Collective Pitch Controller

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Lecture #3 of Course "Controller Design for Wind Turbines and Wind Farms"

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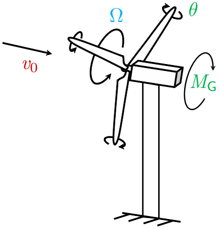
Collective Pitch Controller



Motivation

- Collective pitch is one of the two main control inputs.
- Collective pitch control has an high impact on structural loads and thus on costs.
- Can be implemented with a standard concept (PI control).

→ Together with the baseline torque controller from previous lecture, we have our first version of a controller for the full operation range!

Main questions

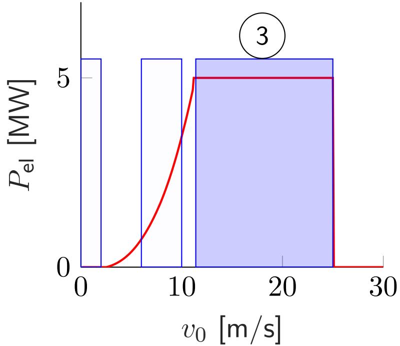
- How can we design a pitch controller in a single operation point?
- How can we make it work over the full operation range?

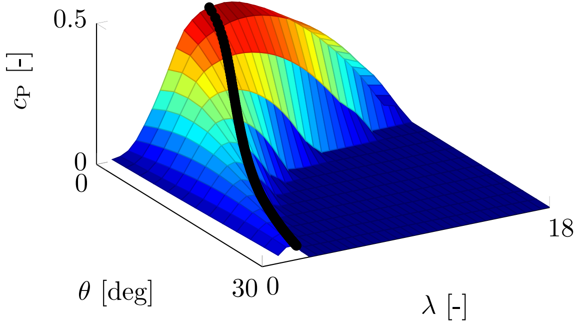
Schedule

Content

1. Collective Pitch Controller Design
2. Conclusion and Learning Objectives

Strategy Baseline Pitch Controller





- Maximum power and rotor speed is reached $\rightarrow$ pitch controller in region 3 aims to maintain $P_{\text{el,rated}} = \frac{1}{2}\rho\pi R^2 c_{\text{P}}(\lambda,\theta)v_0^3\ \eta_{\text{el}}$ and rated rotor speed.
- With increasing v_0, the turbines increases pitch angle to reduce power coefficient c_{P}.
- Compromise between speed regulation, reduction of structural load, and pitch activity.

Closed-Loop Shaping I

Basic Idea [1]

- Combining linearized 1 DOF model and PI controller results in a 2nd order linear model.
- Input is rotor effective wind v_0, output is rotor speed Ω.
- Dynamic of closed-loop can be shaped by parameters of PI controller.
- Parameters of PI controller can be modified to maintain a constant closed-loop behavior.

Procedure

1. Integrate state feedback of torque controller into 1 DOF model.
2. Linearize of 1 DOF model at each operation point (wind speed).
3. Combine linearized 1 DOF model with PI controller to 2nd order linear model.
4. Calculate parameters of PI controller at each operation point with desired dynamics.
5. Design Gain Scheduling to provide continuous parameters.

Closed-Loop Shaping II

1. Integrate state feedback of torque controller into 1 DOF model

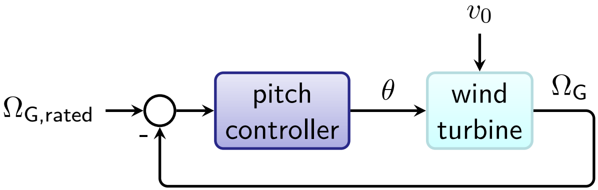
$\dot{\Omega} = \frac{M_{\mathsf{a}}(\Omega,\theta,v_0)}{J} - \frac{P_{\mathsf{a,rated}}}{J\Omega} = f(\Omega, \theta, v_0)$

2. Linearize of 1 DOF model at each operation point (wind speed)

$$\Delta\dot{\Omega} = \underbrace{\frac{\partial f}{\partial \Omega}\Big|_{\mathsf{OP}}}_{a} \Delta\Omega + \underbrace{\frac{\partial f}{\partial \theta}\Big|_{\mathsf{OP}}}_{b_1} \Delta\theta + \underbrace{\frac{\partial f}{\partial v_0}\Big|_{\mathsf{OP}}}_{b_2} \Delta v_0 \quad (1)$$

$$\Delta\Omega_{\mathsf{G}} = \underbrace{\frac{1}{i_{\mathsf{GB}}}}_{c} \Delta\Omega \quad (2)$$

Closed-Loop Shaping III



PI controller

$$\Delta\theta = K_{\mathsf{P}}\Delta\Omega_{\mathsf{G}} + K_{\mathsf{I}}\int_0^t \Delta\Omega_{\mathsf{G}}\mathrm{d}\tau \quad (3)$$

3. Combine linearized 1 DOF model with PI controller to 2nd order linear model

with (1)-(3) and $\dot{x} = \Delta\Omega$, $y = \Delta\Omega_{\mathsf{G}}$, and $u = \Delta v_0$:

$$\ddot{x} + (-a - b_1 c K_{\mathsf{P}})\dot{x} + (-b_1 c K_{\mathsf{I}})x = b_2 u \quad (4)$$

$$y = c\dot{x} \quad (5)$$

Closed-Loop Shaping IV

4. Calculate parameters of PI controller at each operation point with given dynamics

Parameter comparison: closed-loop transfer function vs. desired 2nd order linear model

$$\frac{cb_2\, s}{s^2 + (-a - b_1 c K_\mathsf{P})\, s + (-b_1 c K_\mathsf{I})} \overset{!}{=} \frac{G_0 \omega^2\, s}{s^2 + 2D\omega\, s + \omega^2}$$

Solution

Amplification factor: $G_0 = \frac{cb_2}{\omega^2}$

Proportional gain: $K_\mathsf{P} = -\frac{2D\omega + a}{b_1 c}$

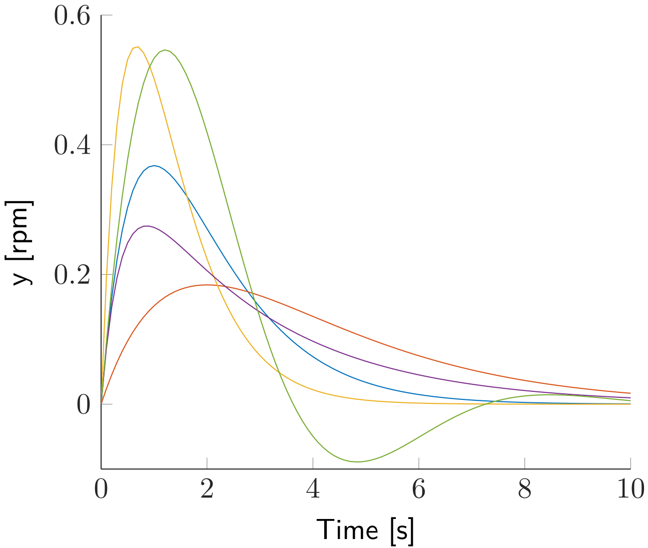
Integral gain: $K_\mathsf{I} = -\frac{\omega^2}{b_1 c}$

with

Desired damping ratio: D

Desired angular frequency: ω

Closed-Loop Shaping V



Response to $1\,\mathrm{m/s}$ wind steps

$G_0 = 1\,\mathrm{rpm/(m/s)}$

- $D = 1.0,\ \omega = 1.0\,\mathrm{rad/s}$
- $D = 1.0,\ \omega = 0.5\,\mathrm{rad/s}$
- $D = 1.0,\ \omega = 1.5\,\mathrm{rad/s}$
- $D = 1.5,\ \omega = 1.0\,\mathrm{rad/s}$
- $D = 0.5,\ \omega = 1.0\,\mathrm{rad/s}$

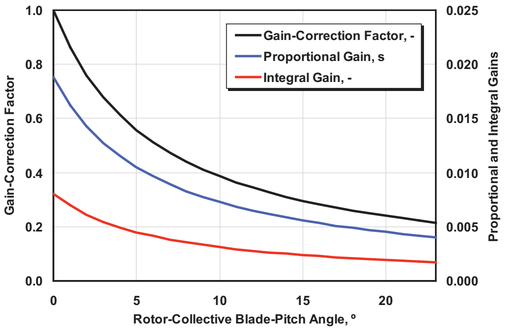
Closed-Loop Shaping VI

5. Design Gain Scheduling to provide continuous parameters

- Necessary, since rotor motion is more sensitive to pitch changes at higher wind speeds.

$\rightarrow$ more aggressive at low wind speeds, less aggressive at high wind speeds

- Since wind speed is not measurable, operation point can be obtained from pitch angle.



Options for Gain Scheduling

1. Interpolation in K_P and K_I or $k_\mathrm{p} = K_\mathrm{P}$ and $T_\mathrm{i} = \frac{K_\mathrm{P}}{K_\mathrm{I}}$.
2. Fit to a function $g(\theta)$ and multiply with error $\Delta\Omega_\mathrm{G}$,
   e.g. $g(\theta) = \frac{1}{1+\frac{\theta}{\theta_K}}$ [2]
   or $g(\theta) = \frac{1}{1+\frac{\theta}{\theta_{K1}}+\frac{\theta^2}{\theta_{K2}}}$ [3]
   .

Stability

Stability of an autonomous linear system

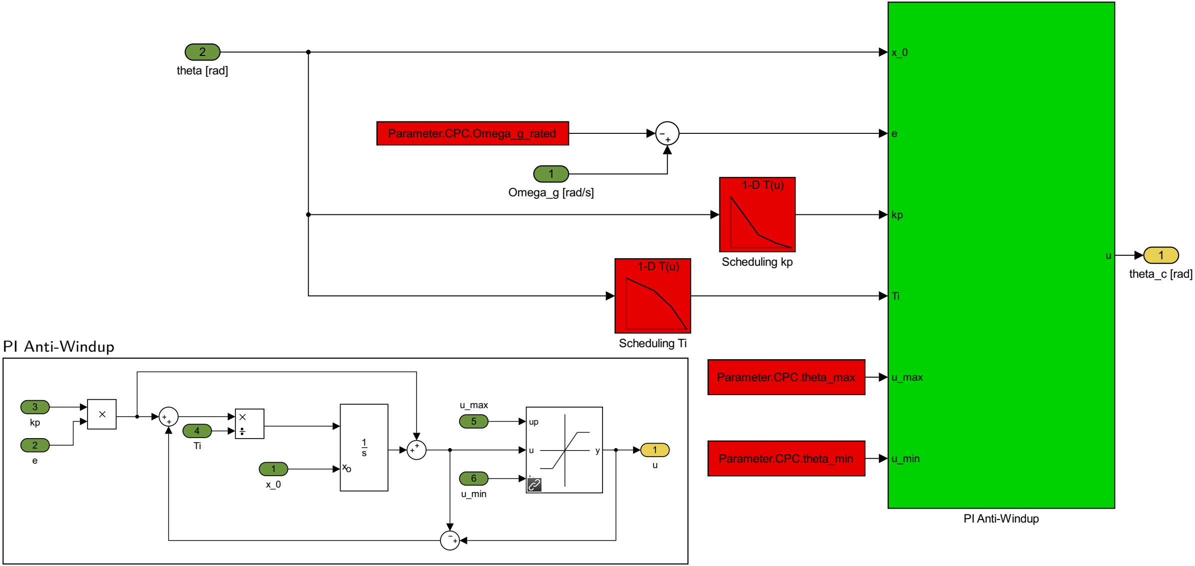
- Stability means that all systems states approach 0 for $t \to \infty$ for all starting values
- A linear system is stable, if the real parts of all poles are negative.

Stability of our closed loop

$$p_{1/2} = -D\omega \pm \omega\sqrt{D^2 - 1} \tag{6}$$

- D>1: two real poles: stable since $D > \sqrt{D^2 - 1}$
- D=1: two real poles at $-D\omega$: stable!
- D<1: two conjugate complex poles: also stable, since $Re(p_{1/2}) = -D\omega < 0$

Implementation in Matlab Simulink



Anti-windup for PI controller

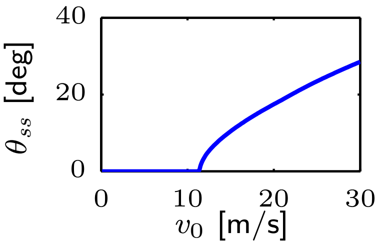
Problem

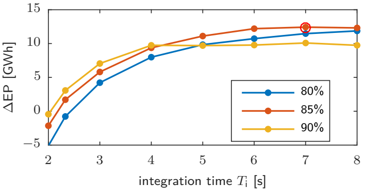
- If wind speed is below rated, generator speed error is negative.
- Pitch is limited (here say 0 deg). Without anti-windup, the negative error will accumulate.
- If wind speed and thus generator speed rises, again, pitch controller will not react before proportional part is larger than integral part and large over-speed can occur!

Two classical solutions

1. integrator clamping: saturation limit for integrator
2. back-calculation: impact of error on integrator is canceled out during saturation.

How do we do it at sowento?





Rule of Thumb for PI-Controller

1. Integrator time T_I equal to time of one rotation
2. Proportional gain k_P such that it follows for 1 m/s wind step and 10% over-speed the static pitch curve
3. Combination with PI-Torque Controller and set-point-fading for coupling (see lecture on advanced torque controller)

Brute-fore optimization

1. run several FAST simulations representing the life-time of a wind turbine with varying parameters
2. evaluate energy versus loads in a cost function

Conclusion

Main questions

- How can we design a pitch controller in a single operation point?
- How can we make it work over the full operation range?

By shaping the closed loop!

- Combine linearized 1 DOF model with PI controller to 2nd order linear model.
- Calculate parameters of PI controller with desired dynamics.

By Gain Scheduling and Anti-windup!

- Gain Scheduling makes pitch controller less aggressive for high wind speeds, since aerodynamics are more sensible to pitch angle changes.
- Anti-windup limits integrator below rated wind speeds.

Quick check on learning objectives

After this lectures you should be able to...

- to describe the main tasks of a collective pitch controller
- to design a collective pitch for above rated wind conditions
- to determine the stability of a linear system
- to describe how anti-windup for a PI controller works
- to describe why gain scheduling is important and how it works

References

[1] M. H. Hansen, A. Hansen, T. J. Larsen, S. Oye, P. Sorensen, and P. Fuglsang. Control design for a pitch-regulated, variable speed wind turbine. Tech. rep. Riso-R-1500(EN). Riso National Laboratory, 2005.

[2] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. Tech. rep. TP-500-38060. NREL, 2009. DOI: 10.2172/947422.

[3] M. Hansen and L. C. Henriksen. Basic DTU Wind Energy controller. E-Report 0028(E). DTU Wind Energy, 2013.

Please let me know if you have further questions!

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