PO.146

High performance nonlinear model predictive control for wind turbines

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automotive engineering iav

Current situation in wind turbine control

Model predictive control (MPC) on the verge of penetrating wind energy sector

- Steadily increasing wind turbine sizes foster a growing interest in alleviating structural fatigue through advanced control
- Scientific & industrial experts rate nonlinear MPC a strong candidate for replacing conventional PID-based control
- **Downside**: nMPC is considered difficult to tune and computationally intractable on industrial control hardware

Why is MPC successful in process industry, but not yet in wind energy sector?

MPC industrial success story in process industry for 3 decades

- Decades of industrial experience (engineering, commissioning & maintenance)
- Applied to evolving plants with complex nonlinear dynamics
- Highly economic at large production plants (ROI < 12 month)
- Commercial MPC suites offered by highly-specialized automation vendors

Challenges & Objectives

Characteristics @ process industry

- Plant operation dominated by stationary behavior at few selected operating points
- Time constants > minutes & hours
- Air-conditioned control rooms
- Continuous supervision by experienced operators
- Plant invest costs > 100M€
- Sophisticated engineering platforms

Characteristics @ wind energy industry

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

→ **Elaborate intuitive tuning rules**

→ **Employ highly efficient algorithms to meet real-time requirements**

→ **Integrate academic & commercial tools into a rapid prototyping suite for MPC**

Solution & Method

Task-oriented modeling, as simple as possible

$$
\begin{aligned}
0 &= J\dot{\omega} + r^{-1}T_G - T_A && \text{Torque balance}\\
0 &= m\ddot{x} + d\dot{x} + kx - F_A && \text{Tower FA acceleration}\\
\ddot{\theta} &= u_\theta && \text{Pitch actuator acceleration}\\
\ddot{T} &= u_T && \text{Generator torque acceleration}\\
T_A &= \tfrac{1}{2}\rho A C_P(\theta,\lambda)\tfrac{v^3}{\omega} && \text{Static inflow model for}\\
F_A &= \tfrac{1}{2}\rho A C_T(\theta,\lambda) v^2 && \text{torque and force}\\
\lambda &= \tfrac{R\omega}{v} && \text{Tip speed ratio}\\
v &= v_{in} - \dot{x} && \text{Blade effective wind speed}
\end{aligned}
$$

Task-oriented economic tracking MPC set-up (etMPC)

$$
\min_{\boldsymbol{X},\boldsymbol{U}} J(\boldsymbol{X},\boldsymbol{U}) = \sum_{k=0}^{N-1} (\bullet)^T \boldsymbol{Q}(v_{in,k}) \begin{pmatrix} \omega_k - \omega^\star(v_{in,k}) \\ \theta_k - \theta^\star(v_{in,k}) \end{pmatrix} + L_F(\boldsymbol{x}_k, \boldsymbol{u}_k)
$$

Suitable performance metric, harmonizing energy capture and component fatigue

$$
\text{s.t.} \quad \boldsymbol{x}_{k+1} = \boldsymbol{f}(\boldsymbol{x}_k, \boldsymbol{u}_k, v_{in,k}), \quad \mathbf{x_0} = \boldsymbol{x}(t_s)
$$

$$
\begin{aligned}
0 \le T &\le \overline{T} : \forall k \\
\underline{\theta} \le \theta &\le \overline{\theta} : \forall k \\
-\dot{\overline{\theta}} \le \dot{\theta} &\le \dot{\overline{\theta}} : \forall k
\end{aligned}
$$

Actuator (rate) constraints → pure input cons.

$$
\begin{aligned}
\underline{\omega} \le \omega &\le \overline{\omega} : \forall k \\
0 \le P_E &\le \overline{P}_E : \forall k \\
-\dot{\overline{P}}_E \le \dot{P}_E &\le \dot{\overline{P}}_E : \forall k
\end{aligned}
$$

Gen. speed constraint; Power (rate) constraints → mixed state-input cons.

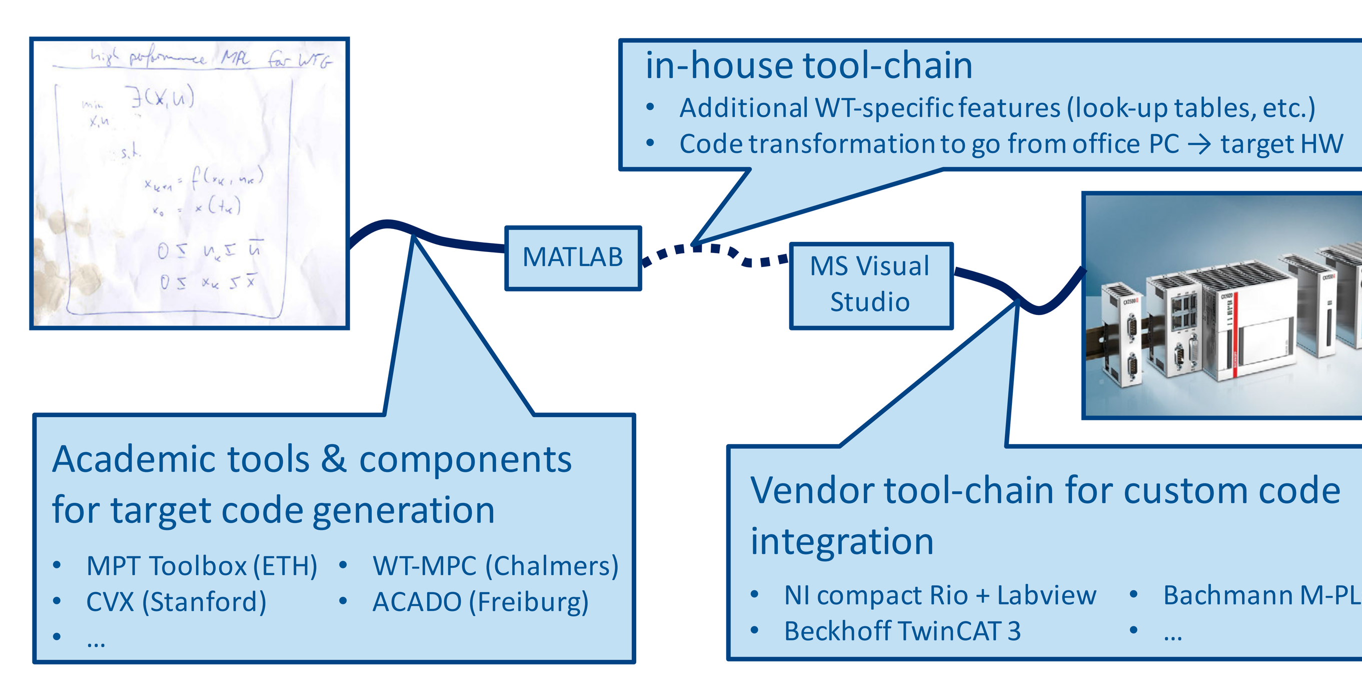
Derivation of wind-scheduled tracking weights to mimic economic performance metric

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

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

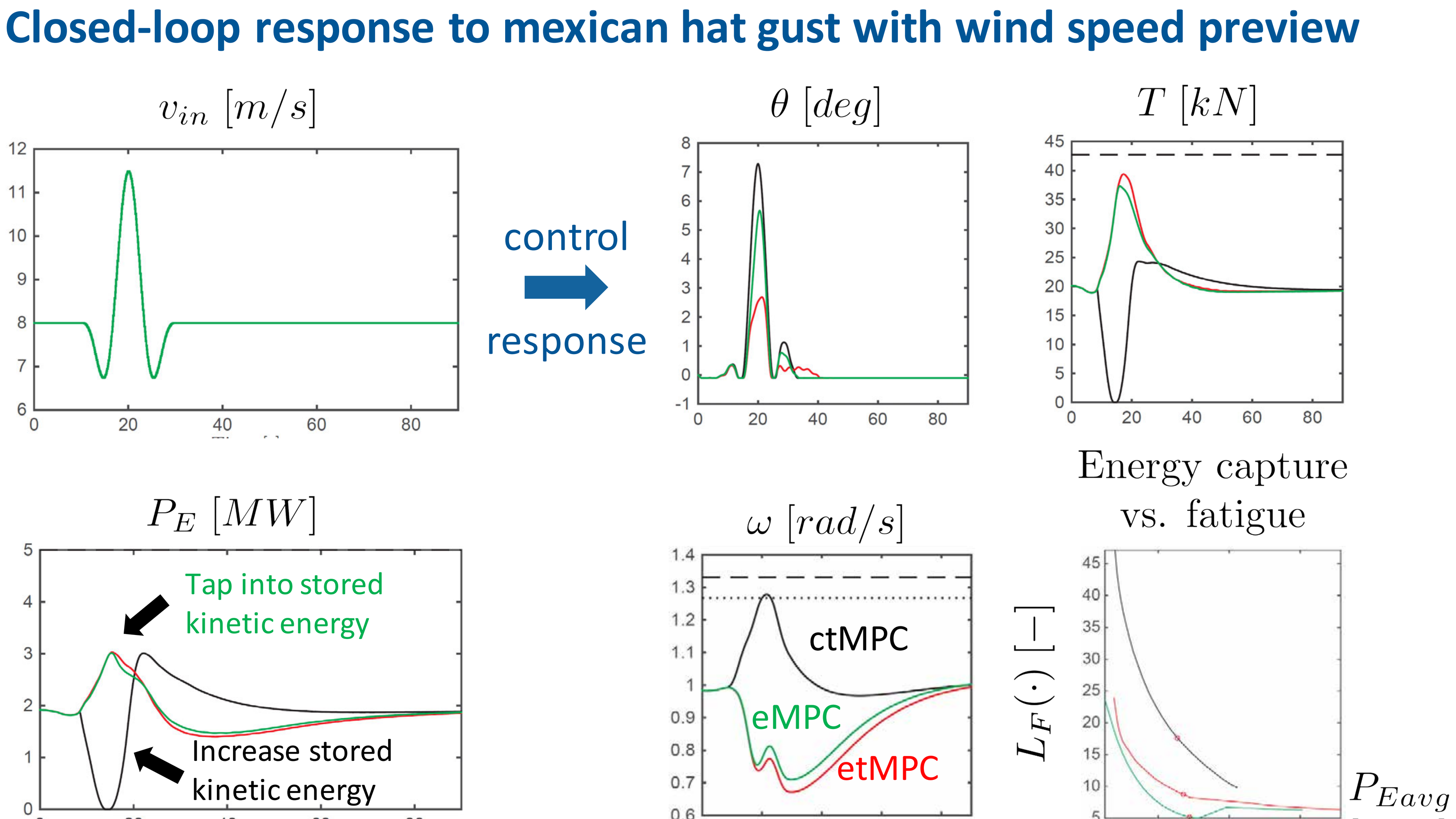
Tool-chain for rapid prototyping of wind turbine MPCs

- Academic components deliver high performance MPC algorithms
- HW-vendor tool-chains enable comfortable integration into WT automation architecture
- IAV in-house tool-chain closes existing gaps

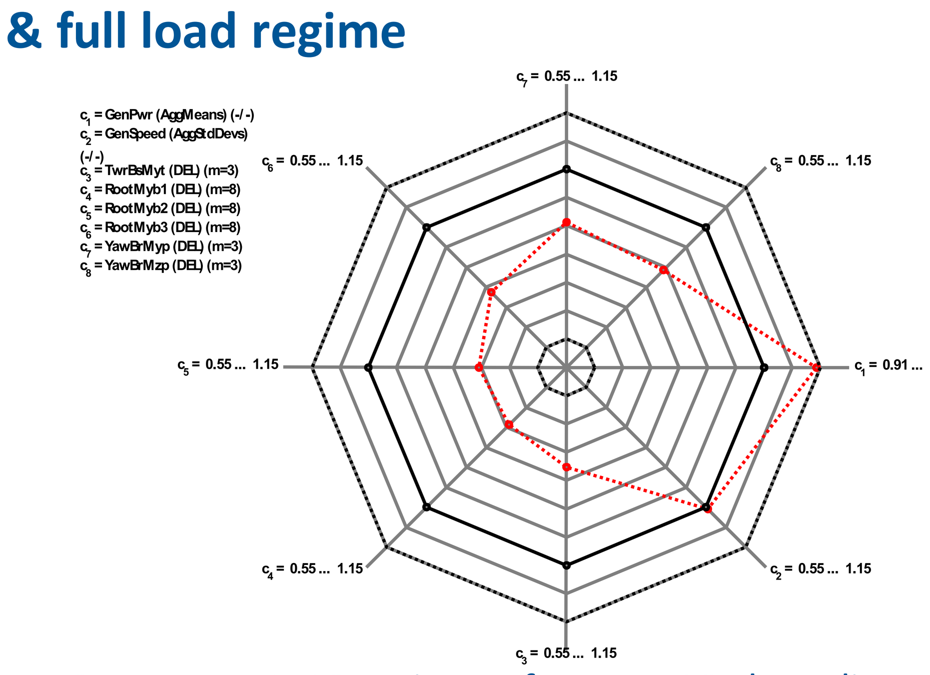


Simulation results @FAST & Conclusions

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



Turbulent wind simulations @FAST covering partial & full load regime



- Compare etMPC against reference FAST base-line controller
- Similar power capture & significant load reduction (~25%)
- Similar pitch activity, but more exploitation of generator torque
- Cycle time < 80 ms on BECKHOFF CX2040 PAC

References

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4. Jonkman et al.: Definition of a 5-MW reference wind turbine for offshore system development, *NREL/TP-500-38060, 2009.*