# High Performance Nonlinear Model Predictive Control for Wind Turbines

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# Presentation Outline

1. Introduction
2. Load balancing Collective Pitch Model Predictive Control for Wind Turbines
3. MPC Tuning via Economic Performance Metrics
4. Rapid Prototyping of MPCs for Wind Turbines
5. Simulation Study: MPC at NRELs FAST

# 1. MPC Well-Researched Attractive PID-Alternative

$$\min_{\boldsymbol{X},\boldsymbol{U}} J(\boldsymbol{X},\boldsymbol{U}) = \boxed{\sum_{0}^{N-1} L\left(\boldsymbol{x}_k,\boldsymbol{u}_k\right)} + \boxed{M\left(\boldsymbol{x}_N\right)}$$

**„performance indicating“ stage costs**

**„stabilizing“ terminal costs**

$$\text{s.t.} \quad \boxed{\boldsymbol{x}_{k+1} = \boldsymbol{f}(\boldsymbol{x}_k,\boldsymbol{u}_k,\boldsymbol{w}_k)}$$

**Plant dynamics**

$$\boxed{\mathbf{x_0} = \boldsymbol{x}(t_s)}$$

**„Feedback“ constraint**

$$\boxed{\begin{array}{ccccccc} \underline{\boldsymbol{u}} & \leq & \boldsymbol{u}_k & \leq & \overline{\boldsymbol{u}} & : & \forall k \\ \underline{\boldsymbol{x}} & \leq & \boldsymbol{x}_k & \leq & \overline{\boldsymbol{x}} & : & \forall k \end{array}}$$

**input & state constraints**

MPC = solve optimal control problem periodically, for current dynamic plant state

**Advantages**

- Intuitive tuning
  mainly via model
- Harmonization of competing objectives
- Explicit handling of
  constraints
- Direct exploitation of
  reference & disturbance forecasts
  → preventive actions

**Scientific community**

1. Koerber und R. King, „Nonlinear model predictive control for wind turbines,“ *Proc.EWEA*, 2011
2. Gros et. al, „A Real-time MHE and NMPC Scheme for the Control of Multi-Mega Watts Wind Turbines,“ *Proc. 52nd IEEE CDC*, 2013

**Industrial community**

1. EP2878811, „Methods of operating a wind turbine, and wind turbines“, 2013
2. EP1911968, „Control system for a wind turbine and method of controlling said wind turbine“, 2008

# 1. MPC Industry-Proven Technology in Other Sectors

**MPC industrial success story in (Petro-) chemical process industry**

- Over 3 decades of industrial experience
- Applicable to continuously evolving processes with complex nonlinear dynamics
- World-wide standard for large continuous plants → has proven to outperform conventional control by large
- Commercial products offered by highly specialized vendors

**→ …then why did it not make it into commercial wind turbines yet?**

# 1. Major Obstacles for Technology Transfer Across Sectors

**(Petro-) chemical sector**

- Operation dominated by stationary plant behavior at few OPs
- Time constants > hours
- Air-conditioned control infrastructure rooms
- Continuous supervision by experienced operators
- Plant invest costs > 100M€
- Sophisticated engineering platforms

**Wind energy sector**

- Operation dominated by transient plant behavior over large regime
- Time constants < seconds
- Adverse installation location (package, heat, vibration)
- Autonomous plant operation
- Plant invest costs < 10M€
- At best (partial) academic solutions

**Three central challenges**

**→ Effective tuning guidelines to shape transient behavior as desired**

**→ Meeting real-time constraints demands for problem-specific algorithms**

**→ Rapid-prototyping tools to migrate from Engineering station to PAC**

# 2. Modeling for Energy Capture vs. Tower Loads

**Task-oriented, very simple WT model : (4+4-DoF**

| | |
|---|---|
| $0 = J\dot{\omega} + r^{-1}T_G - T_A$ | **Torque balance** |
| $0 = m\ddot{x} + d\dot{x} + kx - F_A$ | **Tower FA acceleration** |
| $\ddot{\theta} = u_\theta$ | **Pitch actuator acceleration** |
| $\ddot{T} = u_T$ | **Generator Torque acceleration** |
| $T_A = \frac{1}{2}\rho A C_P(\theta,\lambda)\frac{v^3}{\omega}$<br>$T_A = \frac{1}{2}\rho A C_T(\theta,\lambda)v^2$ | **Static inflow aerodynamic force & torque** |
| $\lambda = \frac{R\omega}{v}$ | **Tip-speed ratio** |
| $v = v_{in} - \dot{x}$ | **Effective collective wind speed** |

- Control inputs: **collective pitch** & **generator torque** acceleration

  $$\boldsymbol{u} = (u_\theta,\, u_T)^T$$

- Disturbance input: collective wind speed $v_{in}$

# 2. Full MPC Configuration for Wind Turbines

**model + performance metric + relevant constraints = „working“ MPC configuration**

$$\min_{\boldsymbol{X},\boldsymbol{U}} \boxed{J(\boldsymbol{X},\boldsymbol{U})}$$

Any suitable performance metric

s.t. $$\boxed{\boldsymbol{x}_{k+1} = \boldsymbol{f}(\boldsymbol{x}_k,\boldsymbol{u}_k,\boldsymbol{w}_k)}$$

Here goes the simple model

$$\mathbf{x_0} = \boldsymbol{x}(t_s)$$

$$\boxed{\begin{array}{rcl} 0 & \leq & T \leq \overline{T} \quad : \quad \forall k \\ \underline{\theta} & \leq & \theta \leq \overline{\theta} \quad : \quad \forall k \\ -\overline{\dot{\theta}} & \leq & \dot{\theta} \leq \overline{\dot{\theta}} \quad : \quad \forall k \end{array}}$$

Control input (rate) constraints

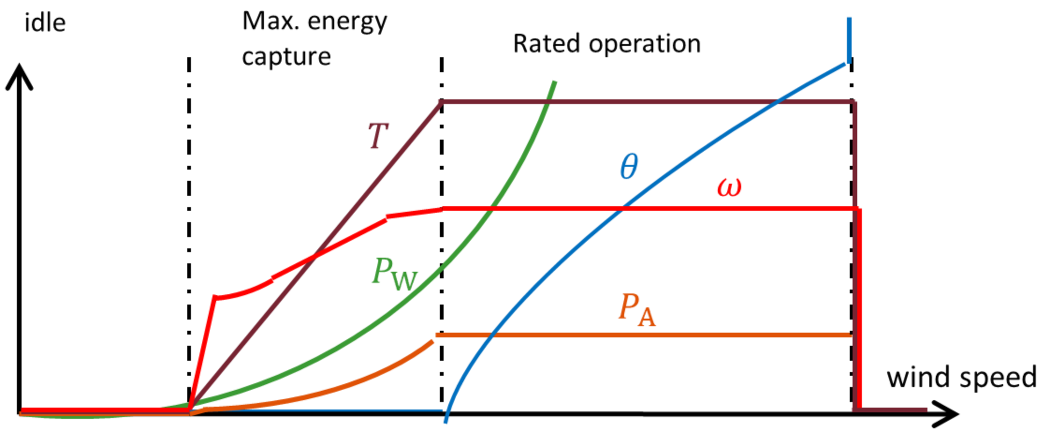
$$\boxed{\underline{\omega} \leq \omega \leq \overline{\omega} \quad : \quad \forall k}$$

Generator speed constraint

$$\boxed{\begin{array}{rcl} 0 & \leq & P_E \leq \overline{P}_E \quad : \quad \forall k \\ -\overline{\dot{P}}_E & \leq & \dot{P}_E \leq \overline{\dot{P}}_E \quad : \quad \forall k \end{array}}$$

Mixed state-input (rate) constraints

# 2. Operating Strategy to Be Realized via Classical Tracking MPC



**Steady-state optimal wind turbine operation**

Scheduling variable: wind speed $v_{in}$

$$\boxed{\begin{matrix}\theta^\star(v_{in})\\ \omega^\star(v_{in})\end{matrix}}$$

$$\begin{matrix}T^\star(v_{in})\\ P_A^\star(v_{in})\end{matrix}$$

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**Associated tracking formulation**

$$J(\boldsymbol{X},\boldsymbol{U}) \quad = \quad \sum_0^{N-1} \boxed{Q_\omega(v_{in,k})\left(\omega_k - \omega^\star(v_{in,k})\right)^2} + \boxed{Q_\theta(v_{in,k})\left(\theta_k - \theta^\star(v_{in,k})\right)^2} + \boxed{L_F\left(\boldsymbol{x}_k,\boldsymbol{u}_k\right)}$$

**Track optimal gen. speed**

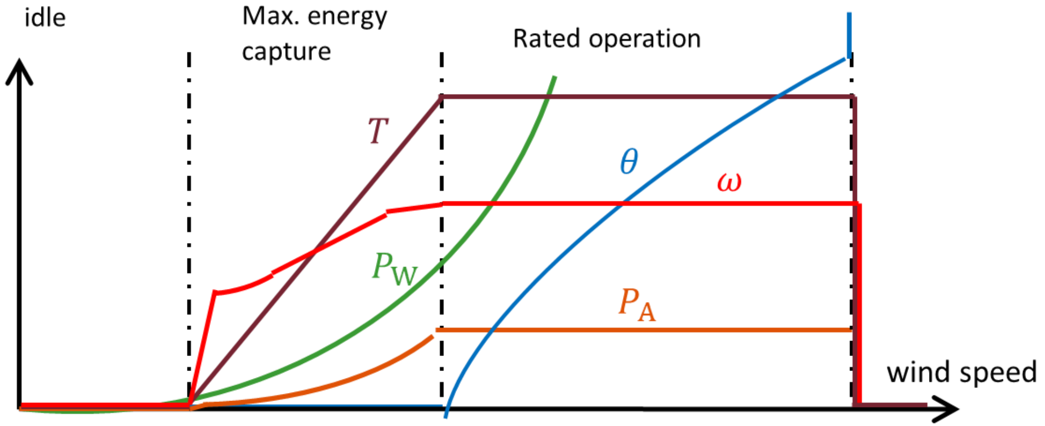
**Track optimal pitch angle**

**Fatigue penalty**

**How to systematically choose wind-scheduled weights?**

$$L_F\left(\boldsymbol{x}_k,\boldsymbol{u}_k\right) = Q_T\dot{x}_k^2 + Q_{\dot\theta}\dot\theta^2 + Q_{\ddot\theta}\ddot\theta^2 + Q_{\dot T}\dot T^2$$

# 3. Operating Strategy to Be Realized via Economic MPC



**Steady-state optimal wind turbine operation**

Scheduling variable: wind speed $v_{in}$

$$\boxed{\begin{matrix}\theta^\star(v_{in})\\ \omega^\star(v_{in})\end{matrix}}$$

$$\begin{matrix}T^\star(v_{in})\\ P_A^\star(v_{in})\end{matrix}$$

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**Associated economic formulation capturing transient & steady state optimum**

$$J(\boldsymbol{X},\boldsymbol{U}) \quad = \quad \textstyle\sum_0^{N-1}\left(\underbrace{\boxed{-\eta P_A(\omega_k,\theta_k,v_{in,k})}}_{\text{Max. energy capture}} + \underbrace{\boxed{L_F(\boldsymbol{x}_k,\boldsymbol{u}_k)}}_{\text{Fatigue penalty}}\right)$$

**Non-convex functional**

$$L_F(\boldsymbol{x}_k,\boldsymbol{u}_k) = Q_T\dot{x}_k^2 + Q_{\dot\theta}\dot\theta^2 + Q_{\ddot\theta}\ddot\theta^2 + Q_{\dot T}\dot T^2$$

# 3. Making tMPC Qualitatively Mimick eMPC

## Wind-scheduled tracking weights via 2nd-order Taylor Expansion

$$
\begin{aligned}
-P_A\left(\omega_k, \theta_k, v_{in,k}\right) \quad \approx \quad & -P_A\left(\omega_k^\star(v_{in,k}), \theta_k^\star(v_{in,k}), v_{in,k}\right) \\
& + \tfrac{1}{2}\left(\omega_k - \omega^\star(v_{in,k}) \quad \theta_k - \theta^\star(v_{in,k})\right) \boldsymbol{Q}\left(v_{in,k}\right) \begin{pmatrix} \omega_k - \omega^\star(v_{in,k}) \\ \theta_k - \theta^\star(v_{in,k}) \end{pmatrix}
\end{aligned}
$$

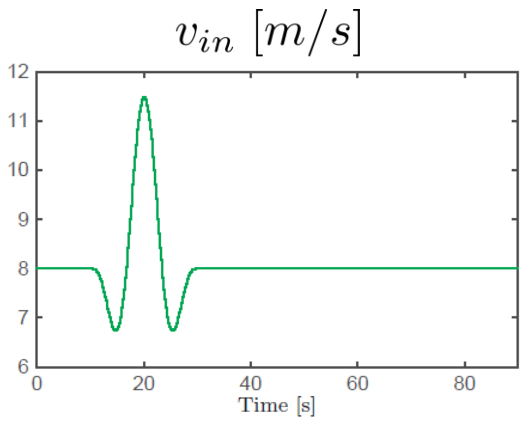
$$
\boldsymbol{Q}\left(v_{in,k}\right) \quad = \quad -\tfrac{1}{2}\rho A v_{in,k} \left.\begin{pmatrix} \frac{\partial^2 C_P}{\partial \lambda^2} R^2 & \approx 0 \\ \approx 0 & \frac{\partial^2 C_P}{\partial \theta^2} v_{in,k}^2 \end{pmatrix}\right|_{\substack{\omega_k = \omega^\star(v_{in,k})^\star(v_{in,k}) \\ \theta_k = \theta^\star(v_{in,k})(v_{in,k})}} \succ 0 \quad \succ 0
$$

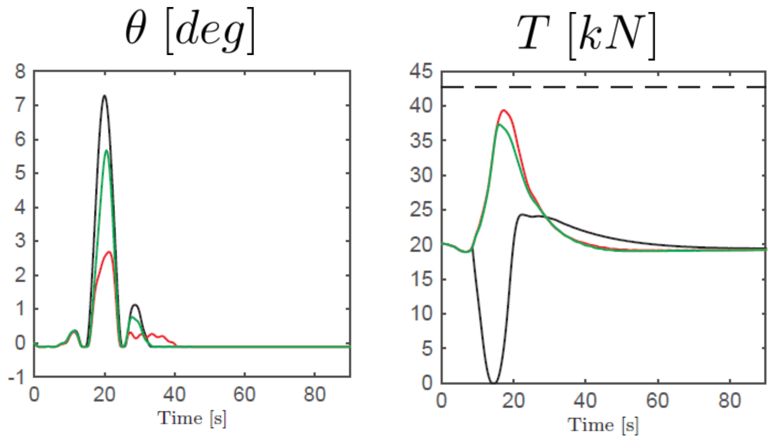
## Goal-oriented tracking weights with single tuning factor $\nu$

$$
\boldsymbol{Q}_\omega\left(v_{in,k}\right) \quad = \quad \nu\left(-\tfrac{1}{2}\rho A \frac{\partial^2 C_P}{\partial \lambda^2}\left(\theta^\star(v_{in,k}), \lambda^\star(v_{in,k})\right) R^2 v_{in,k}\right) > 0
$$

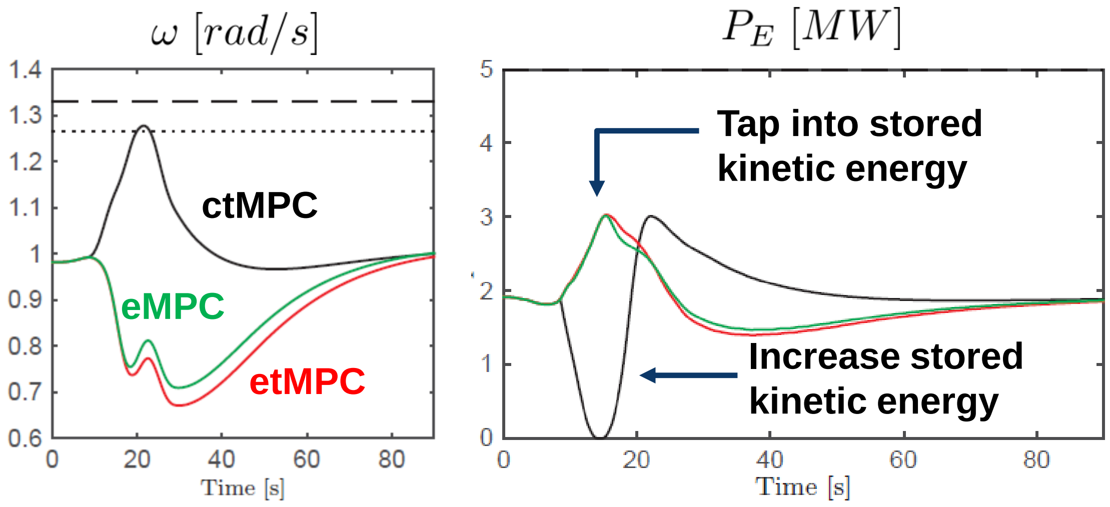
$$
\boldsymbol{Q}_\theta\left(v_{in,k}\right) \quad = \quad \nu\left(-\tfrac{1}{2}\rho A \frac{\partial^2 C_P}{\partial \theta^2}\left(\theta^\star(v_{in,k}), \lambda^\star(v_{in,k})\right) v_{in,k}^3\right) > 0
$$

# 3. Comparison of Conventional tMPC vs. Economic (t)MPC



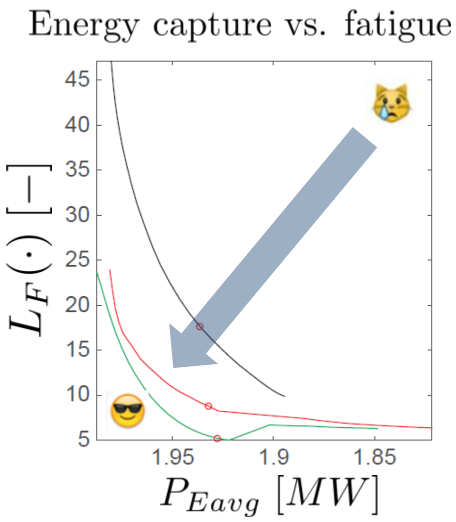


Closed-loop response to mexican hat gust with wind speed preview



**Tap into stored kinetic energy**

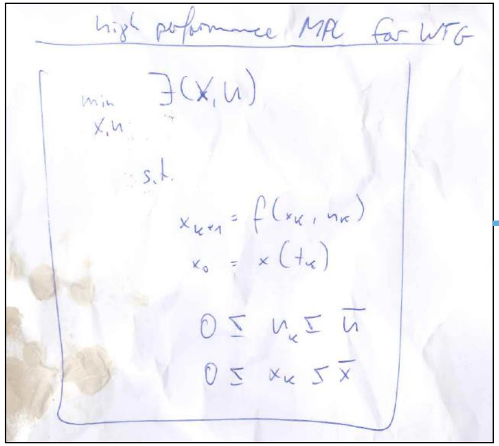
**Increase stored kinetic energy**



# 4. How to Get from Problem Description to Industrial Controller

**in-house tool-chain**

- Additional WT-specific features (look-up tables, etc.)
- Code transformation to go from office PC → target HW



high performance MPC for WTG

$$\min_{x,u} J(x,u)$$

s.t.

$$x_{k+1} = f(x_k, u_k)$$
$$x_0 = x(t_k)$$
$$0 \le u_k \le \bar{u}$$
$$0 \le x_k \le \bar{x}$$

**Highly efficient algorithms**

**MATLAB**

**Academic tools & components for target code generation**

- MPT Tool (ETH)
- CVX (Stanford)
- WT-MPC (Chalmers)
- ACADO (Freiburg)
- …

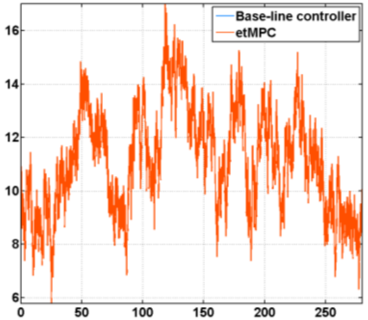
**MS Visual Studio**

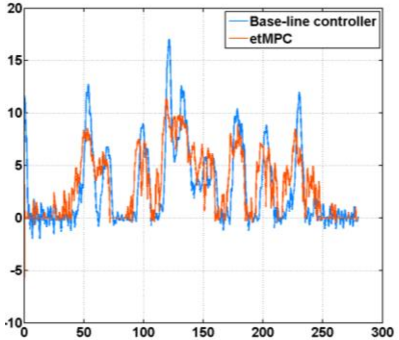
**Vendor tool-chain for custom code integration**

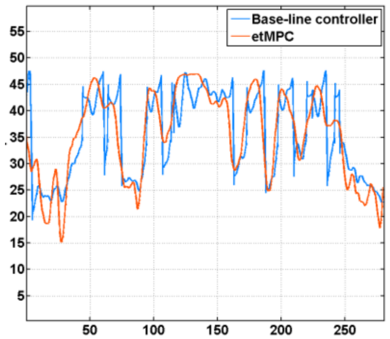
- NI compact Rio
- Beckhoff TwinCAT 3
- Bachmann M-PLC
- …

**Comfortable, effective engineering**

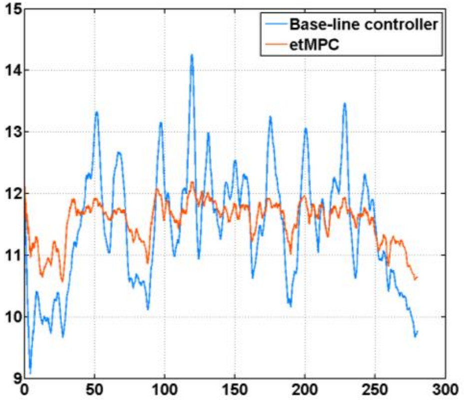
# 5. Simulative Assessment for Turbulent Wind Fields

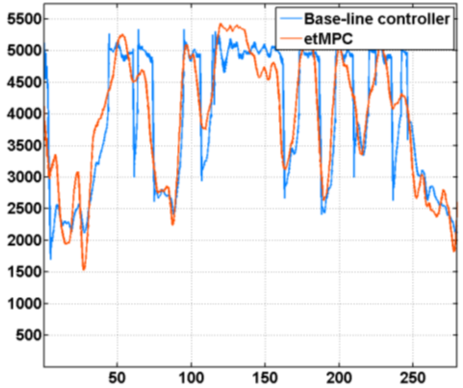

$v_{in}\ [m/s]$

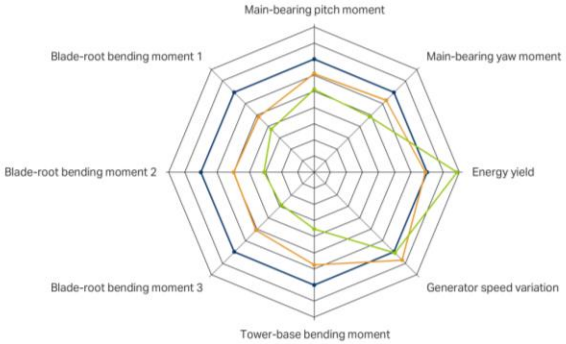

$\theta\ [deg]$


$T\ [kN]$

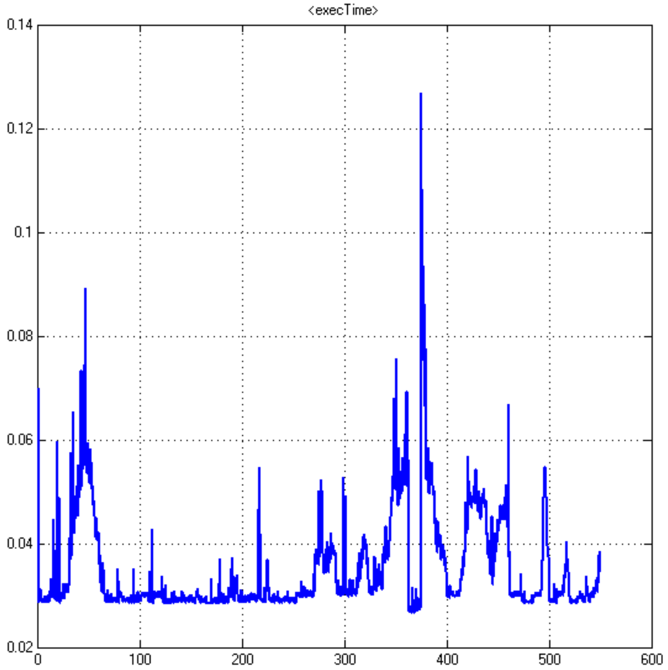
Identical energy capture, much less component wear

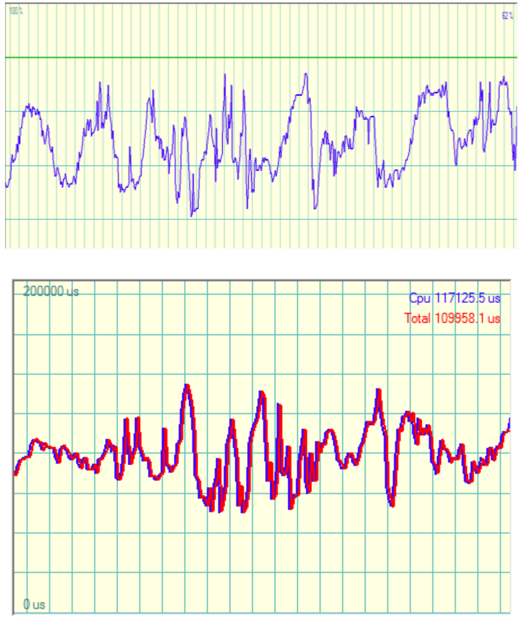

$\omega\ [rad/s]$


$P_E\ [MW]$


Mlife fatigue analysis

# 5. Simulative Assessment for Turbulent Wind Fields





Observed cycle times office PC (~40ms) vs. Industrial PAC (~100 ms)

**→ Target-optimized code allows for reducing computational burden by another order of magnitude**

**→ Volatility due to changing active constraints, to be reduced by further measures**

# Summary

- Economically-inspired WT-MPCs are easy to tune and show very good performance
- Intuitive tuning rule reduces engineering effort & improves transient closed-loop response for tracking WT-MPCs
- Combination and integration of available tool building blocks facilitates easy engineering & migration WT-MPCs onto target hardware with marginal manual effort
- Computational performance of modern HW + modern MPC algorithms allow for fast sampling rates → to be exploited for tackling remaining industrial challenges:
  - autonomous plant operation ←→ safety & robustness measures
  - low system costs ←→ low cost hardware & engineering

# Thank You

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