automotive
engineering

Control-oriented modeling and controller design for wind turbines

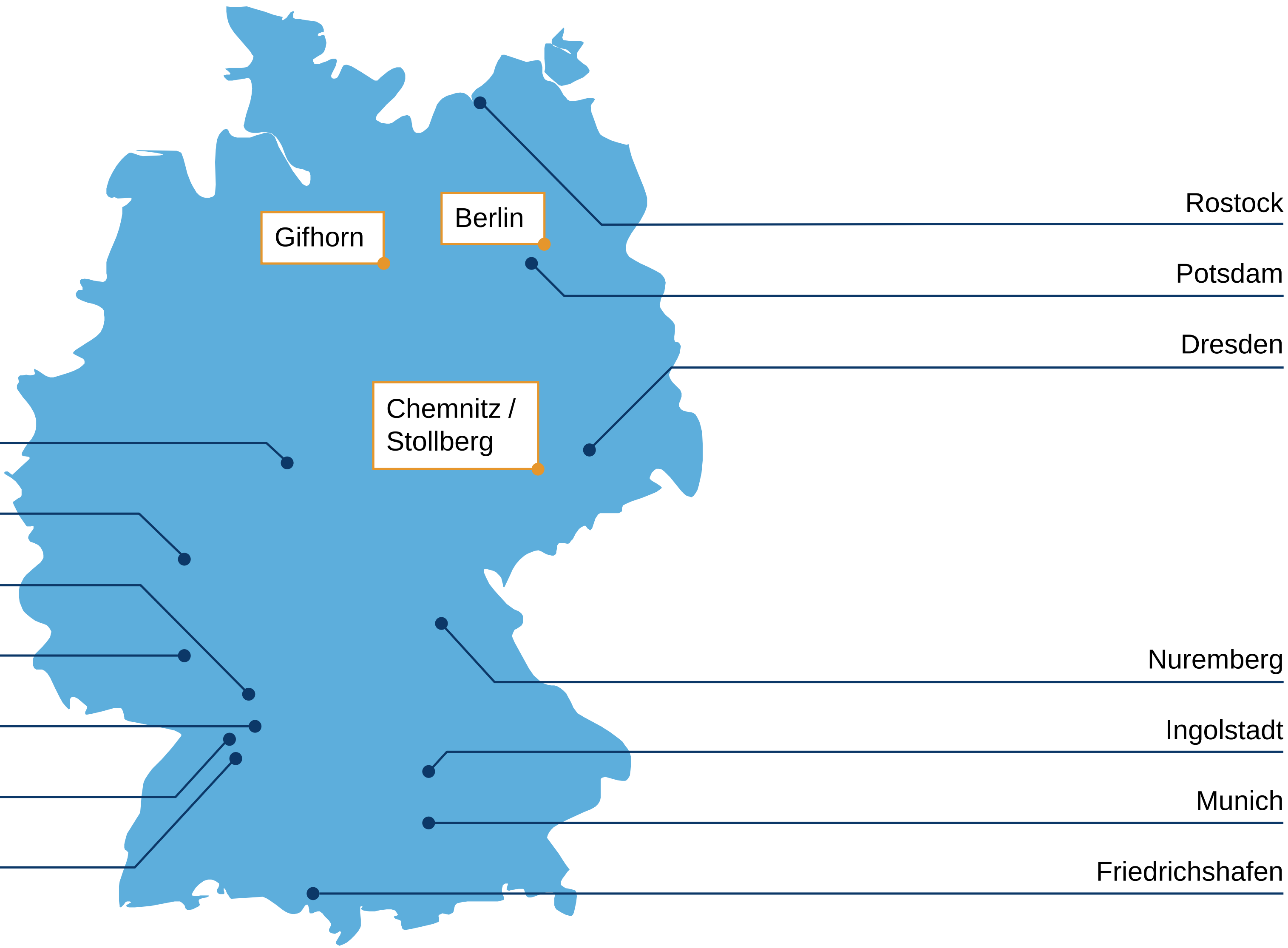
Wind energy systems lecture, University Freiburg
Dr. Axel Schild, Gifhorn, June 2018

Engineering

- **Passenger cars and vans**
- **Commercial vehicles and work machines**
- **Rail, marine, aviation**
- **Energy and water management**

Proximity to Customers in Germany

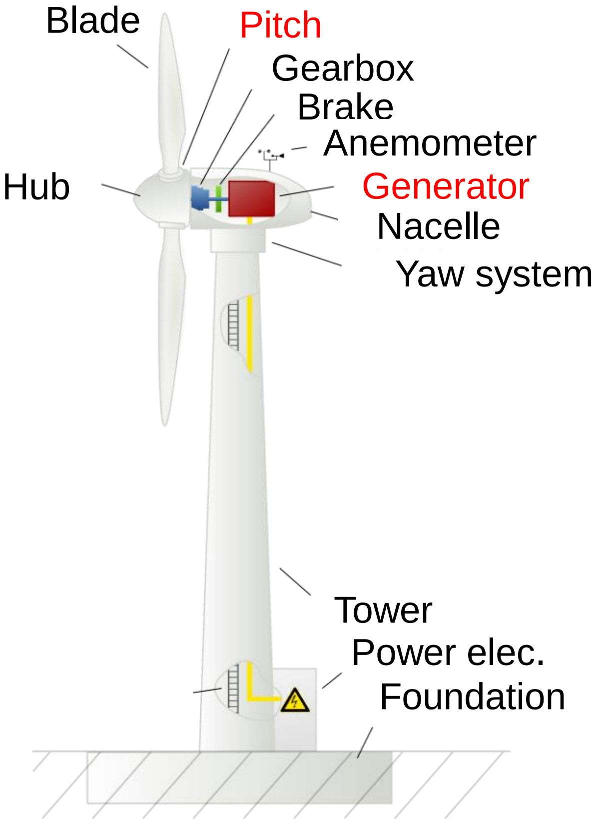
- ● IAV development centers
- ● IAV operations



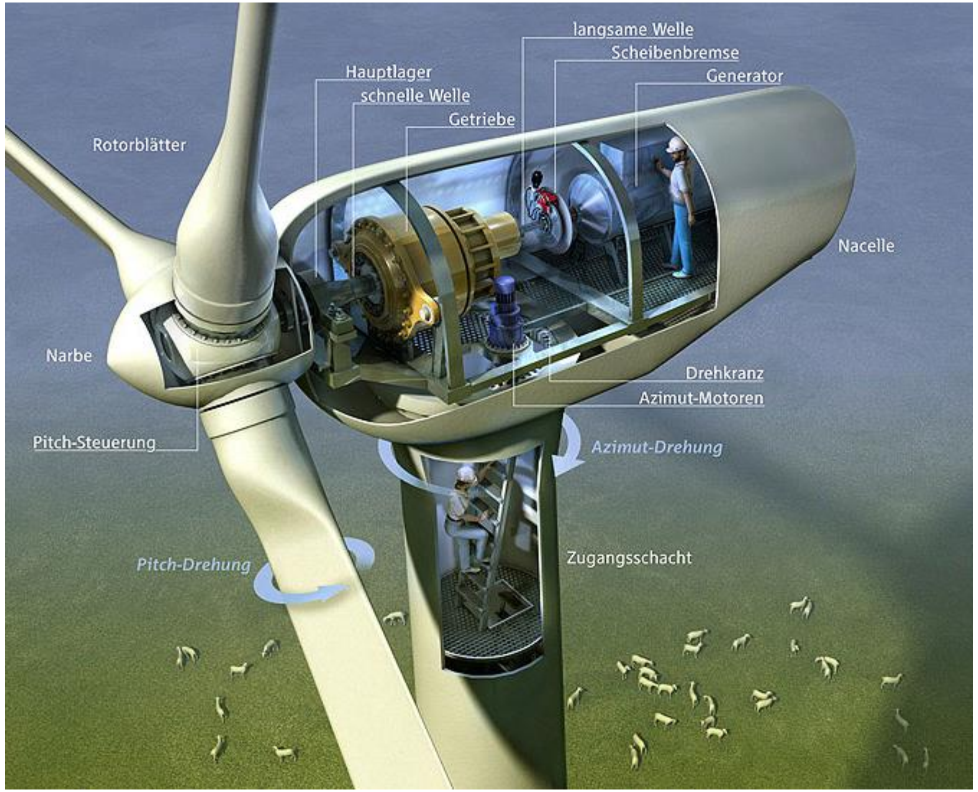
Presentation Outline

1. **Introduction to Wind Turbine control problem**
2. Aero-Elastic modeling of wind turbines
3. Conventional control applied to wind turbines
4. Advanced control concepts for wind turbines

1. Mechanical setup of variable-speed turbines



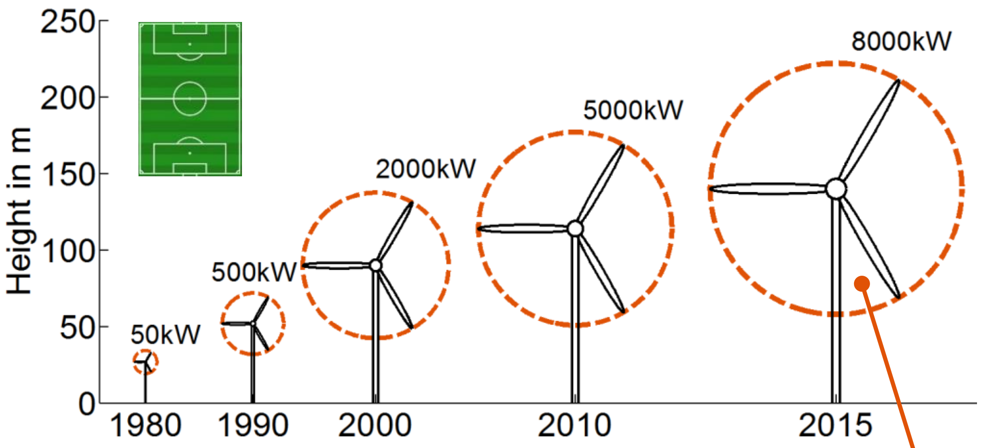
Quelle: Wikipedia.de

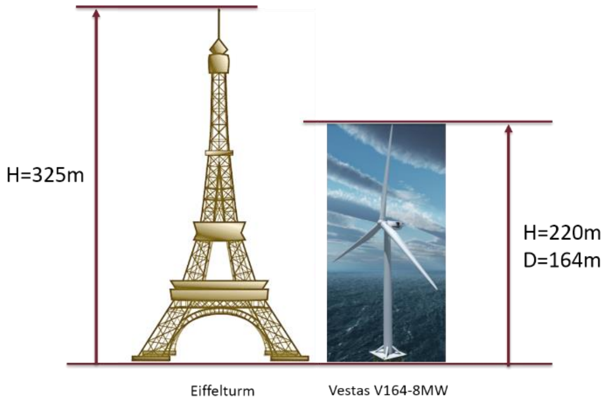


http://www.fkfoundation.com/de/redox-flow.html

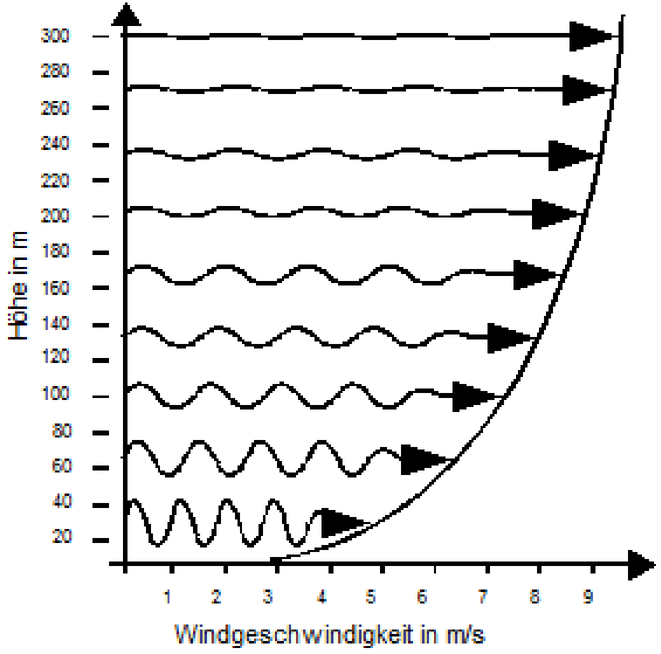
- → **Wind energy is a „mechanical engineering“ dominated domain – lots of steel and concrete**
- → **It‘s a huge, heavy and flexible machine!**

1. Growth is continuous trend in wind energy





$$P = \frac{\rho}{2}\overbrace{\pi \boldsymbol{R^2}}^{A}\, v_w^3 C_\mathrm{P}$$

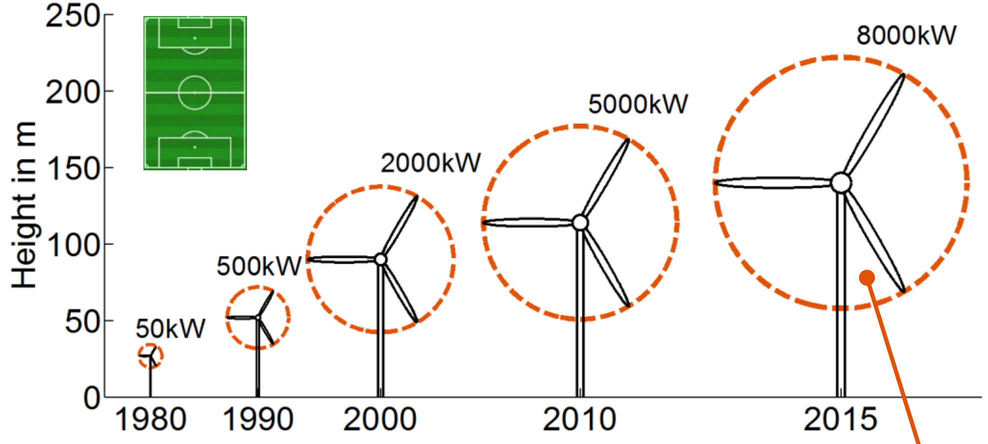


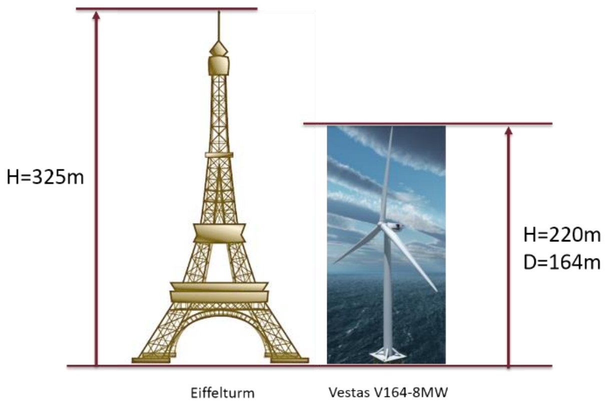
http://www.he-wt.com/documents/HE-WT_Informationen/HE-WT_Informationen.html

→ **Higher hub allows for larger rotor diameters**

→ **More persistent wind conditions higher above ground**

1. Growth is continuous trend in wind energy





$$P = \frac{\rho}{2}\overbrace{\pi \boldsymbol{R}^2}^{A}\, v_w^3 C_\mathrm{P}$$

Quelle: Wikipedia

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{Investment_t + O+M_t + Fuel_t + Carbon_t + Decommisioning_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Electricity_t}{(1+i)^t}}$$

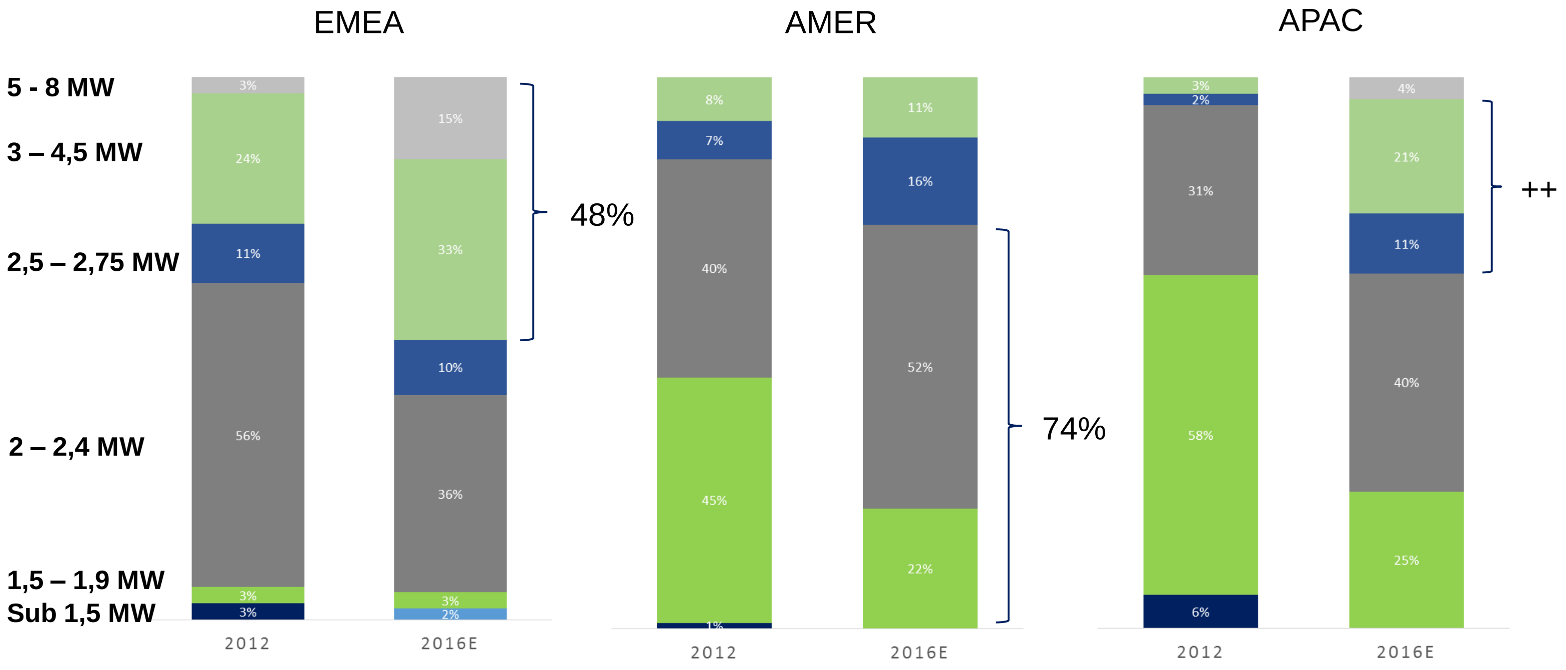
Impacts on LCOE

- Hub height: wind persistence → AEP/capacity factor
- Rotor diameter → AEP/capacity factor
- Generator & Power elec. capacity → rated turbine power
- Component optimization → (material) invest costs
- Intelligent operations and turbine control **(WIND4.0)**
  - AEP/capacity factor
  - Operating costs / O&M

→ Higher hub allows for larger rotor diameters

→ More persistent wind conditions higher above ground

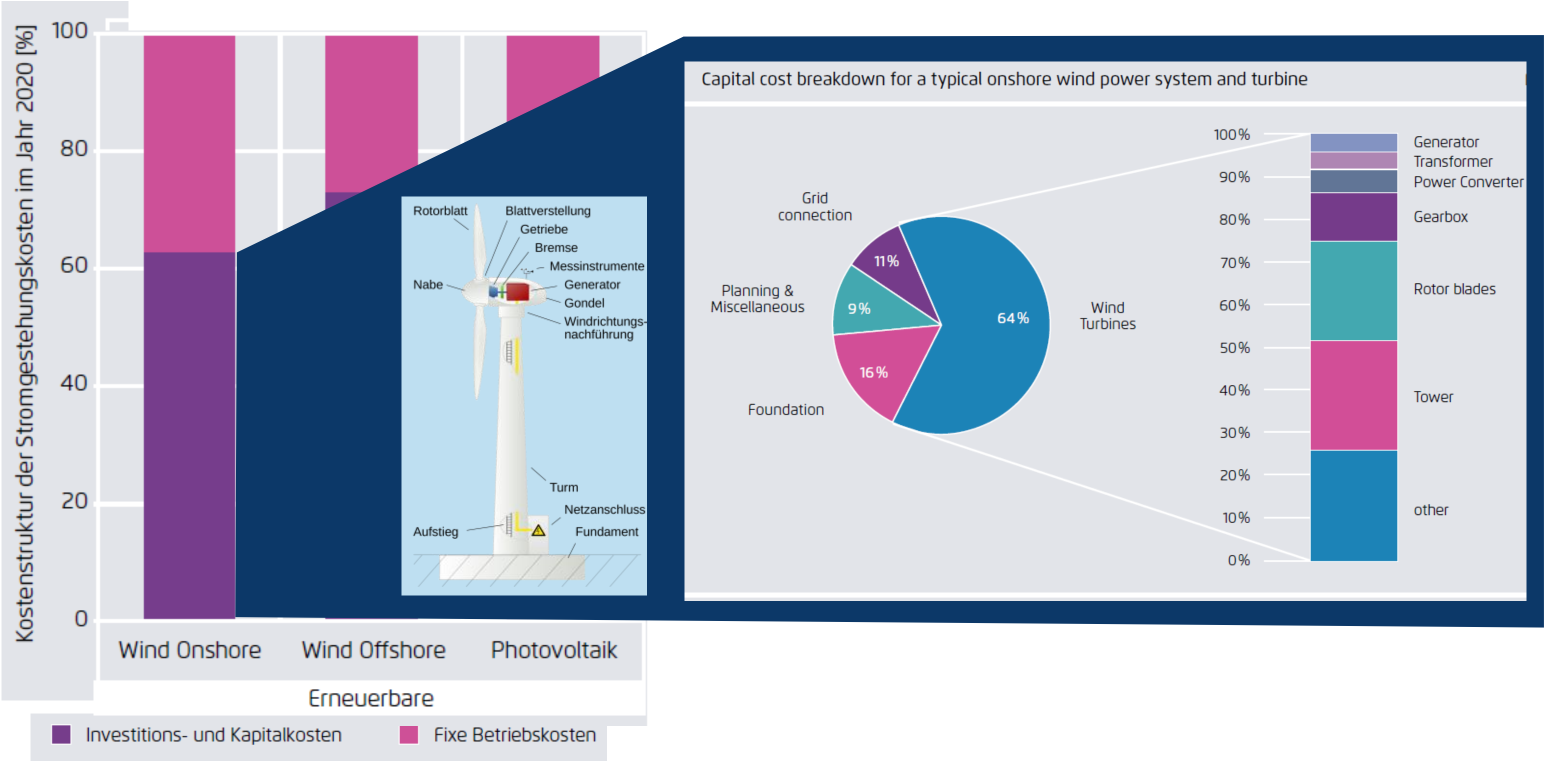
1. „Growth rate“ regionally different – due to economic drivers



Quelle: MAKE

→ **Turbine location, Grid situation, O&M costs, availability of land, etc.**

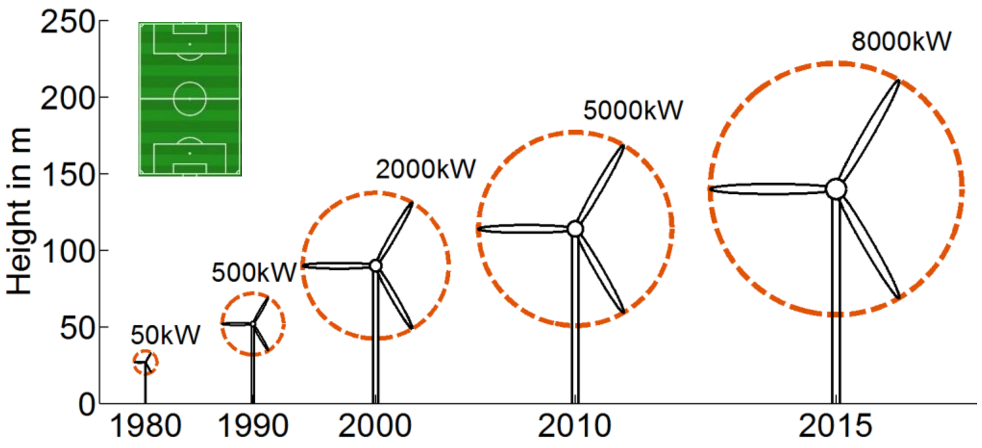
1. Typical life-cycle costs break-down of a wind turbine



Quelle: Agora e.V.

- → **Wind turbine is a capital intensive → costs accumulate in seemingly „simple“ components**
- → **Significant operating costs despite free „fuel“ wind**

1. Negative impact of turbine growth



$$f_{nat} \cong \frac{3.04}{4\pi^2}\frac{E_{steel} I}{\left(\boxed{M_{top}} + 0.227\mu \boxed{L\right) L^3}}$$

f_{nat} – Natural frequency of the support structure [Hz]
E_{steel} – Young's modulus (of steel) [N/m^2]
M_{top} – Mass of the nacelle and rotor [kg]
μ – Mass per unit length of the monopile [kg/m]
L – Length of the monopile [m]
I – Moment of inertia of the monopile cross section [m^4]

$$I = \frac{\pi}{64}(D_o^4 - D_i^4)$$

D_o – Outer diameter of the monopile [m]
D_i – Inner diameter of the monopile [m]

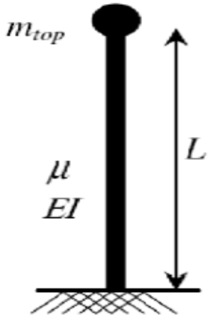


Figure 6-6: Simple model for the monopile

A. Paul: A Comparative Analysis of the Two-Bladed and the Three-Bladed Wind Turbine for Offshore Wind Farms, Master Thesis, 2010

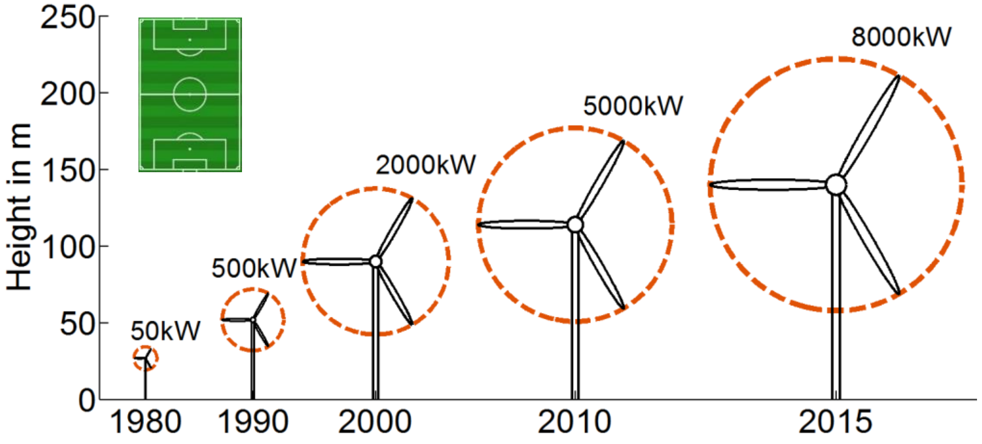
→ **Higher hub allows for larger rotor diameters**

→ **More persistent wind conditions higher above ground**

→ **Higher Hub + larger rotor → higher forces**

→ **Increased mass + inertia → lower eigenfrequencies**

1. Negative impact of turbine growth



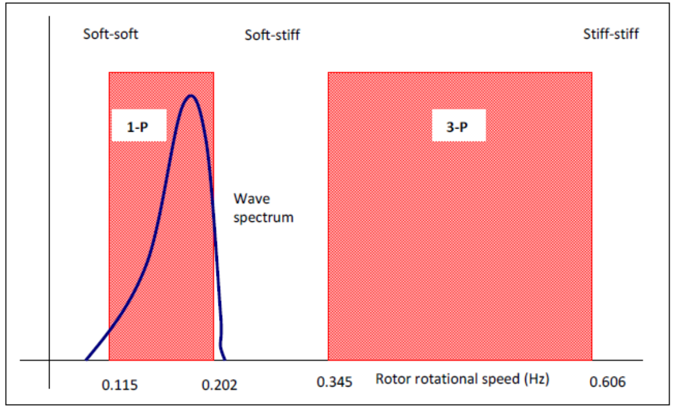
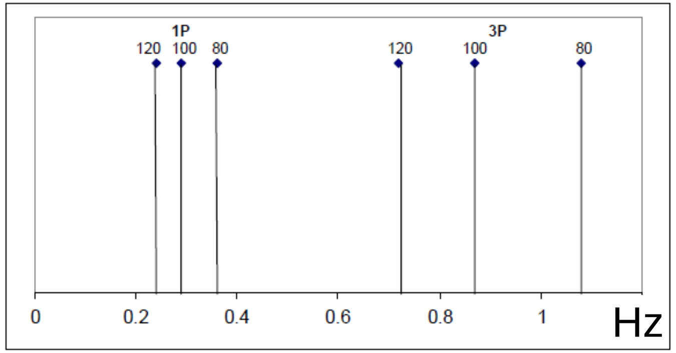


Figure 6-5: 1-P and 3-P regions with wave spectrum

Excitation of structural oscillations

- Temporal stochastic wind field
- Aerodynamic imbalace / tower shadow
- Rotor mass imbalance
- Waves (offshore)



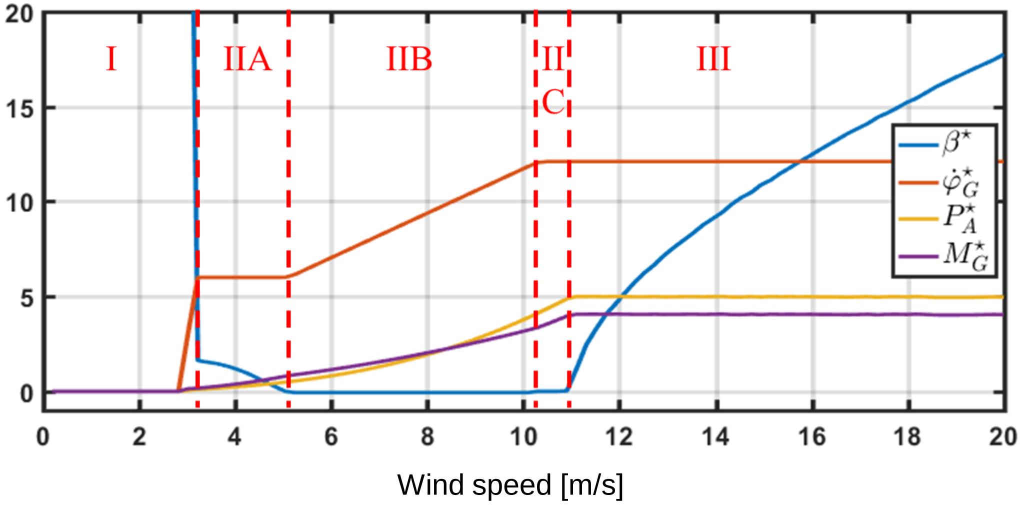
A. Paul: A Comparative Analysis of the Two-Bladed and the Three-Bladed Wind Turbine for Offshore Wind Farms, Master Thesis, 2010

→ Higher Hub + larger rotor → higher forces

→ Increased mass + inertia → lower eigenfrequencies

→ Eigenfrequencies move into excitation spectrum

1. Operarting strategy for wind turbines



Competing control objectives

- Maximize energy capture
- Limit of aerodynamic torques and forces (maintain power and rotor speed limits)

❖ Minimize mechanical loads and fatigue

❖ Damp torsional oscillations in drive-train

❖ Avoid excessive actuator usage (esp. pitch)

❖ Limit power fluctations

Operational intervals

I. Low wind / idle

IIA. Minimal rotor speed

IIB. Subrated regime → max. energy capture

IIC. Enforce max. rotor speed

III. Rated regime → min. power jitter / constraint enforcement

IV. Excessive wind speed → shut-down

→ Look-up table derived from steady state considerations

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1. Introduction to Wind Turbine control problem
2. **Aero-Elastic modeling of wind turbines**
3. Conventional control applied to wind turbines
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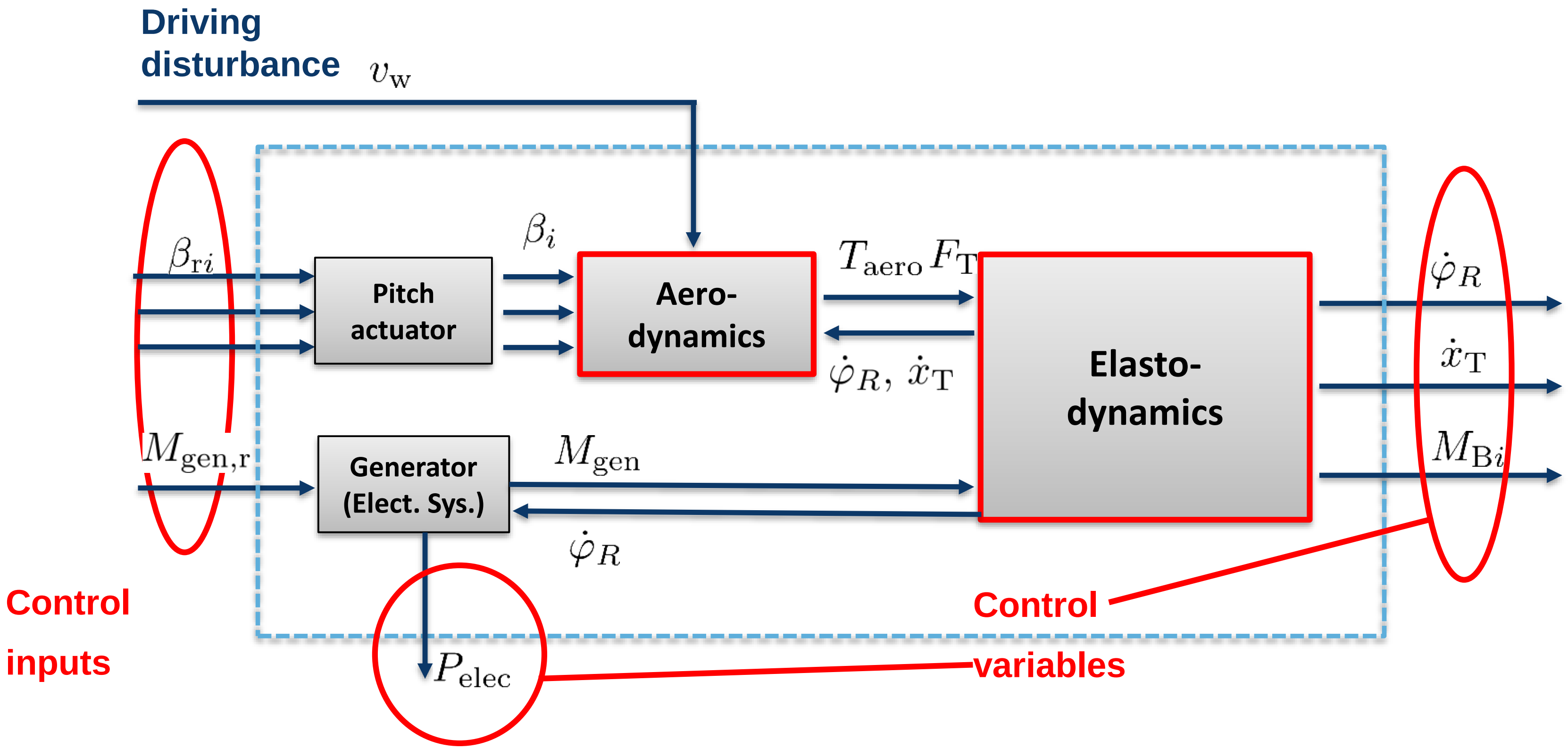
2. System theoretic view of a wind turbine

Available measurements

- Electrical power
- Generator speed
- Tower top accel.
- Single-point wind speed
- Blade accel. / blade root bending moment



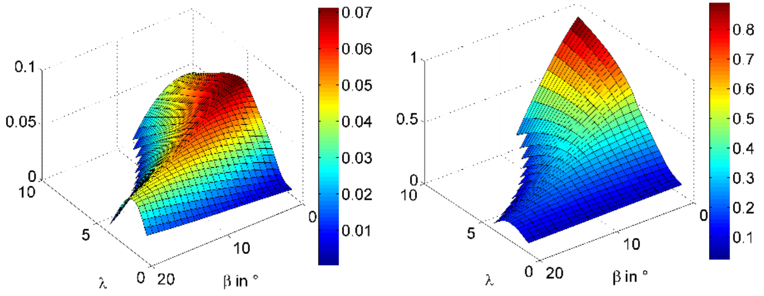
2. Aero-dynamics – static model

Energy transformation

Wind speed into torque (rotation)

$$T_{\text{aero}} = \frac{\rho}{2} A_r R C_M(\beta,\lambda) {v_{\text{w}}}^2$$

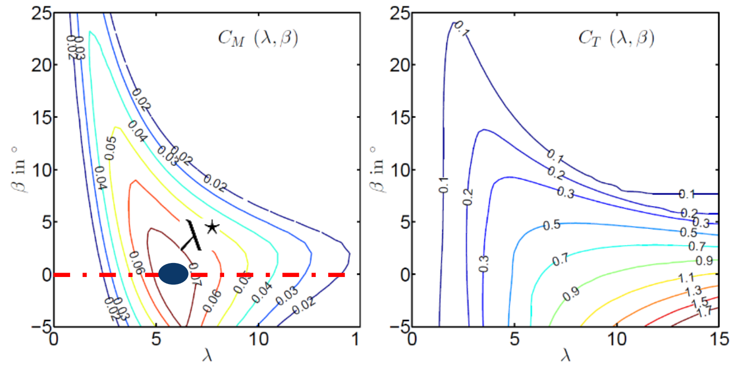
$$C_P(\beta,\lambda) = \lambda C_M(\beta,\lambda)$$



Tip speed ratio (TSR)

$$\lambda = \frac{\varphi_R R}{v_{\text{w}}}$$

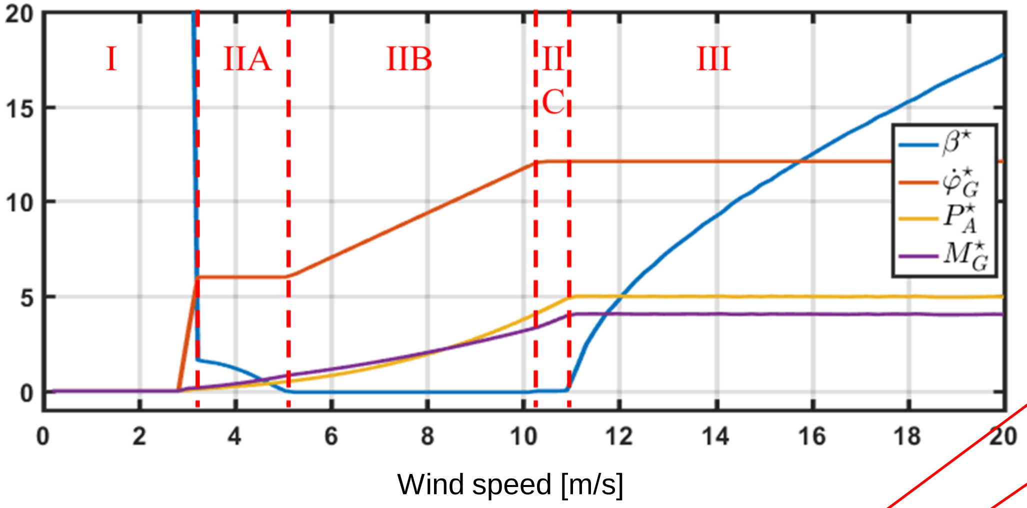
Maximum at $\beta = 0$

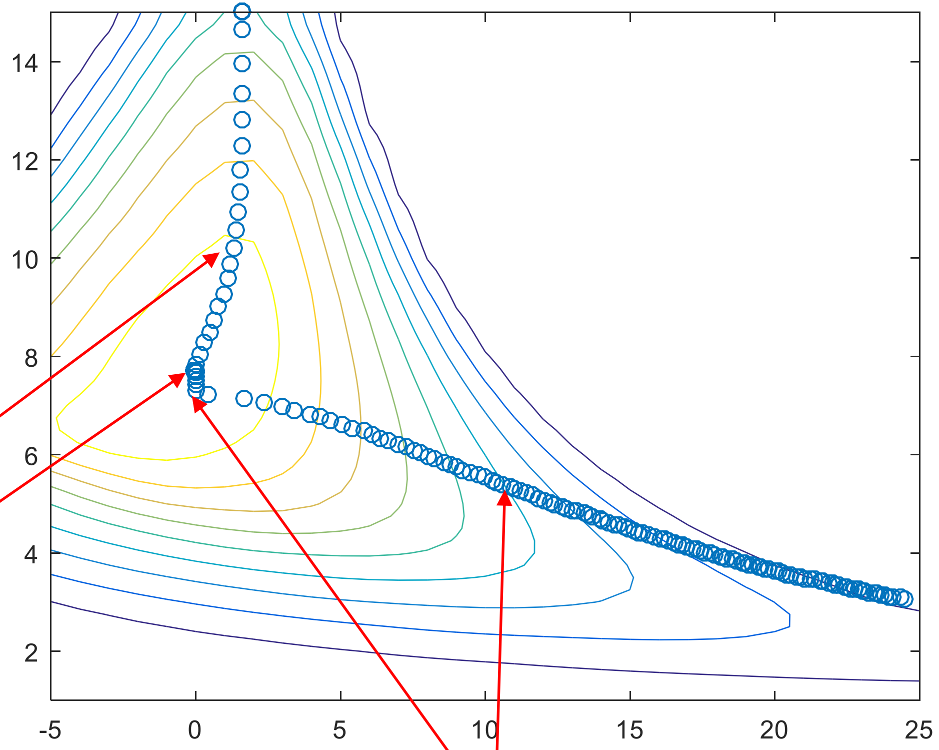


Wind speed into thrust (bending)

$$F_{\text{T}} = \frac{\rho}{2} A_r C_T(\beta,\lambda) {v_{\text{w}}}^2$$

2. Aero-dynamics fully define operating strategy





Operational intervals

IIA. Minimal rotor speed / fine pitch to maximize C_p

IIB. Subrated regime → enforce $\lambda^\star$, no pitching

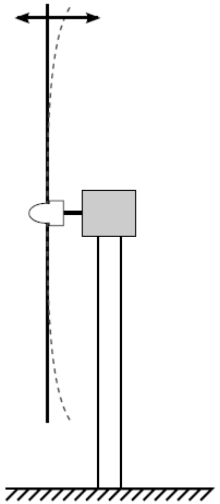
IIC. Max. rotor speed → maximize C_p, no pitching

III. Rated regime → maintain energy balance

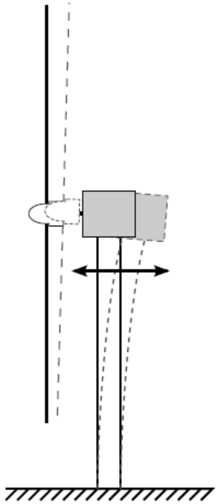
→ **Look-up table derived from steady state considerations**

2. Elasto-dynamics – dynamical model (Diss. Arne Körber, 2014)

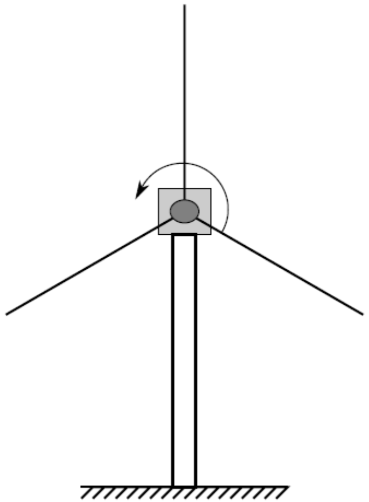
Model simplification – only capture what is relevant for control



Blade flap motion



Tower FA motion



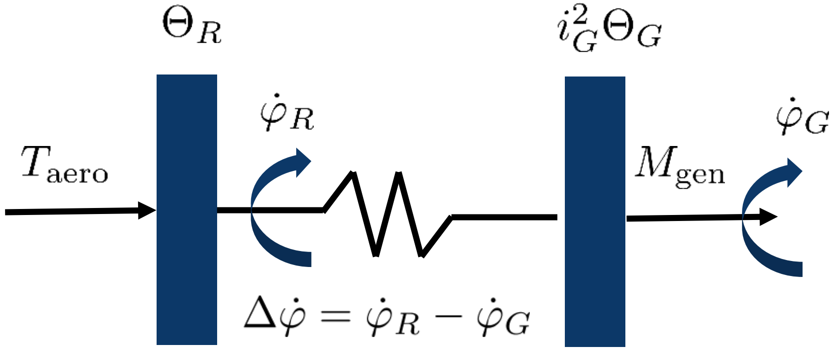
DT rotational motion

Modeling assumptions:

- Blade is a stiff rotating beam
- Tower approx. as simple mass-spring-damper
- Drive-train modeled as 2-mass-oscillator

2. Elasto-dynamics – dynamical model based on first principles

Drive-train schematics



Equations of motions (ODEs)

$$
\begin{aligned}
0 &= \Theta_g\ddot\varphi_{\mathrm{G}} - (b_\phi\Delta\dot\varphi + k_\phi\Delta\varphi) + i_{GB}\boxed{M_{\mathrm{G}}}\\
0 &= \Theta_{\mathrm{R}}(\ddot\varphi_{\mathrm{G}} + \Delta\ddot\varphi) + b_\phi\Delta\dot\varphi + k_\phi\Delta\varphi - \boxed{T_{\text{aero}}(\lambda,\beta,v_{\mathrm{e}})}
\end{aligned}
$$

Tower-blades schematics (inverted pendulum like)

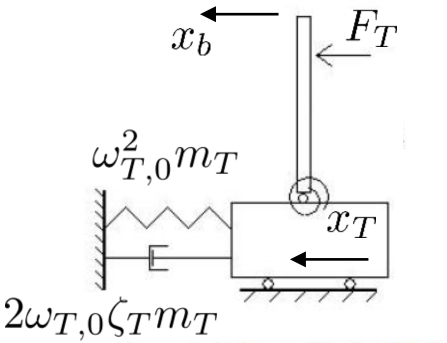


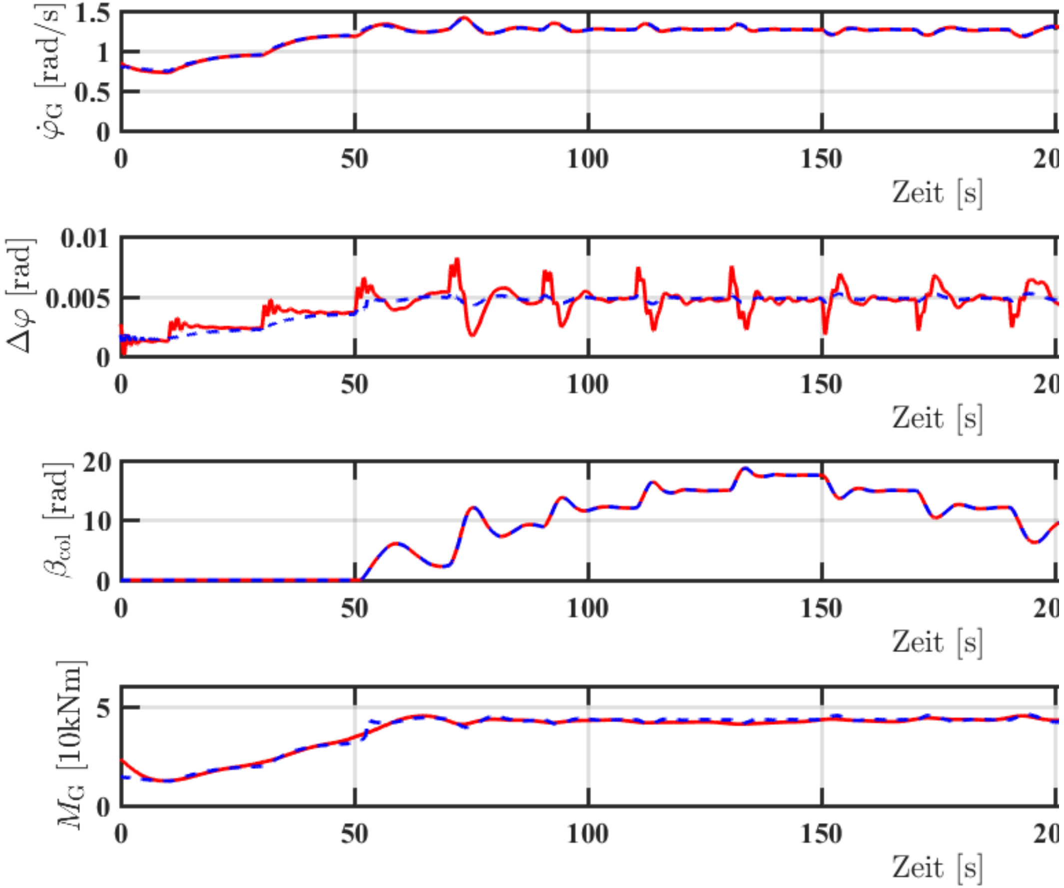
Figure 4.5.: Mechanical Turbine Model

$$
\begin{aligned}
0 &= \ddot x_{\mathrm{T}} + \boxed{3a_{FG}\omega_{T,0}^2 m_{bl}a_{1p}\ddot x_{\mathrm{B}}} + 2\omega_{T,0}\zeta_T\dot x_{\mathrm{T}} + \omega_{T,0}^2 x_{\mathrm{T}} - a_{FG}\omega_{T,0}^2\boxed{F_T(\lambda,\beta,v_{\mathrm{e}})}\\
0 &= \boxed{3m_{bl}l_{g-a}k_b\omega_{0,f}^2\ddot x_{\mathrm{T}}} + \ddot x_{\mathrm{B}} + 2\omega_{0,f}\zeta_b\dot x_{\mathrm{B}} + \omega_{0,f}^2 x_{\mathrm{B}} - a_{FG}\omega_{0,f}^2\boxed{F_T(\lambda,\beta,v_{\mathrm{e}})}
\end{aligned}
$$

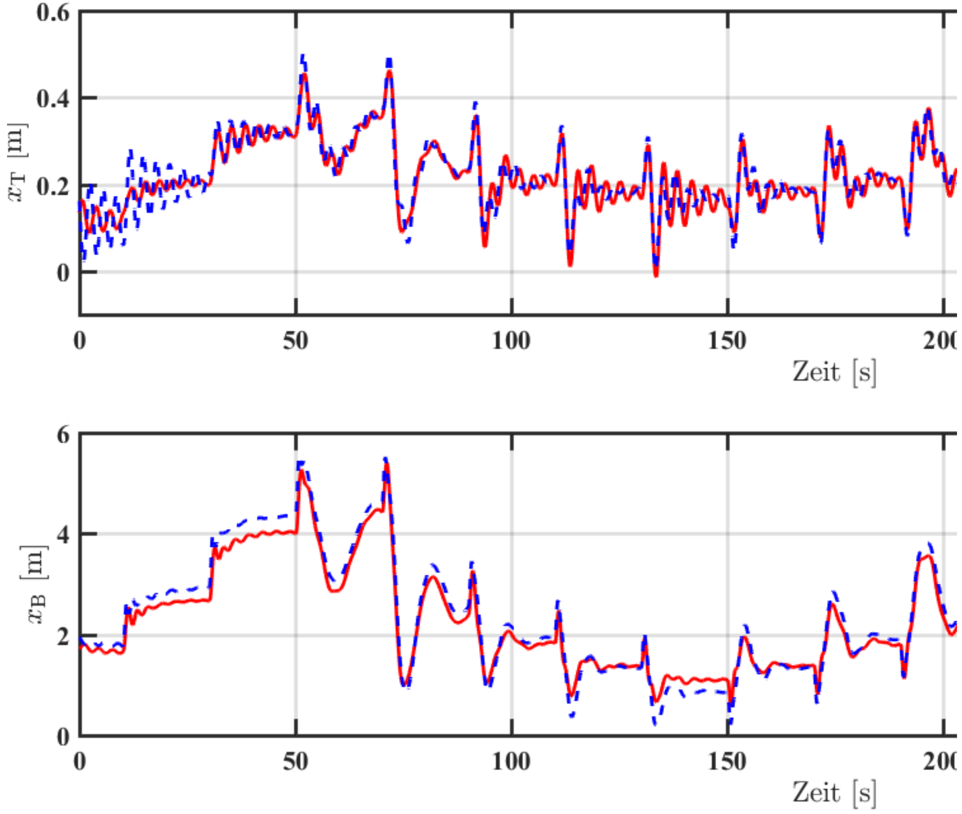
A. Körber: Extreme and Fatigue Load Reducing Control for Wind Turbines: A Model Predictive Control Approach using Robust State Constraints, 2014 Diss., TU Berlin

2. Open-loop simulation for NRELs FAST 5MW Turbine

Stepwise wind excitation response



Tower and Blade motion



JONKMAN, et al. *Definition of a 5-MW reference wind turbine for offshore system development*. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.

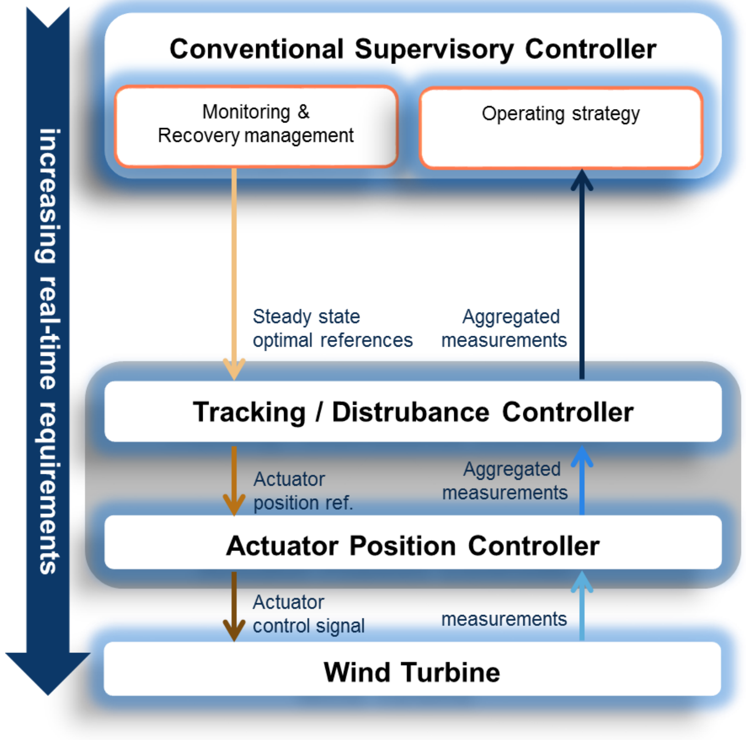
→ Flap-wise motions of blades are mainly damped aerodynamically through effective wind speed feedback

Presentation Outline

1. Introduction to Wind Turbine control problem
2. Aero-Elastic modeling of wind turbines
3. **Conventional control applied to wind turbines**
4. Advanced control concepts for wind turbines

3. State-of-the-art turbine control in commercial turbines

Conventional turbine control architecture dominated by SISO (PID) control loops + complex switching logics



increasing real-time requirements

Conventional Supervisory Controller

Monitoring & Recovery management

Operating strategy

Steady state optimal references

Aggregated measurements

Tracking / Distrubance Controller

Actuator position ref.

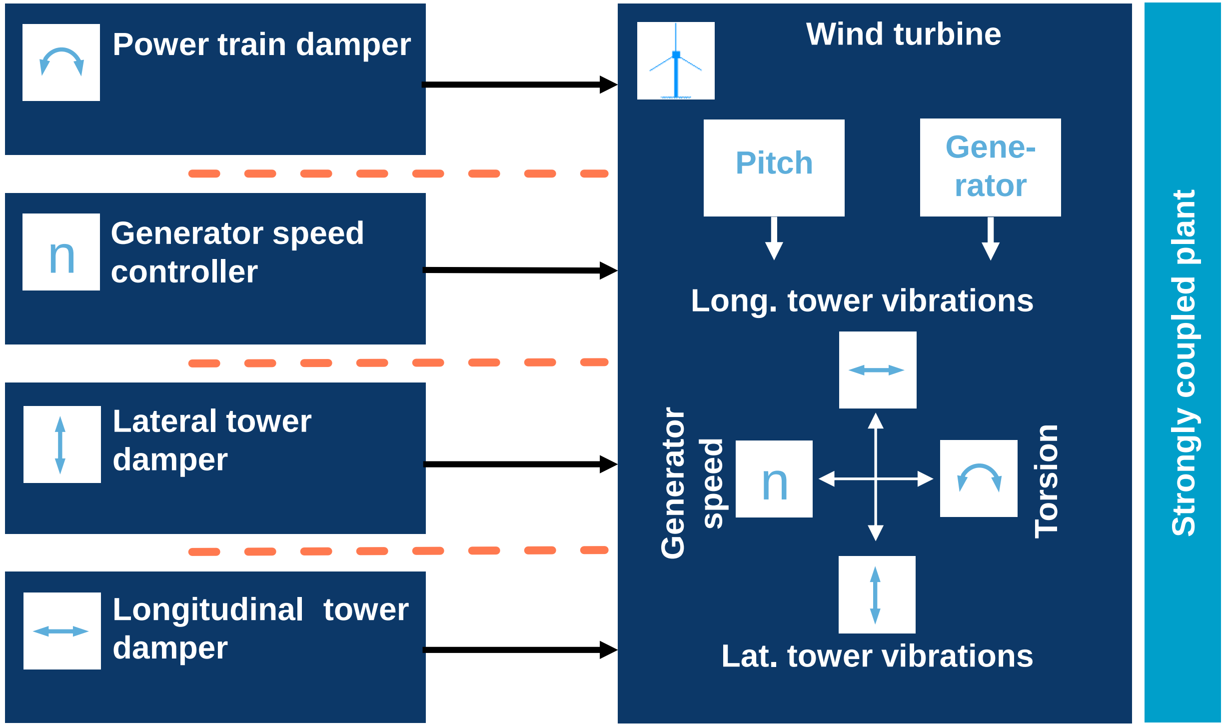
Aggregated measurements

Actuator Position Controller

Actuator control signal

measurements

Wind Turbine



Power train damper

Generator speed controller

Lateral tower damper

Longitudinal tower damper

Wind turbine

Pitch

Gene-rator

Long. tower vibrations

Generator speed

n

Torsion

Lat. tower vibrations

Strongly coupled plant

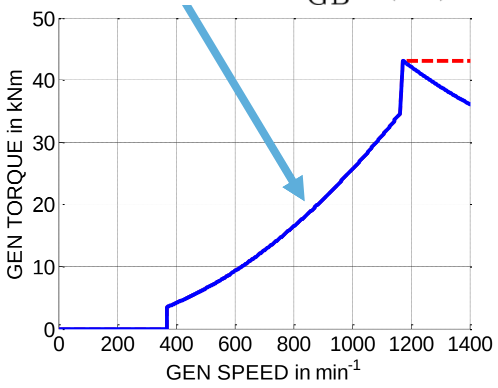
3. State-of-the-art turbine control in commercial turbines

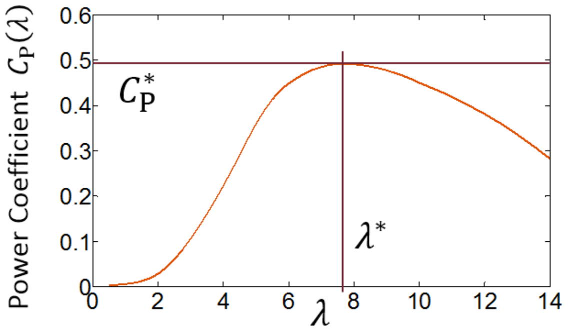
Generator speed controller

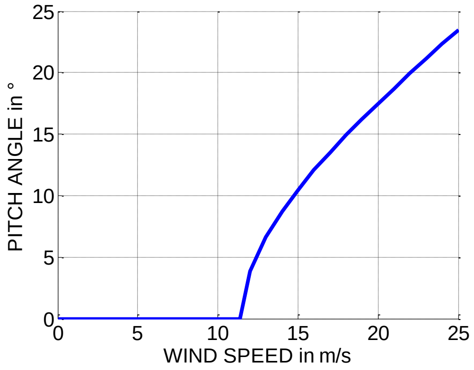
- Regime IIA-IIB: zero pitch, maintain torque balance
- Regime III: max. torque/P_{elec} , only pitch

$$M_{\text{gen}}(\dot{\varphi}_G) = \frac{\rho A_R R^3}{2 i_{\text{GB}}^2} \frac{C_P^\star}{(\lambda^\star)^3} \dot{\varphi}_G^2$$

$$\beta(\dot{\varphi}_G, \dot{\varphi}_{\text{Gr}}) = k_p e_\varphi + k_i \int_0^t e_\varphi \text{d}t$$







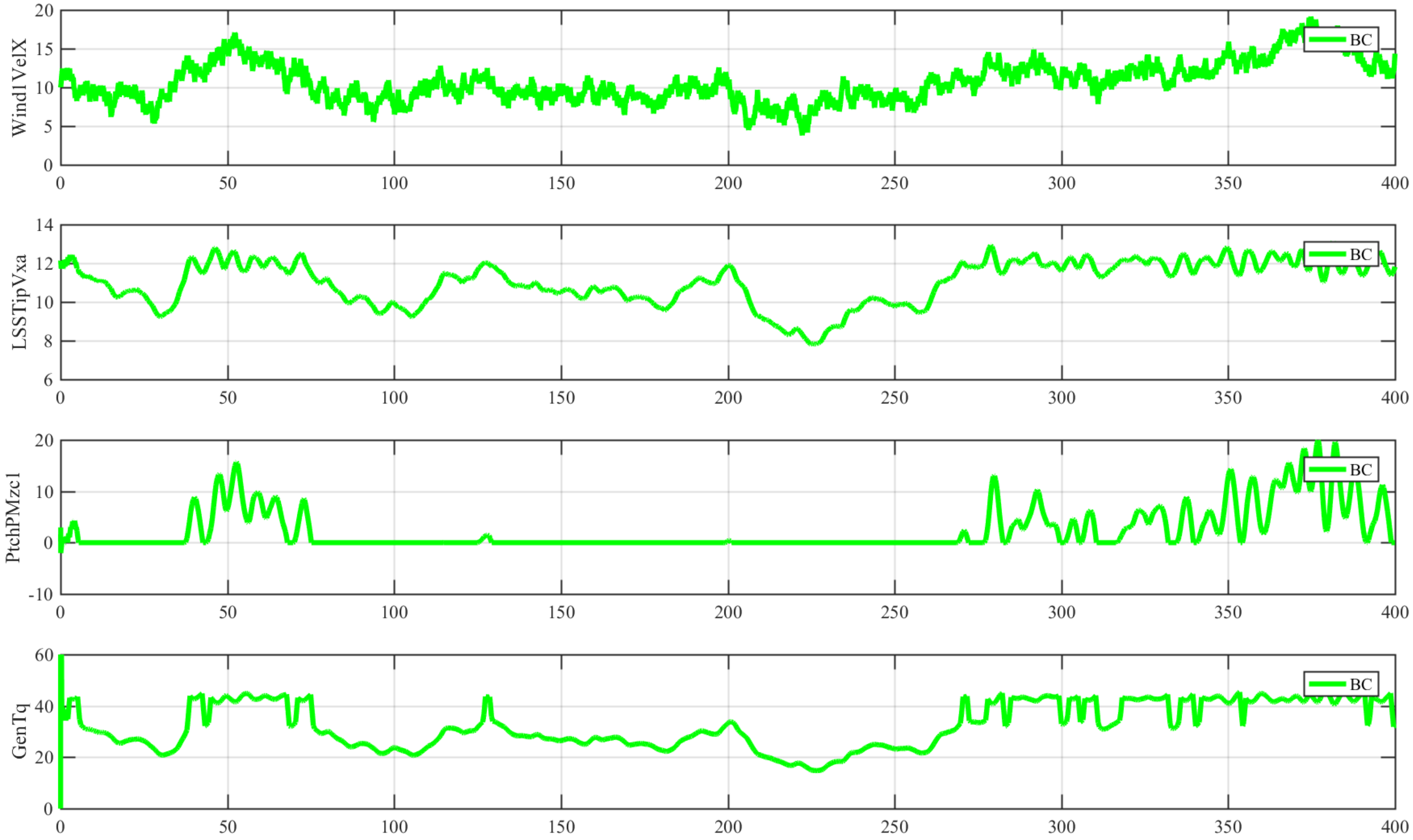
E. Bossanyi: Wind Turbine Control for Load Reduction, Wind Energy, 2003

→ **Reference-free torque control law → „*C_{pmax} Tracking Law*“**

→ **Pitch-loop uses constant reference (rated GenSpd)**

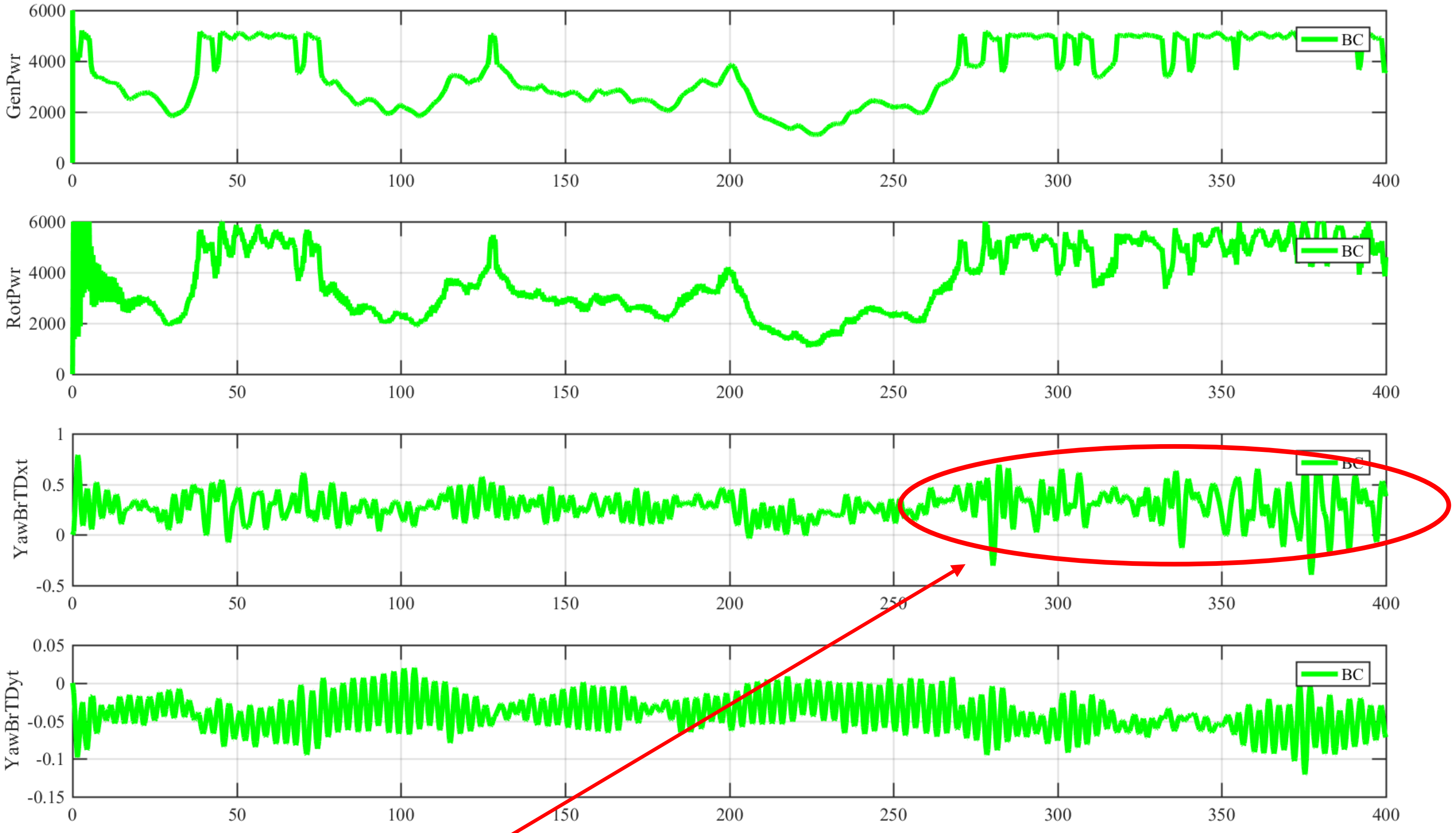
→ **Coordination of „competing“ control loops via „complex“ blending and switching logic**

3. Closed-loop simulation for NRELs FAST 5MW Turbine



→ **Response to temporally turbulent wind around rated operation**

3. Closed-loop simulation for NRELs FAST 5MW Turbine



→ **Strong tower movements visible**

3. Model-based controller design (your favourite type)

MIMO state-feedback controller for rated turbine operation

- Linearize model at rated wind speed (at steady-state OP)

$$\begin{aligned}\delta\dot{\boldsymbol{x}} &= \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}(\boldsymbol{x}^r,\boldsymbol{u}^r,\boldsymbol{d}^r)\delta\boldsymbol{x} \;+\; \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{u}}(\boldsymbol{x}^r,\boldsymbol{u}^r,\boldsymbol{d}^r)\delta\boldsymbol{u} \;+\; \frac{\partial \boldsymbol{f}}{\partial \boldsymbol{d}}(\boldsymbol{x}^r,\boldsymbol{u}^r,\boldsymbol{d}^r)\delta\boldsymbol{d}\\ &= \boldsymbol{A}\delta\boldsymbol{x} \;+\; \boldsymbol{B}\delta\boldsymbol{u} \;+\; \boldsymbol{E}\delta\boldsymbol{d}\end{aligned}$$

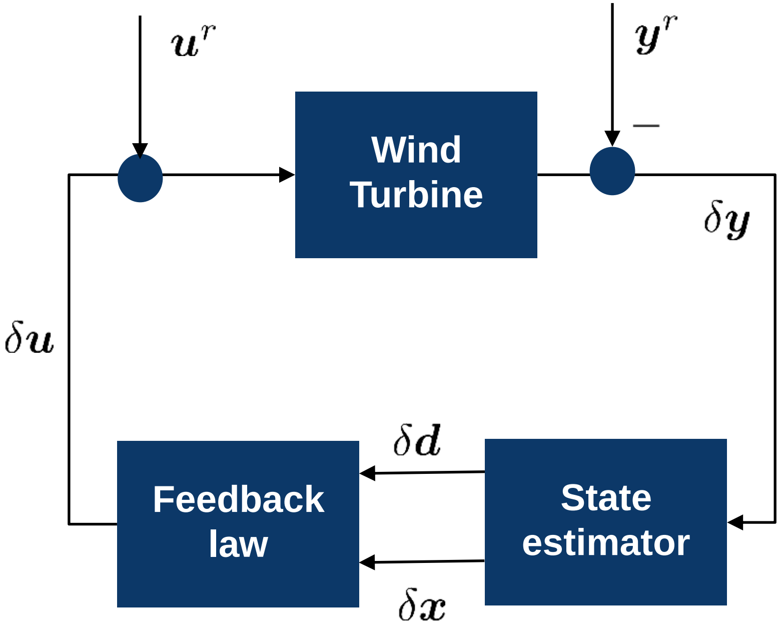
$$\begin{aligned}\delta\boldsymbol{y} &= \frac{\partial \boldsymbol{h}}{\partial \boldsymbol{x}}(\boldsymbol{x}^r,\boldsymbol{u}^r,\boldsymbol{d}^r)\delta\boldsymbol{x} \;+\; \frac{\partial \boldsymbol{f}h}{\partial \boldsymbol{u}}(\boldsymbol{x}^r,\boldsymbol{u}^r,\boldsymbol{d}^r)\delta\boldsymbol{u} \;+\; \frac{\partial \boldsymbol{h}}{\partial \boldsymbol{d}}(\boldsymbol{x}^r,\boldsymbol{u}^r,\boldsymbol{d}^r)\delta\boldsymbol{d}\\ &= \boldsymbol{C}\delta\boldsymbol{x} \;+\; \boldsymbol{D}\delta\boldsymbol{u} \;+\; \boldsymbol{F}\delta\boldsymbol{d}\end{aligned}$$

Observe, that here $\delta\boldsymbol{y} = \begin{pmatrix} 1 & 0 \\ \eta i_{\mathrm{GB}} M^r_{\mathrm{gen}} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \delta x_1 \\ \delta x_3 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \eta i_{\mathrm{GB}} \dot{\varphi}^r_G \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \delta u_1 \\ \delta u_3 \end{pmatrix}$

- LQR Design to track rated GenSpd and electrical power

$$J(\delta\boldsymbol{x},\delta\boldsymbol{u}) \;=\; \delta\boldsymbol{x}^{\mathrm{T}}\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{C}\delta\boldsymbol{x} + 2\delta\boldsymbol{x}^{\mathrm{T}}\boldsymbol{C}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{D}\delta\boldsymbol{u} + \delta\boldsymbol{u}^{\mathrm{T}}\boldsymbol{D}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{D}\delta\boldsymbol{u} + \delta\boldsymbol{u}^{\mathrm{T}}\boldsymbol{R}\delta\boldsymbol{u}$$

$\rightarrow \delta\boldsymbol{u} = \boldsymbol{K}\delta\boldsymbol{x}$ Feedback law coordinates torque and pitch



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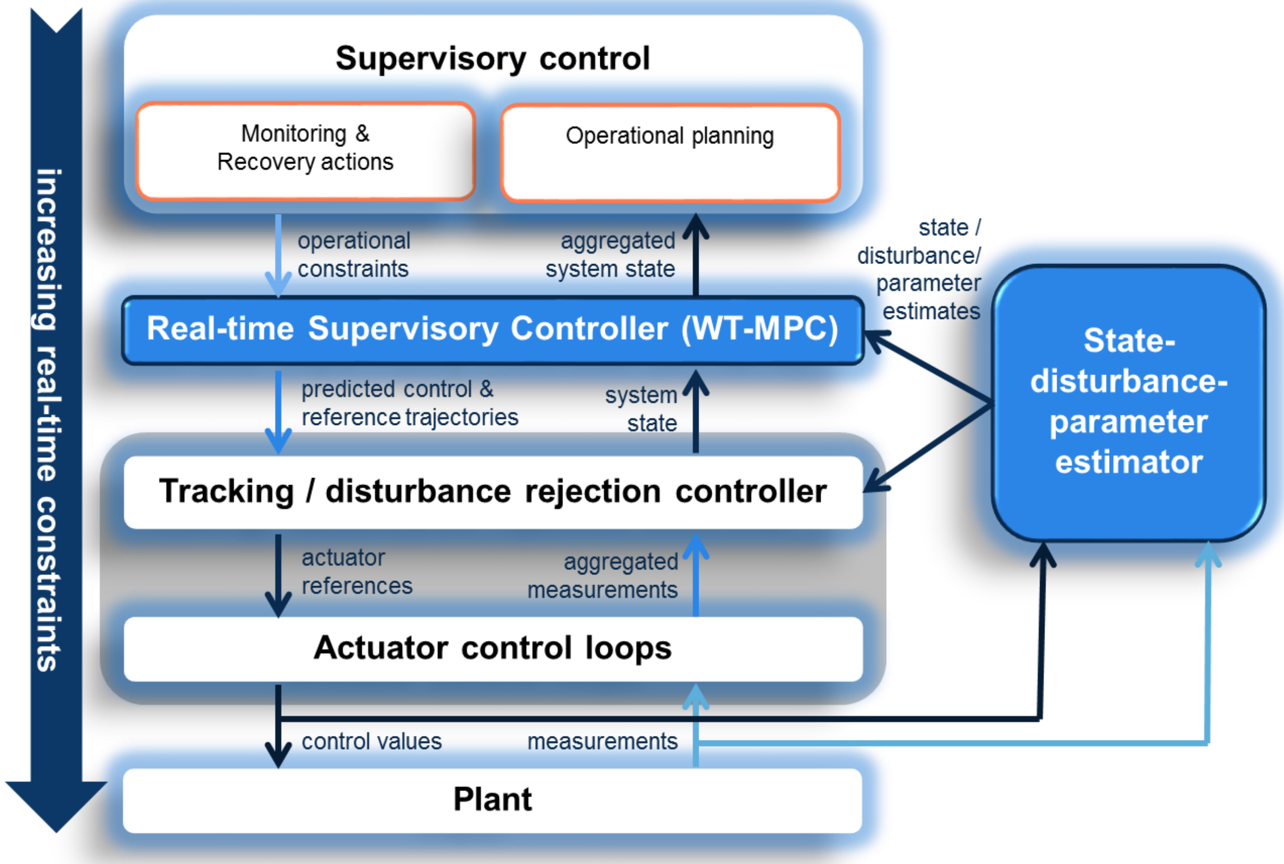
1. Introduction to Wind Turbine control problem
2. Aero-Elastic modeling of wind turbines
3. Conventional control applied to wind turbines
4. **Advanced control concepts for wind turbines**

4. Advanced turbine control via model predictive control



Advantages

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

State-feedback and recurrent optimization at appropriate rate

- Compensate for modeling errors
- Robustness to unknown external disturbances

→ MPC focuses on optimizing the economics of plant operation

→ Tracking controller stabilizes rotor speed reference in the face of unexpected wind speed disturbances

4. Ingredients of model predictive turbine control

Performance metric

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

„performance indicating” stage costs

„stabilizing“ terminal costs

Dynamic plant model

s.t.

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

$$\boxed{\mathbf{x}_0 = \boldsymbol{x}(t_s)}$$

„Feedback“ constraint

Valid operating regime

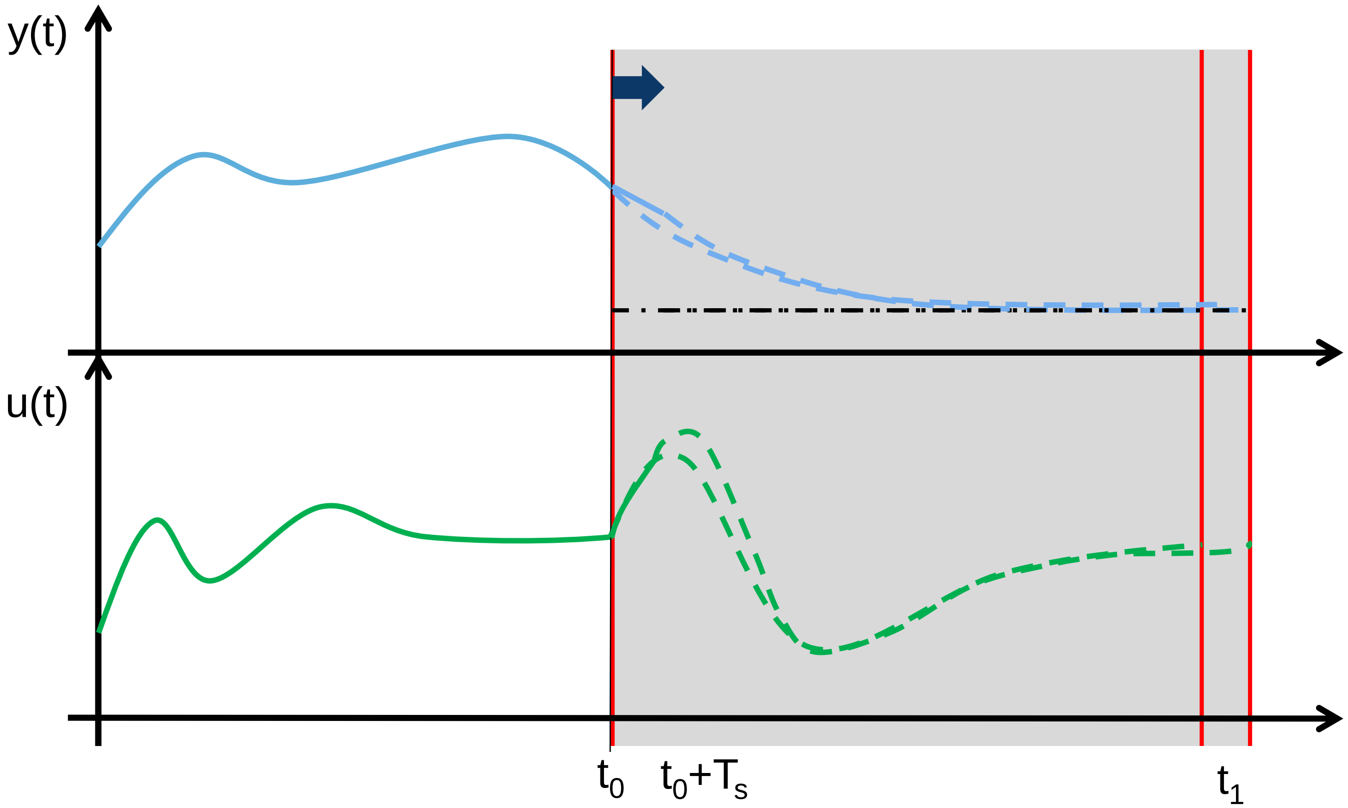
$$\boxed{\begin{array}{ccccccc} \underline{\boldsymbol{u}} & \leq & \boldsymbol{u}_k & \leq & \overline{\boldsymbol{u}} & : & \forall k \\ \underline{\boldsymbol{x}} & \leq & \boldsymbol{x}_k & \leq & \overline{\boldsymbol{x}} & : & \forall k \end{array}}$$

input & state constraints

4. Working principle of model predictive control

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

→ Look into the future, instead into the past!



Basic steps:

1. Dynamic model to make forecast of plant's future behavior
2. Online optimization to compute optimal control moves for defined prediction horizon
3. Application of initial control trajectory
4. Observe response & update state information

4. Typical controller configuration

„Economically“ inspired tracking MPC performance metric

$$J\left(\boldsymbol{X},\boldsymbol{U}\right) \;=\; \textstyle\sum_0^{N-1} Q_{\dot\varphi}(v_{\mathrm{wk}})\left(\dot\varphi_{\mathrm{G}k} - \dot\varphi_G^{\star}(v_{\mathrm{wk}})\right)^2 + Q_{\beta}(v_{\mathrm{wk}})\left(\beta_k - \beta_k^{\star}(v_{\mathrm{wk}})\right)^2 + L_F\left(\boldsymbol{x}_k, \boldsymbol{u}_k\right)$$

Proxy fatigue metric

$$L_F\left(\boldsymbol{x}_k, \boldsymbol{u}_k\right) = Q_T \dot{x}_{\mathrm{T}k}^2 + Q_B \dot{x}_{\mathrm{B}k}^2 + Q_{\dot\beta} \dot\beta_k^2 + Q_{\dot M_{\mathrm{G}}} \dot M_{\mathrm{G}k}^2$$

Constraints:

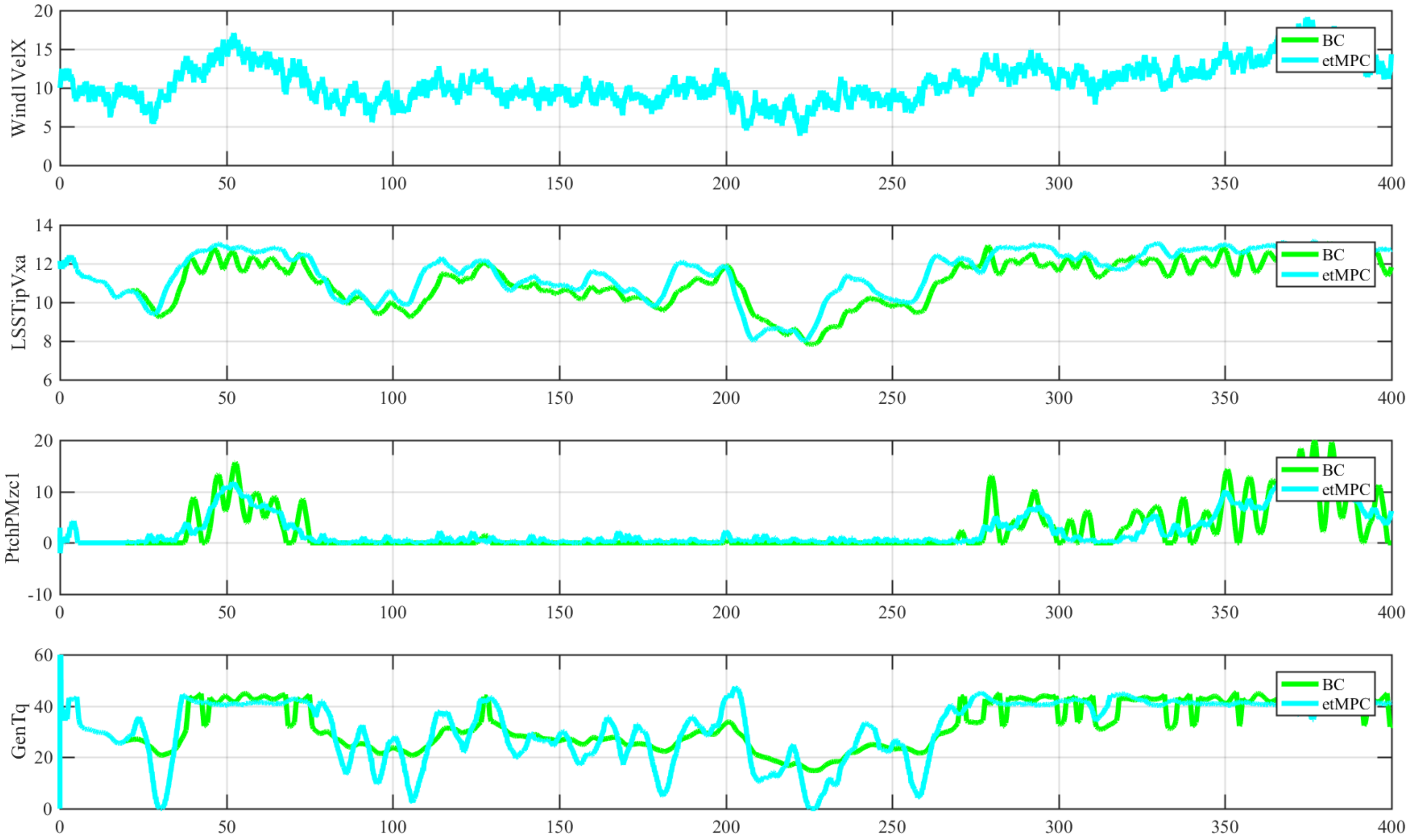
$$\begin{array}{ccccc} \underline{\dot\beta} & \leq & \dot\beta & \leq & \overline{\dot\beta} \\ 0 & \leq & \dot M_{\mathrm{G}} & \leq & \overline{\dot M}_{\mathrm{G}} \end{array}$$

$$\begin{array}{ccccc} \underline{\dot\varphi}_{\mathrm{G}} & \leq & \dot\varphi_{\mathrm{G}} & \leq & \overline{\dot\varphi}_{\mathrm{G}} \\ 0 & \leq & P_{\mathrm{E}} & \leq & \overline{P}_{\mathrm{E}} \\ 0 & \leq & M_{\mathrm{G}} & \leq & \overline{M}_{\mathrm{G}} \end{array}$$

GROS, SCHILD: Real-time economic nonlinear model predictive control for wind turbine control. *International Journal of Control*, 2017

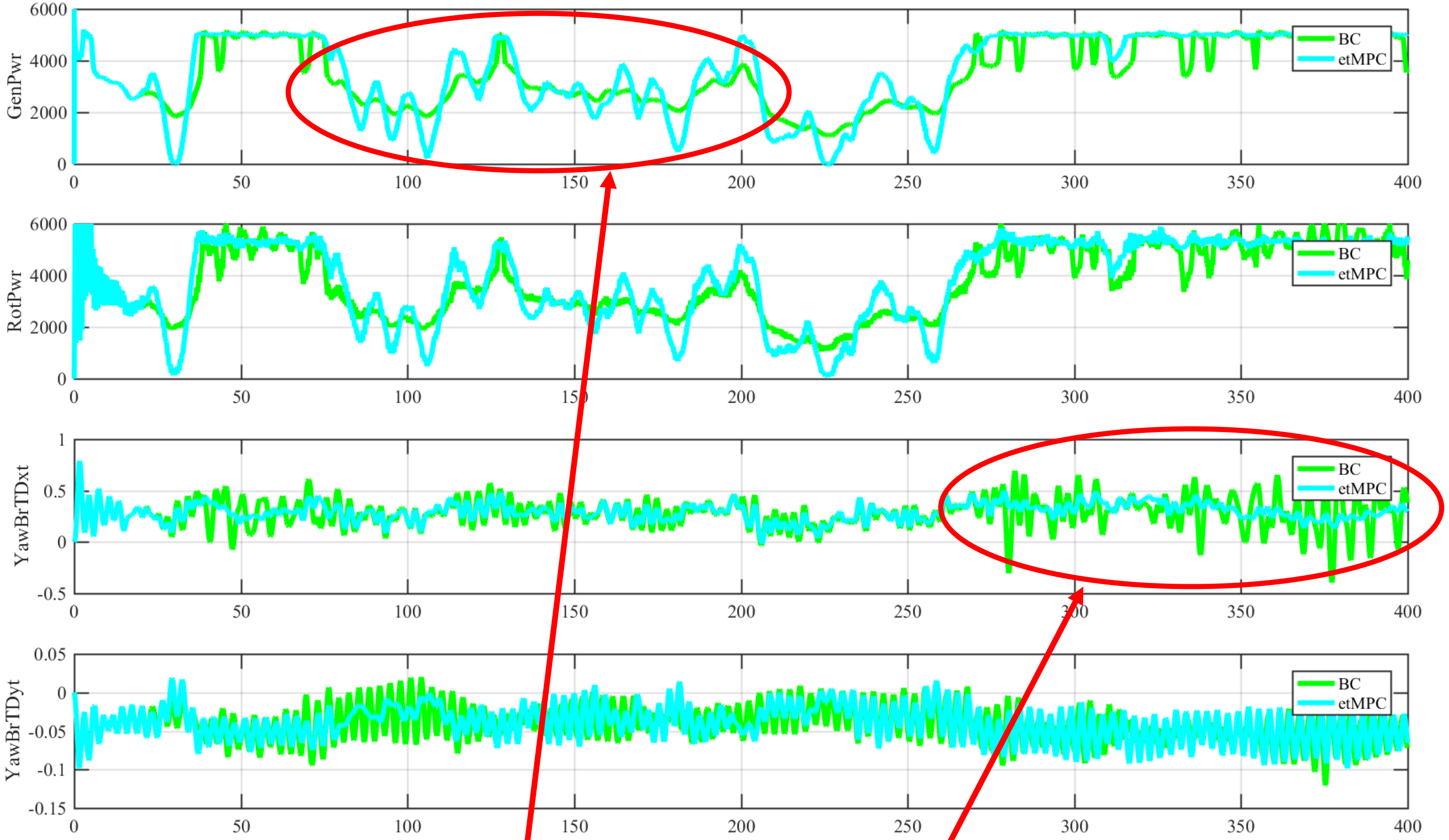
→ Objectives: power capture ↔ structural loads ↔ actuator wear

4. Closed-loop simulation comparison BC vs. MPC @ NRELs 5W Turbine



→ **MPC achieves better GenSpd tracking and softer pitch utilization**

4. Closed-loop simulation comparison BC vs. MPC @ NRELs 5W Turbine



- → **Positive: MPC improves power capture & reduces tower oscillations**
- → **Negative: higher power fluctuations observed**

Conclusions

- Wind energy enters digitization era → innovations by means of „intelligence“ and IoT
- Traditional control concepts focus on energy maximization
- Progressing energy revolution demands for much more complex operating strategies
- Control-oriented modeling of wind turbines requires significant abstraction and simplification
- Advanced control concepts like MPC will be part of the solution to overcome future challenges

- Sustainable market penetration of such innovative technologies requires industrialization of research results → significant effort to increase reliability & robustness

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