
  - How do IPC results change if constraints on blade pitch angle deviation are included?
  - How can we still achieve significant DEL reduction with tight limits on blade pitch angle deviation?

Motivation: Previous Work IPC-PI Control

- [Hoffmann16]: Augmentation of CPC-PI with IPC-PI for DTU 10 MW, IPC-PI offline parameter optimization

- Controller configurations
  - Base: Torque and CPC
  - Base and IPC
  - Base, IPC, tower damper (TD)
  - Base, IPC, TD, tuned manually

- Minimization criteria
  - **Blade** damage
  - **Tower** damage
  - **Actuator** activity
  - **Power tracking error**
  - and **standard deviation**

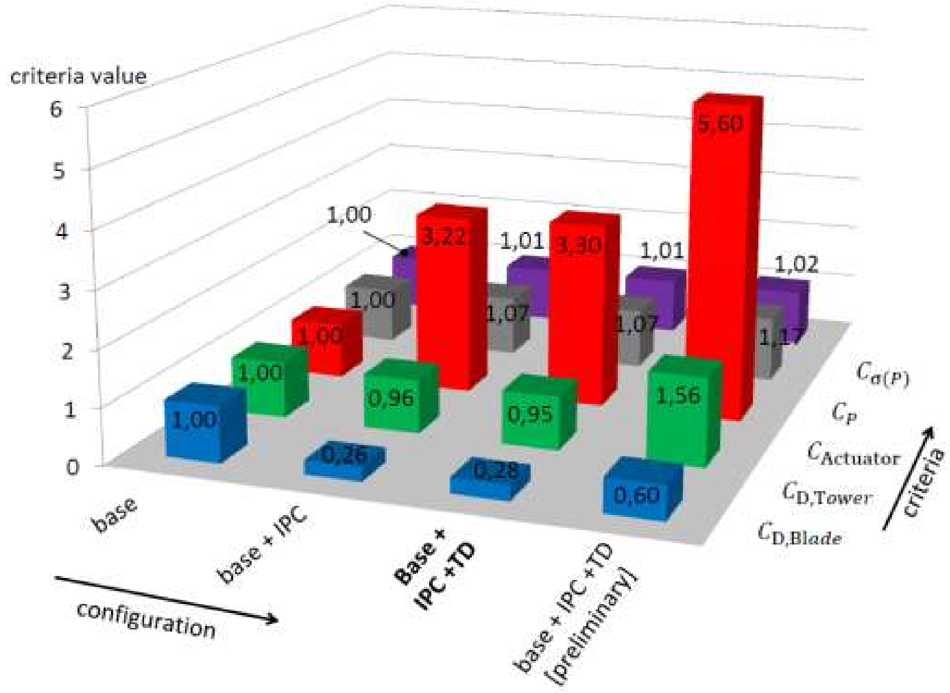
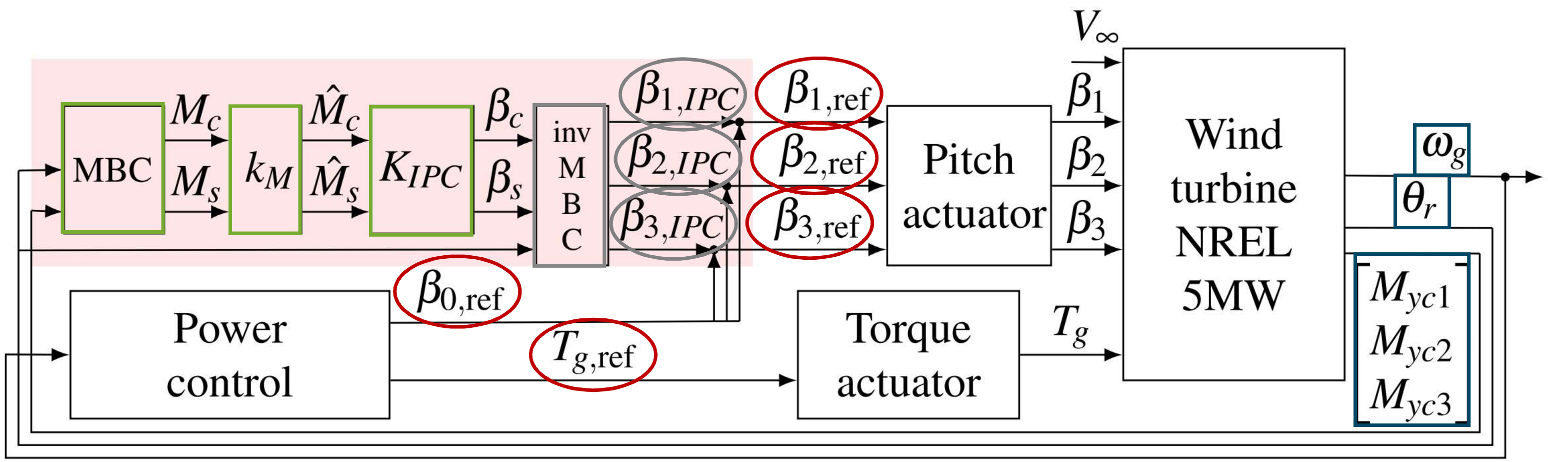


Figure 6. Fulfilment of criteria for different controller configurations

IPC Design



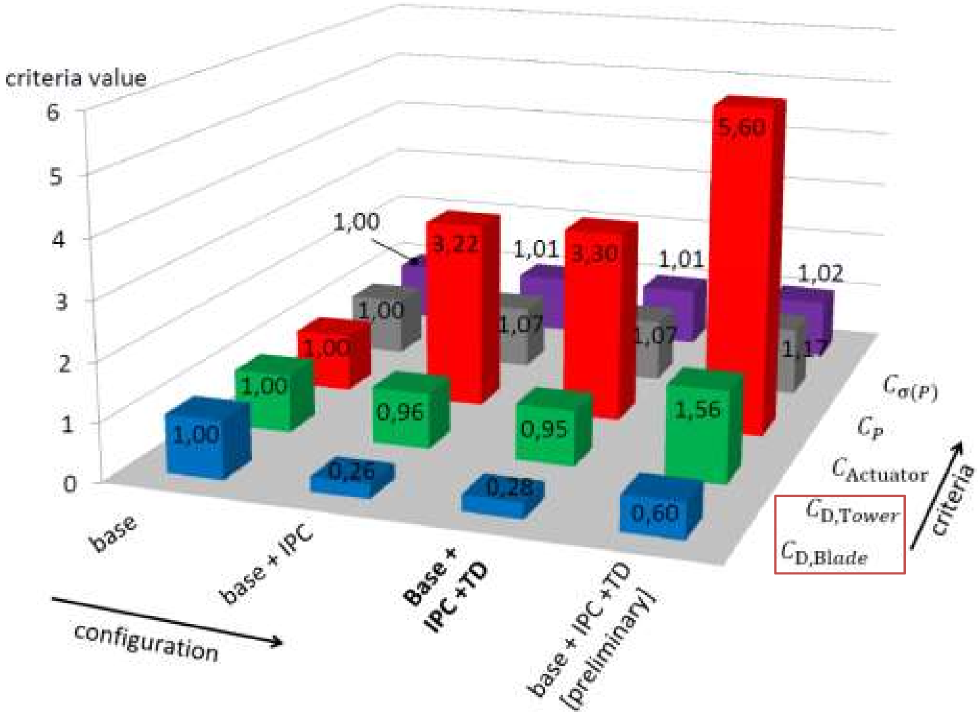
- Power baseline controller from FASTTool [Mulders et al. 2020]: Feedback signal generator speed ω_g
  - Generator torque $T_{g,\mathrm{ref}}$ set via k·ω^2 law, collective blade pitch $\beta_{0,\mathrm{ref}}$ set via gain-scheduled PI controller
- IPC: Feedback signals rotor position θ_r and three out-of-plane blade root moments M_{yci} for blades *i* = 1,2,3
  - Moments multiplied with Multi-Blade Coordinate (MBC) matrix, scaled ($k_M = 10^{-5}$), and processed through two Single Input Single Output (SISO) PI controllers
  - Resulting blade tilt and yaw signals β_c and β_s tranformed back with inverse MBC to additional individual blade pitch signals and added to collective pitch command to form individual blade pitch commands $\beta_{i,\mathrm{ref}}$

Controller Evaluation Criteria 1 & 2: Blade and Tower DEL

- Criteria 1 and 2: Miner's rule

$$D = \sum_{i=1}^{k} \frac{l_i}{L_i} = \sum_{i=1}^{k} \left[\frac{l_i}{L_D} \left(\frac{\sigma_i}{\sigma_D} \right)^m \right]$$

- D: Damage fraction
- k: Different stress levels
- l_i: observed cycles at stress S_i
- L_i: Mean number of cycles to failure at stress S_i
- σ_i: Amplitude of stress
- m: Wöhler coefficient



$$C_{D,Blade} = \frac{1}{\tilde{D}_{Blade,ref}} \cdot \frac{1}{3} \cdot \sum_{b=1}^{3} \sum_{i=1}^{k_b} (l_{b,i} \cdot M_{flap,b,i}^{m_{CFK}})$$

$$C_{D,Tower} = \frac{1}{\tilde{D}_{Tower,ref}} \cdot max \left[\sum_{b=1}^{k_{long}} (l_{b,i} \cdot M_{long,i}^{m_{Steel}}), \sum_{b=1}^{k_{lat}} (l_{b,i} \cdot M_{lat,i}^{m_{Steel}}) \right]$$

Controller Evaluation Criterion 3: Actuator Energy

- Criterion 3
  - Limit actuator usage

$$C_{Actuator} = \frac{1}{P_{act}, ref} \cdot \frac{1}{3} \cdot \sum_{b=1}^{3} \overline{|\dot{\theta}_i \cdot M_{act,i}(t)|}$$

with reference actuating power as mean of the product of

1. blades‘ pitch rate and
2. actuating pitch moments:

$$P_{act} = \dot{\theta}_i \cdot M_{act}$$

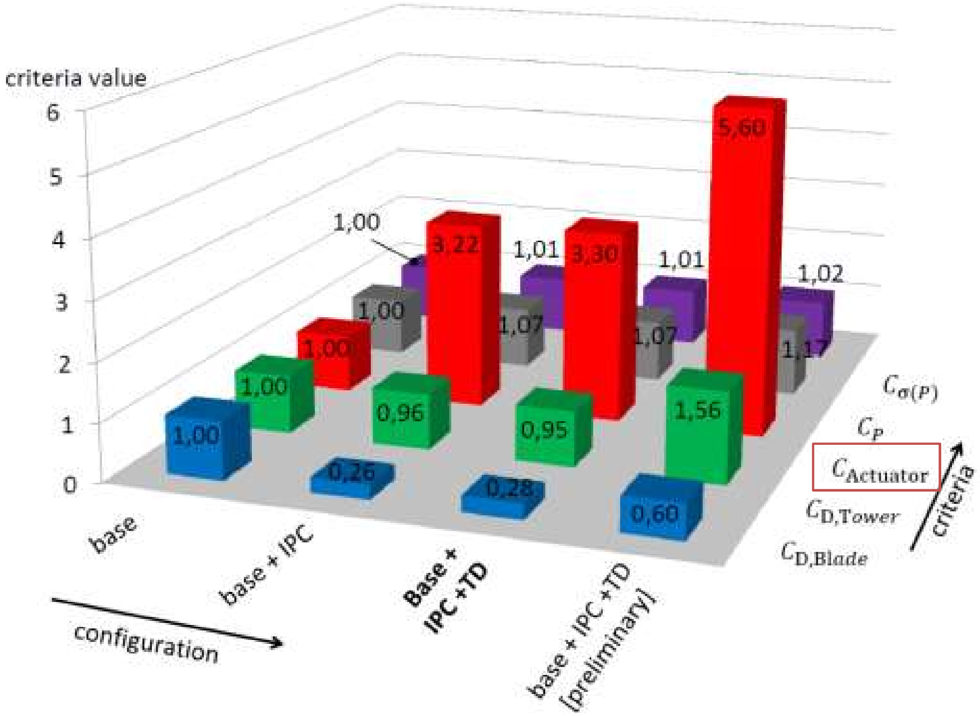


Figure 6. Fulfilment of criteria for different controller configurations

Controller Evaluation Criteria 4 and 5: Power

- Criterion 4: Power reference tracking error
  - ‚Quantity of Power‘

$$C_P = \left|\frac{P}{P_{ref}} - 1\right|$$

$$P_{ref} = \begin{cases} \frac{\rho}{2}\pi R^2 c_P V^3 & V \leq 11\ m/s \\ P_0 & V > 11\ m/s \end{cases}$$

- Criterion 5: Standard deviation
  - ‚Quality of Power‘
  - Minimize standard deviation: Important in small networks

$$C_{\delta(P)} = \frac{\delta(P)}{\delta_{\mathrm{ref}}(P)} \quad \text{with} \quad \delta(P) = \sqrt{\frac{t_{\mathrm{s}}}{T}\sum_{i=1}^{T/t_{\mathrm{s}}+1}\left(P_{\mathrm{i}} - \bar{P}\right)^2}$$

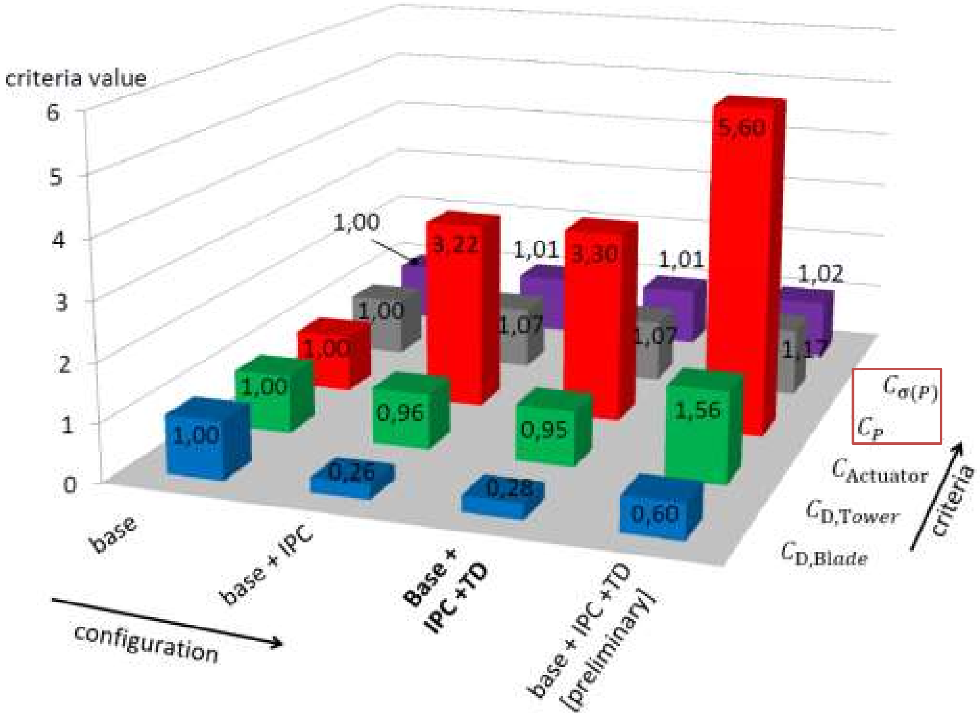


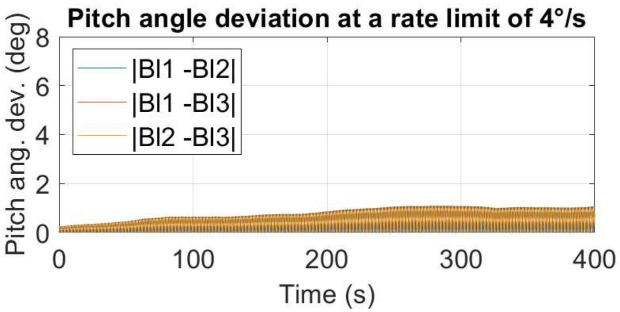
Figure 6. Fulfilment of criteria for different controller configurations

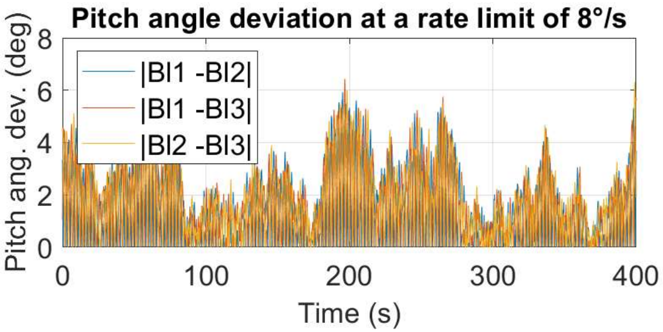
Controller Evaluation Criterion 6: Pitch Deviation

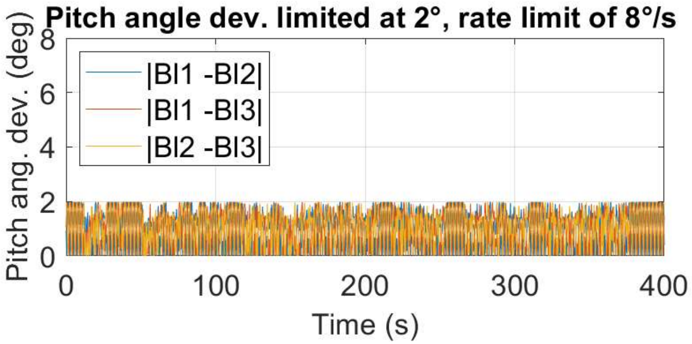
- Additional evaluation criterion blade pitch deviation

$$\Delta\beta = \max_{i,j} \left| \beta_i - \beta_j \right|, \quad i,j \in \{1,2,3\}$$

- Limits wrong control decision due to errors in blade root moment signals
- Helps limit IPC pitch rate
- Reduces potentially higher loads during emergency shutdowns due to blades stopping at different angles







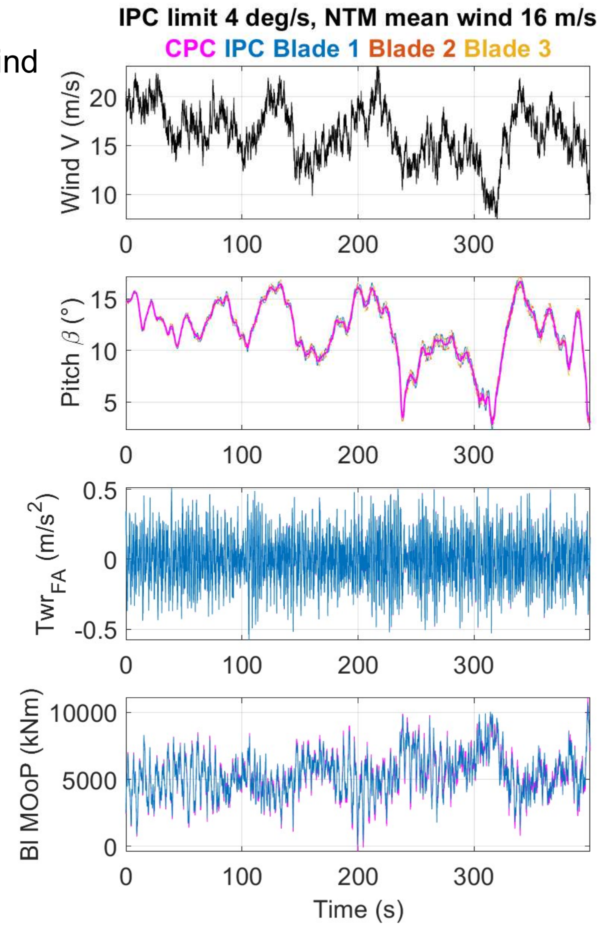
Results Timeseries with 4°/s and 8°/s Rate Limit

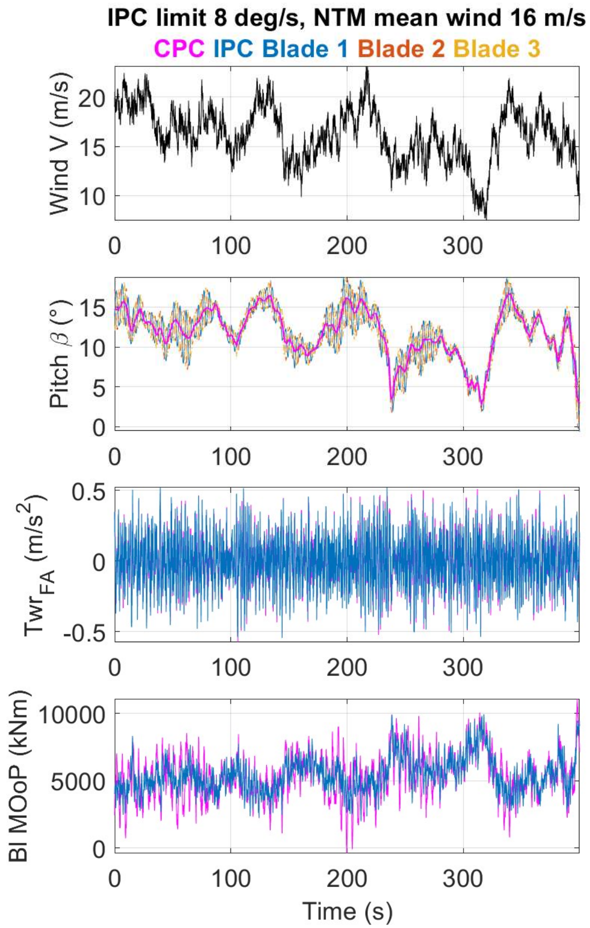
Test Case: Normal Turbulent Wind Class A, mean speed 16 m/s

IPC rate limit 4°/s: Only very small increase in pitch activity

No change in variance of tower fore-aft acceleration visible

Only small decrease in variance of blade moments visible





IPC rate limit 8°/s: Considerable increase in pitch activity

Small decrease in tower fore-aft acceleration visible

Considerable decrease in tower fore-aft acceleration visible

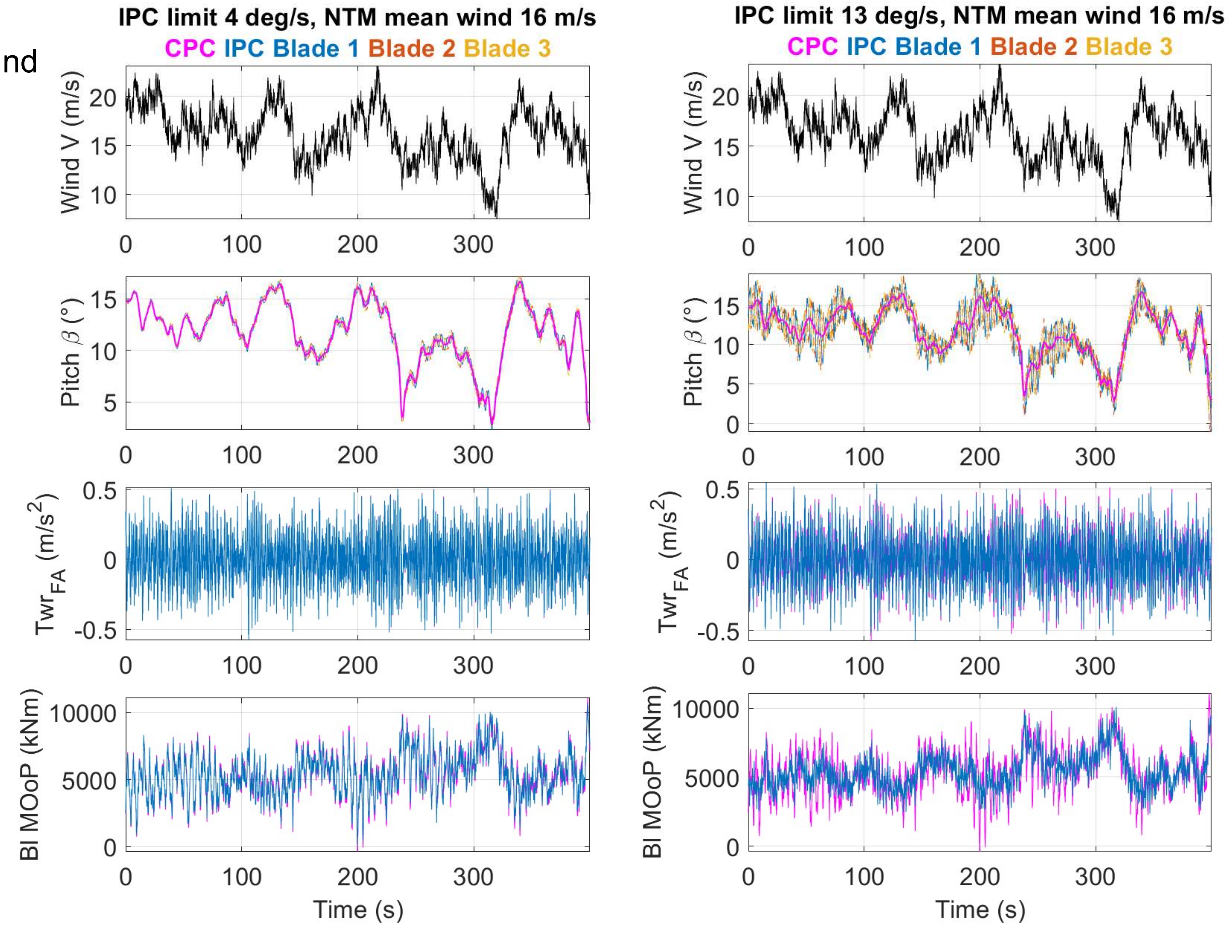
Results Timeseries with 4°/s and 13°/s Rate Limit

Test Case: Normal Turbulent Wind Class B, mean speed 16 m/s

IPC rate limit 4°/s: Only very small increase in pitch activity

No change in variance of tower fore-aft acceleration visible

Only small decrease in variance of blade moments visible

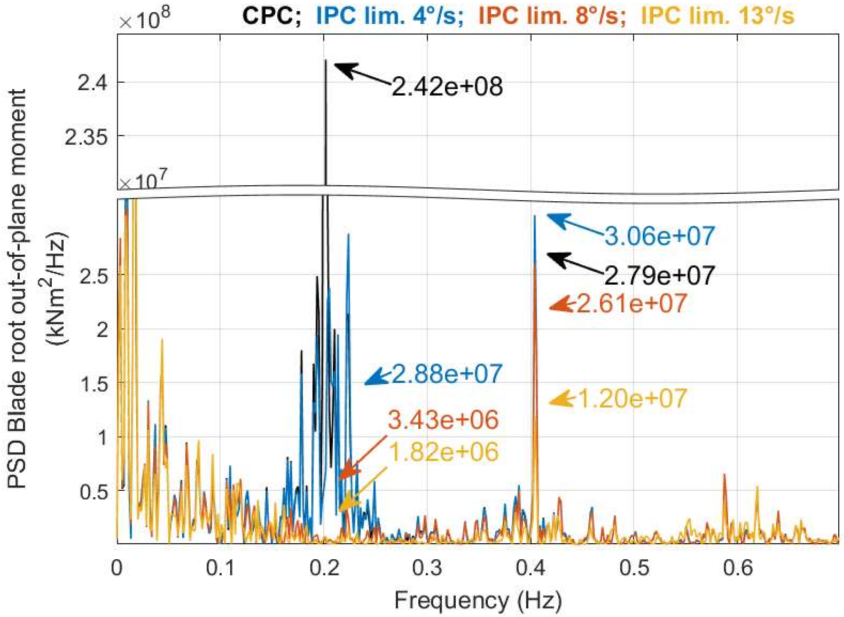


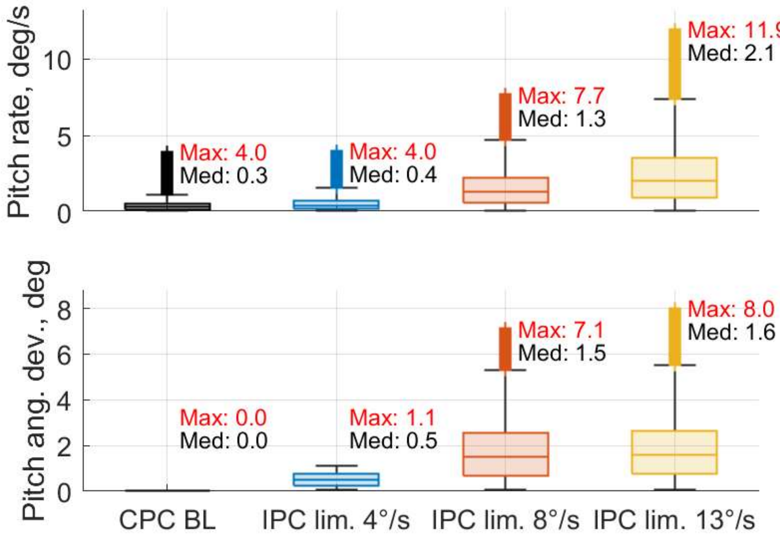
IPC rate limit 13°/s: Further increase in pitch activity compared to 8°/s

Slightly more decrease in tower fore-aft acceleration visible

Further decrease in tower fore-aft acceleration visible

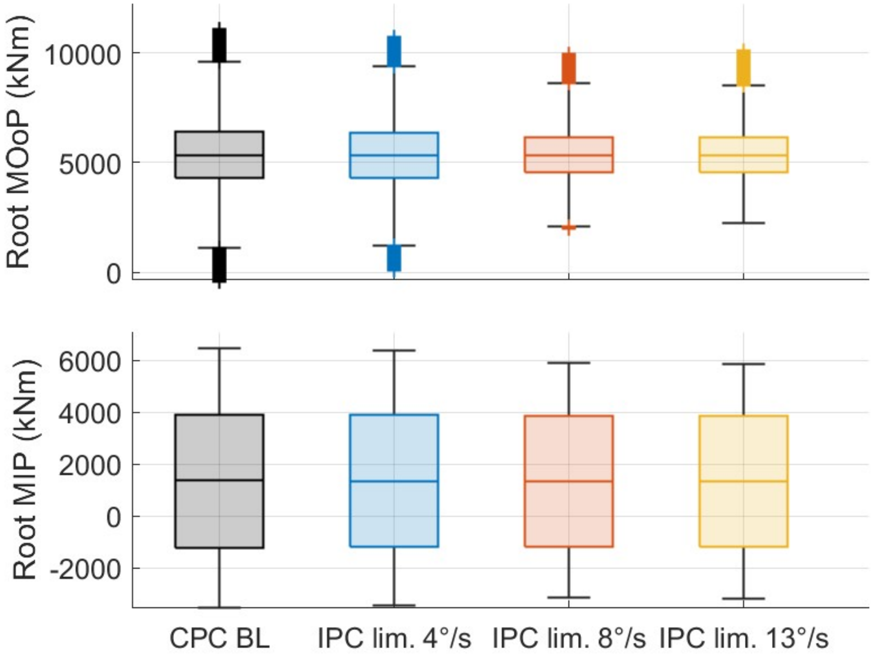
Power spectral density, Pitch rate and Pitch deviation

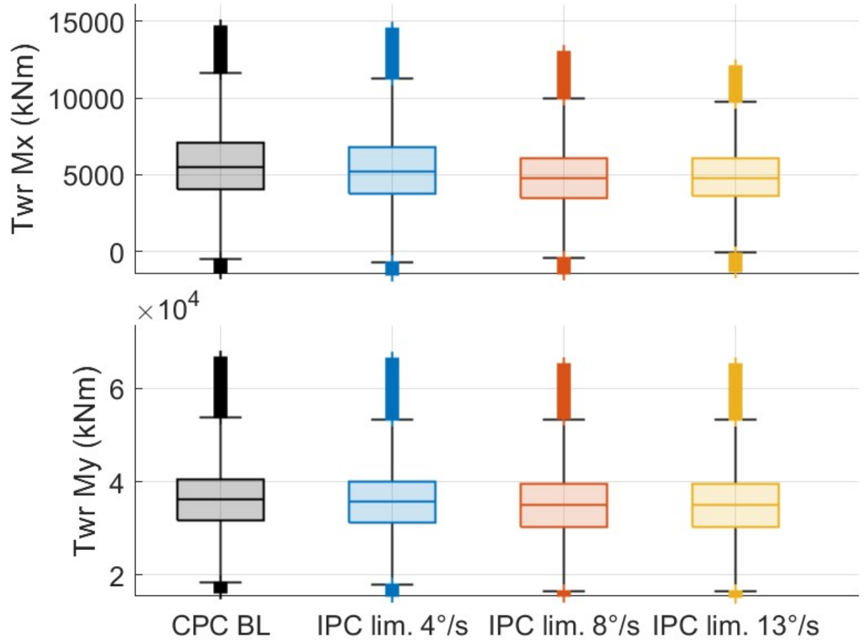




- Power spectral density (PSD): 1P reduction all rate limits, 2P reduction for 8°/s and 13°/s limit
- Increase on pitch rate and blade angle deviation distributions for PID IPC with increased different rate limits

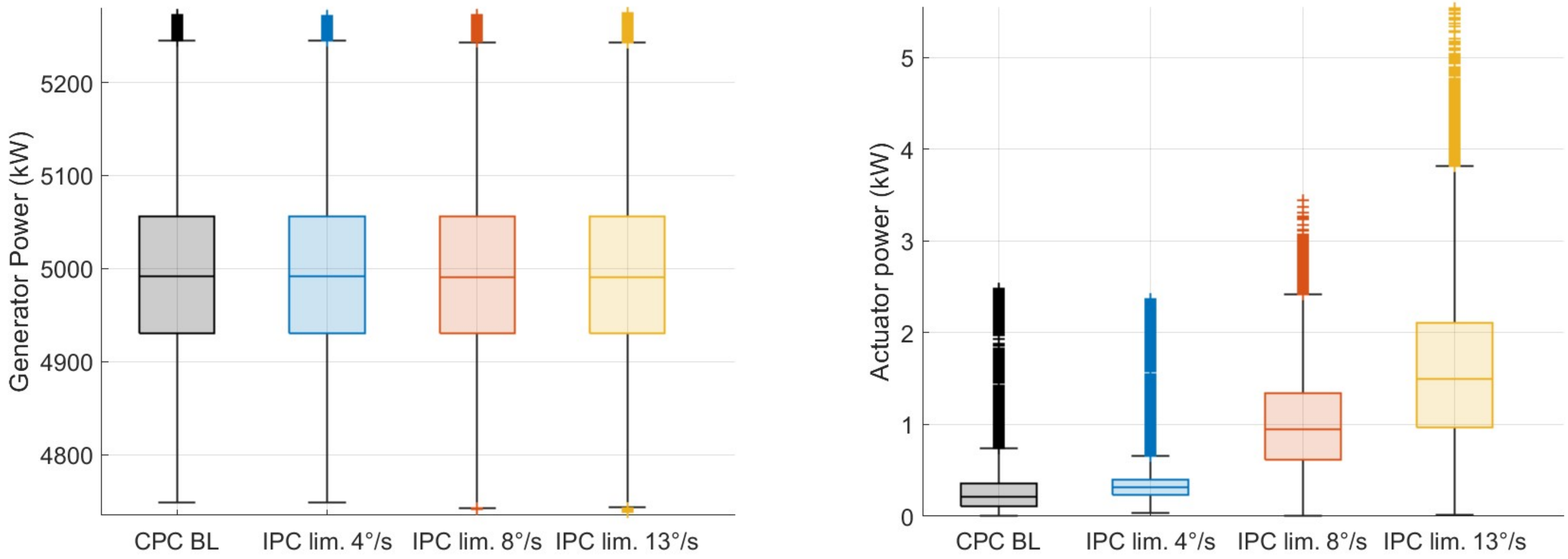
Statistics Blade Root and Tower Base Moments





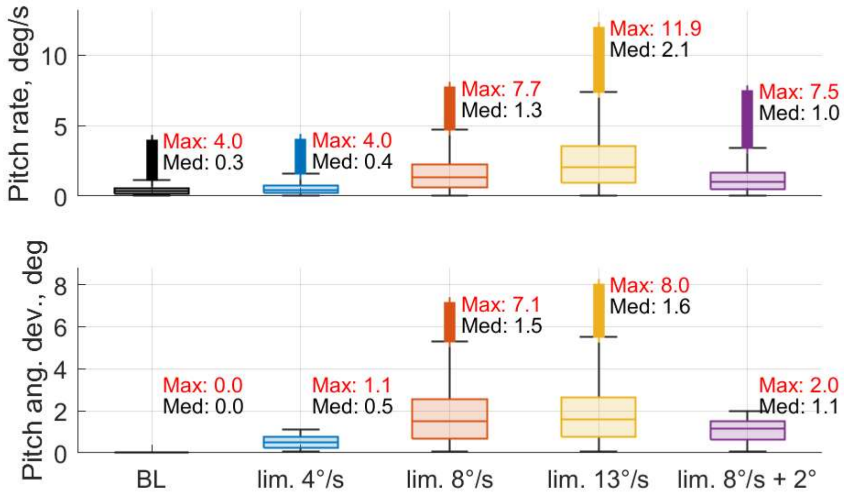
- Decrease in blade root moments with increasing pitch rate limits
- Decrease in tower base moments with increasing pitch rate limits
- Less difference between 8°/s and 13°/s than between 4°/s and 8°/s

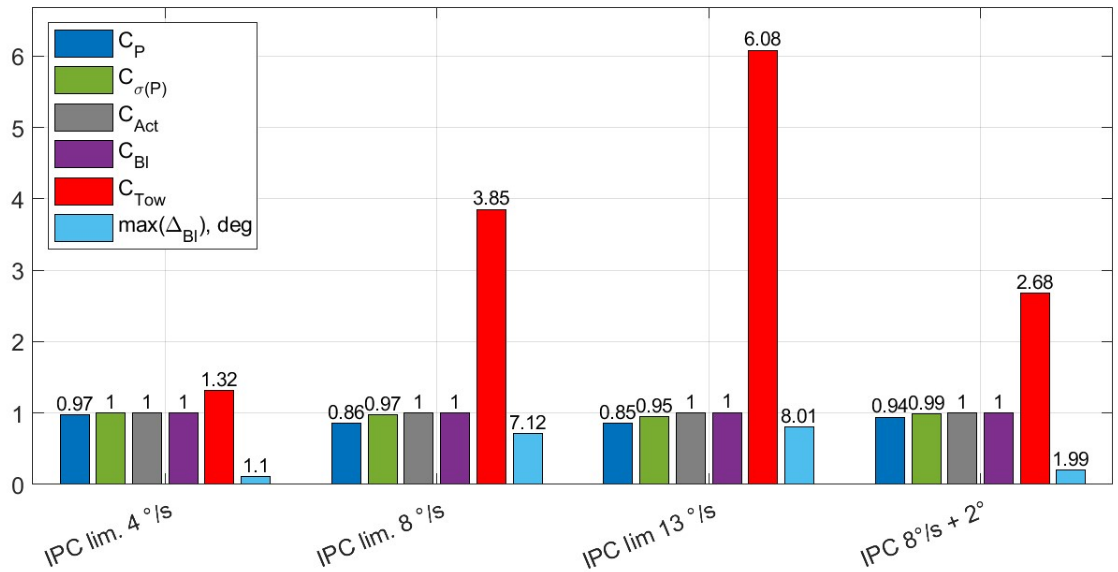
Statistics Power Output and Actuator Energy



- Power quantity and power variance remain unchanged
- Increase Actuator power with increasing rate limits

Influence Blade Deviation Limit on Objectives

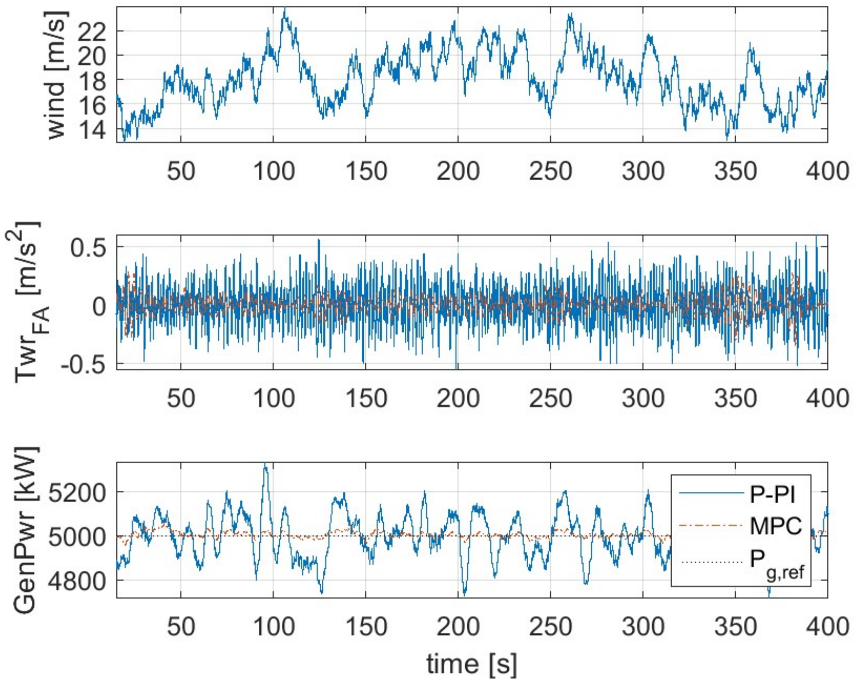




- Constraint on blade pitch deviation limits pitch angle
- Trade-off: Smaller blade and tower DEL reduction

Motivation Model Predictive Control (MPC)

- Previous work [Cisneros and Werner 2019]: Velocity-based quasi-linear parameter-varying (qLPV) MPC
- Previous work [Mulders et. al 2020]: Wind turbine SISO torque controller
- Wind turbine MIMO pitch and torque qLPV MPC control [Dittmer et al. 2021]



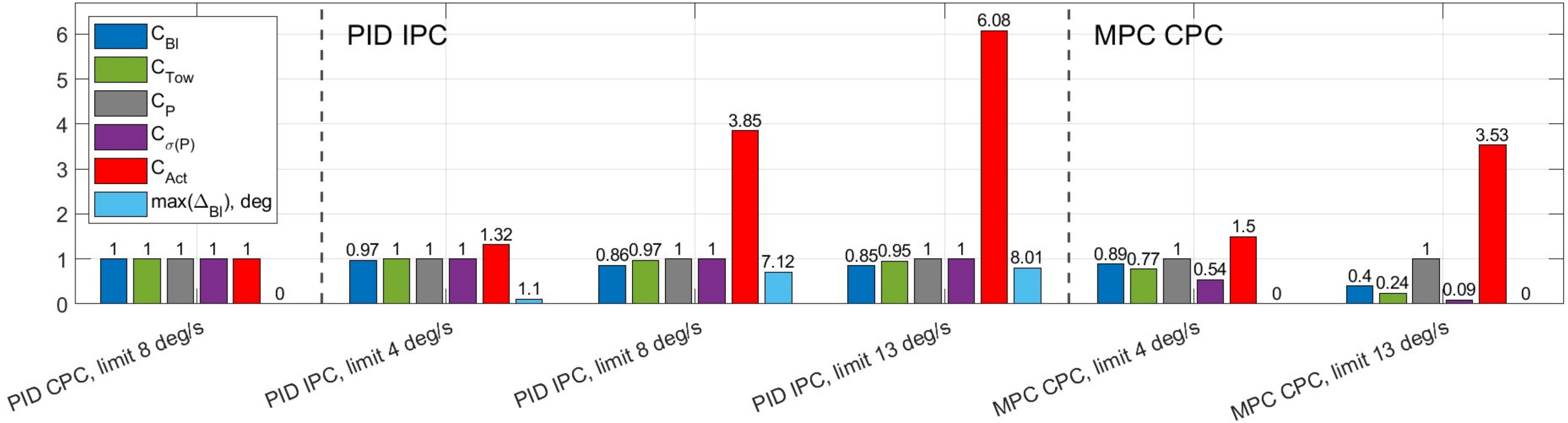
Normal turbulent wind (FASTTool) mean speed 18 m/s

Baseline P-PI (FASTTool, proportional torque ($K^*\omega^2$), gain-scheduled PI pitch control) vs. qLPV MPC → **ratio 4.6**

P-PI, qLPV MPC, power reference → **ratio 28**

MPC online optimization: 2ms CPU time

Comparison PID IPC and MPC CPC



- MPC generally outperforms PID IPC: Greater blade and tower DEL reduction, at smaller power variance, smaller additional actuator power, and no blade deviation
- Blade DELs decrease for all controllers, tower DELs for all but IPC with a limit of 4°/s
- Power output unchanged for all controllers, power variance unchanged for IPC and decreased for MPC
- Actuator power as well as blade deviation increases significantly for high rate limits, highlighting the trade-off for DEL reduction.

Summary

- Investigate trade-offs in DEL reduction vs. pitch actuator activity
  - Trade-off between DEL reduction on the one hand and actuator energy and blade deviation on the other
  - Constraint on blade deviation reduces risk, but also decrease DEL reduction
- Controller comparison
  - IPC with tighter rate limits: Limited DEL reduction, minimal increase in actuator energy
  - IPC with looser limits: Greater DEL reduction, but higher actuator energy and blade deviation
  - MPC: Superior DEL reduction with minimal power variance and no blade deviation
- Outlook
  - Take coupling between blade tilt and yaw in the non-rotating system into account by using shift in MBC angle or MIMO controller
  - Combine MPC and IPC

Thank you very much for your attention!

Model Predictive Control for Wind Farms

- Objectives for wind farm MPC: Minimize **error**, **change in turbine controls**, and **yaw angle**

$$\min_{\boldsymbol{U}_k} J(\boldsymbol{U}_k) = \boldsymbol{E}_k^T \boldsymbol{Q} \boldsymbol{E}_k + \Delta \boldsymbol{U}_k^T \boldsymbol{R} \Delta \boldsymbol{U}_k + \boldsymbol{U}_k^T \boldsymbol{R}_\gamma \boldsymbol{U}_k$$

$$s.t.$$

$$\begin{bmatrix} \zeta_{d,k+1} \\ P_{WF,k} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{\hat{\boldsymbol{K}}} & \boldsymbol{B}_{\hat{\boldsymbol{K}}} \\ \boldsymbol{C}_{\hat{\boldsymbol{K}}} & \boldsymbol{D}_{\hat{\boldsymbol{K}}} \end{bmatrix} \begin{bmatrix} \zeta_{d,k} \\ \boldsymbol{u}_k \end{bmatrix}, \quad k \in \{1, 2, \ldots, n_h - 1\}$$

$$e = P_{ref} - P_T = [e_1, e_2, \ldots, e_{n_h}]^T \in \mathbb{R}^{n_h}$$

$$\Delta u = \left[u_1^T - c^T, u_2^T - u_1^T, \ldots, u_{n_h}^T - u_{n_h-1}^T\right]^T \in \mathbb{R}^{n_h n_u}$$

- Use **Koopman wind farm models** to predict wind farm states over a **finite time horizon**
- Solve **optimization problem** to obtain **optimal control inputs** at **minimal yaw angle** for each turbine under input constraints
- Set the next control inputs and update predictions and optimisation problem at each time step

Results Timeseries with 4 deg/s and 8 deg/s Rate Limit

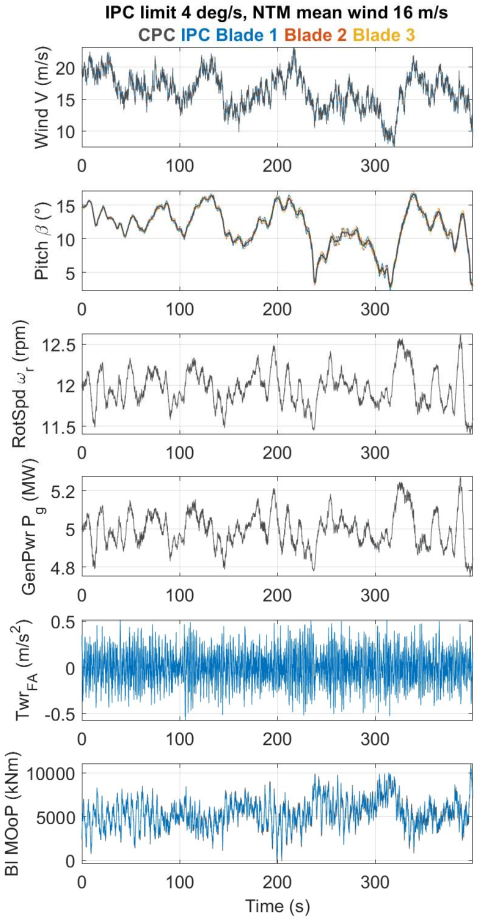
Test Case: Normal Turbulent Wind Class B, mean speed 16 m/s

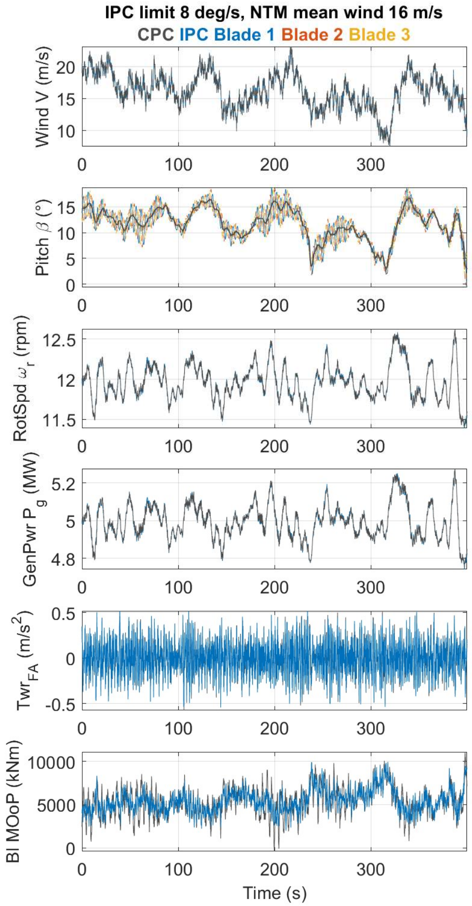
IPC rate limit 4 deg/s: Only very small increase in pitch activity

No visible change between CPC and IPC rotor speed and generator power

No change in variance of tower fore-aft acceleration visible

Only small decrease in variance of blade moments visible





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Results Timeseries with 4 deg/s and 13 deg/s Rate Limit

Motivation | Controller | Eval. Criteria | **Results IPC** | Comparison IPC/MPC | Summary

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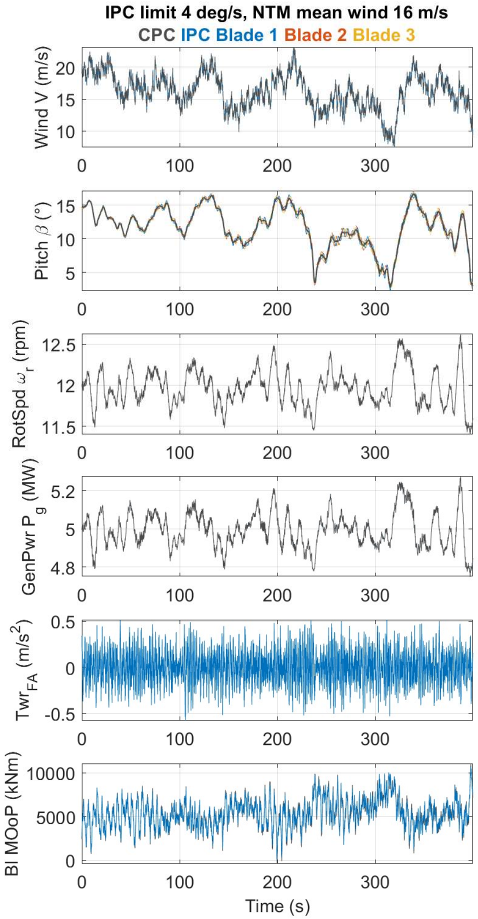

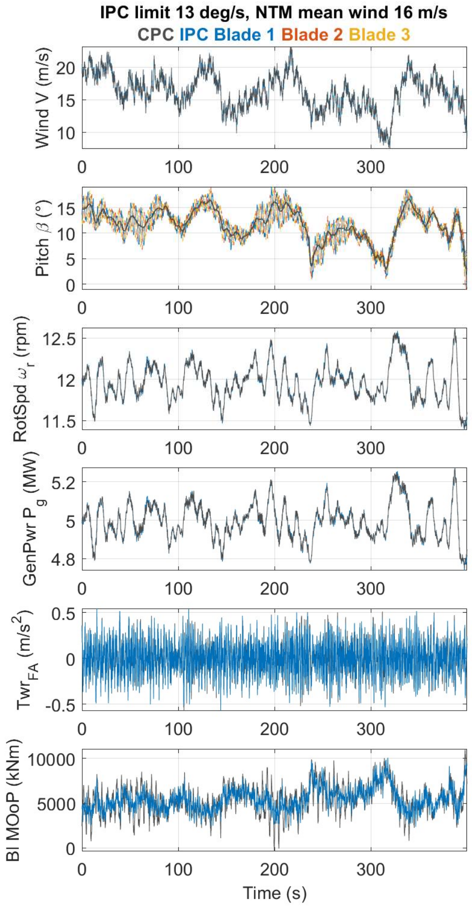

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