Advanced Torque Controller

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Lecture #6 of Course "Controller Design for Wind Turbines and Wind Farms"

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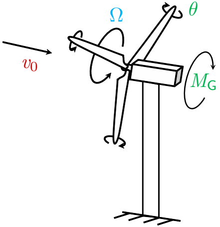
Schedule

19.09.	1	Controller Design Objectives and Modeling
26.09.	2	Baseline Generator Torque Controller (online)
10.10.	3	Collective Pitch Controller (online)
17.10.	4	Filter Design (online)
24.10.	5	Tower Damper
07.11.	6	Advanced Torque Controller
14.11.	7	Wind Field Generation
21.11.	8	Steady State Calculations
28.11.	10	Lidar-Assisted Control I
05.12.	11	Lidar-Assisted Control II
12.12.	12	Wind Farm Effects
19.12.	13	Wind Farm Control
09.01.	14	Floating Wind Control ???

Advanced Generator Torque Controller



Motivation

- Generator torque is one of the two main control inputs.
- Baseline controller implemented in a quite simple form.
- Baseline controller performance and tuning options limited.

$\rightarrow$ More advanced methods should get better results!

Main questions

- How can we design an advanced generator torque controller?
- How can we tune the advanced torque controller?

Content

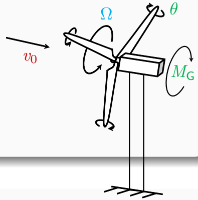
1. Recapitulation Torque Controller
2. Advanced Torque Controller Design
3. Conclusion and Learning Objectives

Controller Design Model

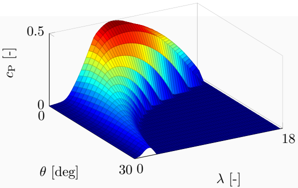
Structural dynamics

rotor motion: $J\dot{\Omega} = \boxed{M_\mathsf{a}} - \frac{M_\mathsf{G}}{i_\mathsf{GB}}$

Generator: $P_\mathsf{el} = M_\mathsf{G}\frac{\Omega}{i_\mathsf{GB}}\eta_\mathsf{el}$



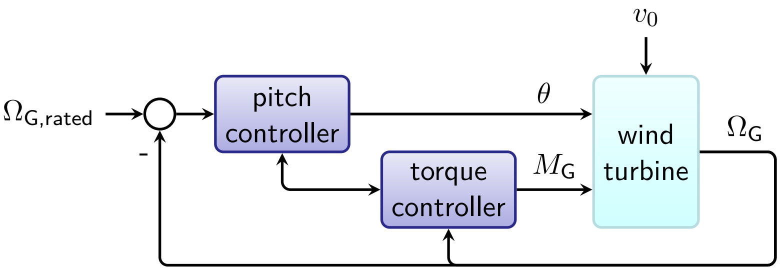
Aerodynamics



torque: $\boxed{M_\mathsf{a} = \frac{1}{2}\rho\pi R^2 \frac{c_\mathsf{P}(\lambda,\theta)}{\Omega} v_0^3}$

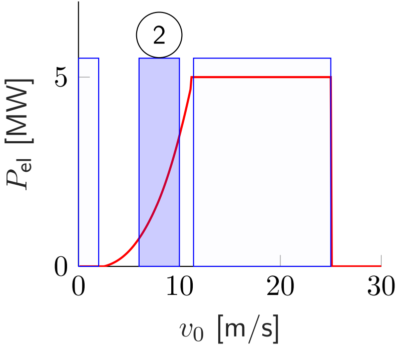
with tip speed ratio $\lambda = \frac{\Omega R}{v_0}$.

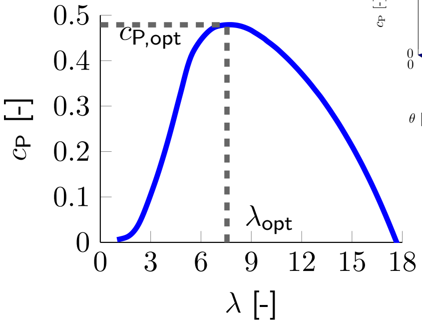
Baseline Wind Turbine Controller

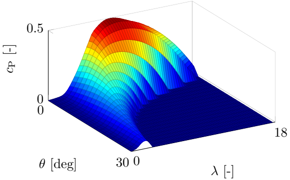


- Torque controller optimizes power below and maintains rated power above rated wind speed by adjusting generator torque M_{G} based on generator speed Ω_{G}.
- Pitch control maintains rated generator speed $\Omega_{\text{G,rated}}$ by adjusting blade pitch angle θ.
- Interactions for transition between above and below rated wind very important!

Strategy Baseline Torque Controller



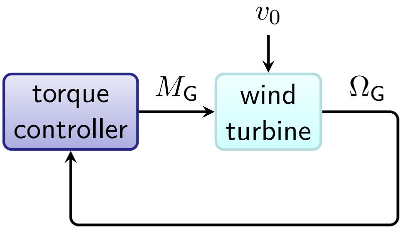


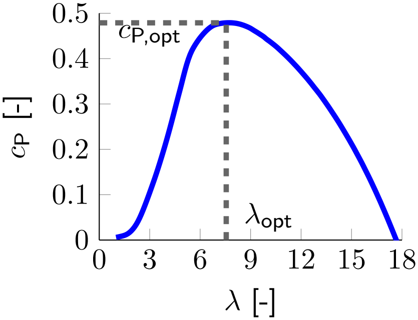


$\leftarrow \theta = 0\,\mathrm{deg}$

- Torque controller in region 2 aims to maximize $P_{\mathrm{el}} = \frac{1}{2}\rho\pi R^2 c_{\mathrm{P}}(\lambda,\theta)v_0^3\ \eta_{\mathrm{el}}$.
- Optimum $c_{\mathrm{P,opt}}$ is reached for $\lambda = \lambda_{\mathrm{opt}}$ and $\theta = 0\,\mathrm{deg}$.
- Rotor-effective wind speed v_0 is not measurable.
- Indirect Speed Control: Feedback $M_{\mathrm{G}}(\Omega_{\mathrm{G}})$ can be designed such that $\lambda \rightarrow \lambda_{\mathrm{opt}}$.

Optimal Torque Control





Optimal feedback

$$J\dot{\Omega} = M_a - \frac{M_G}{i_{GB}} \overset{!}{=} 0$$

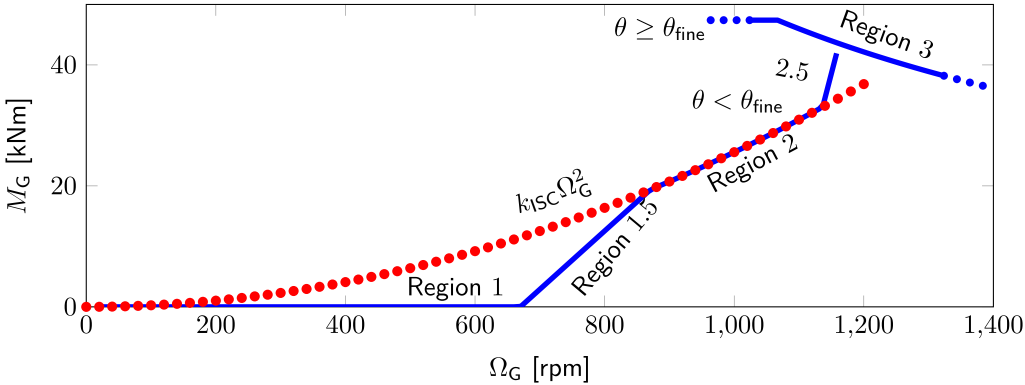
$$\frac{\Omega R}{\lambda_{opt}}$$

$$\frac{1}{2}\rho\pi R^2 \frac{c_{P,opt}}{\Omega} v_0^{\,3}$$

$$\Omega_G \, i_{GB}$$

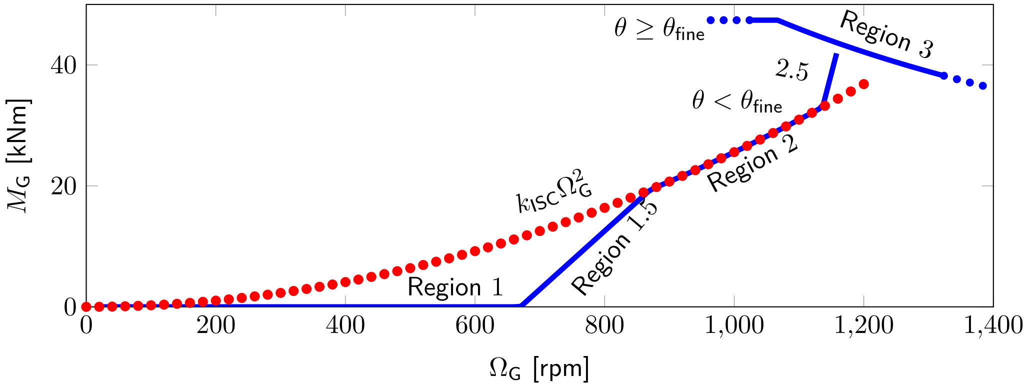
$$\rightarrow \quad M_G = \underbrace{\frac{1}{2}\rho\pi R^5 \frac{c_{P,opt}}{\lambda_{opt}^3} i_{GB}^3}_{k_{ISC}} \Omega_G^2$$

Baseline Torque Controller: Nonlinear State Feedback



- Region 2: $k_{\text{ISC}}\ \Omega_G^2$ brings turbine to chosen power coefficient
- Region 1.5 and 2.5: linear functions for transition, Region 3: onshore usually constant power
- Fine pitch value θ_{fine} to determine, whether Region 3 or 2.5 should be applied

Limitations of Baseline Torque Controller



- With ramps, optimal curve is reached later and left earlier compared to vertical lines.
- Dynamic on ramps can only indirectly tuned by steepness.
- Switching due to fine pitch usually results in high loads.

Strategy Advanced Torque Controller

- Torque PI controller for Region 1.5 and 2.5.
- Torque PI controller parameters with closed-loop shaping similar to pitch PI controller.
- Torque controller in Region 2 and 3 by adjustment of limits.
- Interaction with pitch controller in Region 2.5 necessary to avoid competing interactions.
- Compromise between energy production, reduction of structural load, speed regulation, 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 generator speed Ω_G.
- Dynamic of closed-loop can be shaped by parameters of PI controller.
- Usually no Gain-Scheduling necessary.

Procedure

1. Linearize of 1 DOF model at central operation point.
2. Combine linearized 1 DOF model with PI controller to 2nd order linear model.
3. Calculate parameters of PI controller at central operation point with desired dynamics.

Closed-Loop Shaping II

1 DOF model with $\theta =$ const.

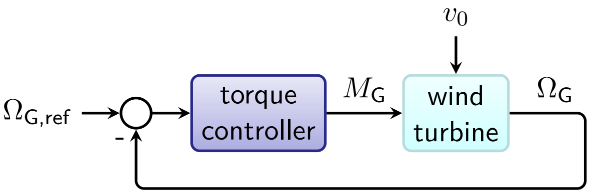
$\dot{\Omega} = \frac{M_{\mathsf{a}}(\Omega, v_0)}{J} - \frac{M_{\mathsf{G}}}{J i_{\mathsf{GB}}} = f(\Omega, v_0, M_{\mathsf{G}})$

1. Linearize of 1 DOF model at central operation point

$$\Delta\dot{\Omega} = \underbrace{\frac{\partial f}{\partial \Omega}\Big|_{\mathsf{OP}}}_{a} \Delta\Omega + \underbrace{\frac{\partial f}{\partial M_{\mathsf{G}}}\Big|_{\mathsf{OP}}}_{b_1} \Delta M_{\mathsf{G}} + \underbrace{\frac{\partial f}{\partial v_0}\Big|_{\mathsf{OP}}}_{b_2} \Delta v_0 \tag{1}$$

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

Closed-Loop Shaping III



PI controller

$$\Delta M_{\mathsf{G}} = K_{\mathsf{P}} \Delta\Omega_{\mathsf{G}} + K_{\mathsf{I}} \int_0^t \Delta\Omega_{\mathsf{G}} \mathrm{d}\tau \tag{3}$$

2. 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 $u = \Delta v_0$:

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

$$y = c\dot{x} \tag{5}$$

Closed-Loop Shaping IV

3. Calculate parameters of PI controller at central operation point

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

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

Solution

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

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

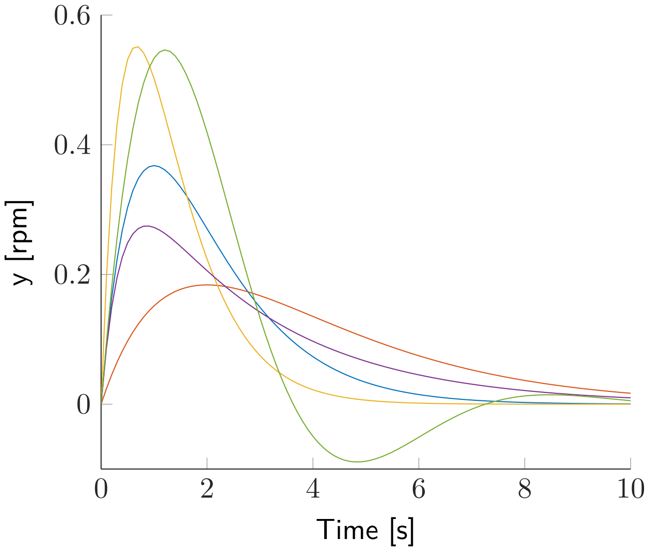
Integral gain: $K_\mathsf{I} = -\frac{\omega^2}{b_1 c}$

with

Desired damping ratio: D

Desired angular frequency: ω

Closed-Loop Shaping V



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

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

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

Reference Values and Limits

Reference Values $\Omega_{\text{G,ref}}$

- In Region 1.5: lowest generator speed $\Omega_{\text{G,1.5}}$, usually to avoid 3P frequency to interact with tower eigenfrequency.
- In Region 2.5: $\Omega_{\text{G,2.5}} = \Omega_{\text{G,rated}}$
- Switch from $\Omega_{\text{G,1.5}}$ to $\Omega_{\text{G,2.5}}$, if measured generator speed $\Omega_{\text{G}} > \Omega_{\text{G,R2switch}} = \frac{1}{2}(\Omega_{\text{G,1.5}} + \Omega_{\text{G,2.5}})$

Lower bound $M_{\text{G,lb}}$ and upper bound $M_{\text{G,ub}}$

Limits depend on measured generator speed Ω_{G} and are used together with Anti-Windup.

$$
\begin{aligned}
\Omega_{\text{G}} < \Omega_{\text{G,R2switch}}: \quad & M_{\text{G,lb}} = 0, & M_{\text{G,ub}} &= k_{\text{ISC}}\Omega_{\text{G}}^2 \\
\Omega_{\text{G}} > \Omega_{\text{G,R2switch}}: \quad & M_{\text{G,lb}} = k_{\text{ISC}}\Omega_{\text{G}}^2, & M_{\text{G,ub}} &= \min(P_{\text{a,rated}}/\Omega_{\text{G}}, M_{\text{G,max}})
\end{aligned}
$$

Methods for Pitch and Torque PI interactions [2]

Double PI

- The difference to the rated power is multiplied with a proportional and integral gain and added to the proportional and integral gain for the speed error (only one integrator).
- Problem: not clear how to tune.

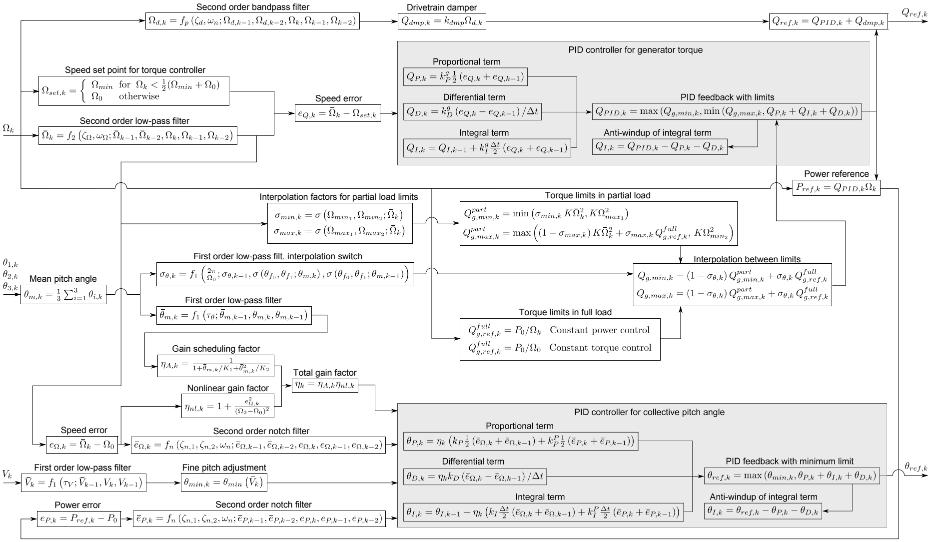
State machine

- Based on conditions for pitch angle etc. a state machine is defined including hysteresis to avoid both controller reacting at the same time.
- Problem: Very nonlinear, controller can be caught in the “wrong” mode.

Set-point fading

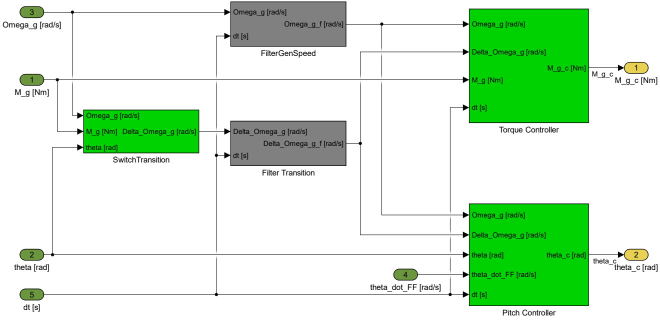
- An additional term $\Delta\Omega_G$ is added/subtracted from the reference speed, that only one of the two PI controller has the rated generator speed as reference value.
- Relatively easy to tune and used here.

Double PI [3]



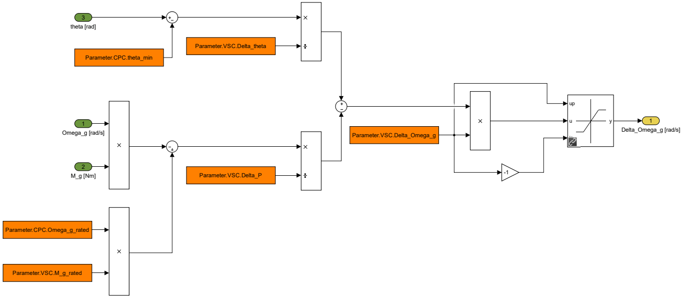
Second order bandpass filter
$\Omega_{d,k} = f_p(\zeta_d, \omega_n; \Omega_{d,k-1}, \Omega_{d,k-2}, \Omega_k, \Omega_{k-1}, \Omega_{k-2})$
Drivetrain damper
$Q_{dmp,k} = k_{dmp}\Omega_{d,k}$
$Q_{ref,k} = Q_{PID,k} + Q_{dmp,k}$
$Q_{ref,k}$
PID controller for generator torque
Proportional term
$Q_{P,k} = k_P^g \frac{1}{2}(e_{Q,k} + e_{Q,k-1})$
Speed set point for torque controller
$\Omega_{set,k} = \begin{cases} \Omega_{min} & \text{for } \Omega_k < \frac{1}{2}(\Omega_{min} + \Omega_0) \\ \Omega_0 & \text{otherwise} \end{cases}$
Speed error
$e_{Q,k} = \bar{\Omega}_k - \Omega_{set,k}$
Differential term
$Q_{D,k} = k_D^g (e_{Q,k} - e_{Q,k-1})/\Delta t$
PID feedback with limits
$Q_{PID,k} = \max(Q_{g,min,k}, \min(Q_{g,max,k}, Q_{P,k} + Q_{I,k} + Q_{D,k}))$
Ω_k
Second order low-pass filter
$\bar{\Omega}_k = f_2(\zeta_\Omega, \omega_\Omega; \bar{\Omega}_{k-1}, \bar{\Omega}_{k-2}, \Omega_k, \Omega_{k-1}, \Omega_{k-2})$
Integral term
$Q_{I,k} = Q_{I,k-1} + k_I^g \frac{\Delta t}{2}(e_{Q,k} + e_{Q,k-1})$
Anti-windup of integral term
$Q_{I,k} = Q_{PID,k} - Q_{P,k} - Q_{D,k}$
Power reference
$P_{ref,k} = Q_{PID,k}\Omega_k$
Interpolation factors for partial load limits
$\sigma_{min,k} = \sigma(\Omega_{min_1}, \Omega_{min_2}; \bar{\Omega}_k)$
$\sigma_{max,k} = \sigma(\Omega_{max_1}, \Omega_{max_2}; \bar{\Omega}_k)$
Torque limits in partial load
$Q_{g,min,k}^{part} = \min(\sigma_{min,k} K\bar{\Omega}_k^2, K\Omega_{max_1}^2)$
$Q_{g,max,k}^{part} = \max((1-\sigma_{max,k}) K\bar{\Omega}_k^2 + \sigma_{max,k} Q_{g,ref,k}^{full}, K\Omega_{min_2}^2)$
$\theta_{1,k}$
$\theta_{2,k}$
$\theta_{3,k}$
Mean pitch angle
$\theta_{m,k} = \frac{1}{3}\sum_{i=1}^{3}\theta_{i,k}$
First order low-pass filt. interpolation switch
$\sigma_{\theta,k} = f_1\left(\frac{2\pi}{\Omega_0}; \sigma_{\theta,k-1}, \sigma(\theta_{f_0}, \theta_{f_1}; \theta_{m,k}), \sigma(\theta_{f_0}, \theta_{f_1}; \theta_{m,k-1})\right)$
Interpolation between limits
$Q_{g,min,k} = (1-\sigma_{\theta,k}) Q_{g,min,k}^{part} + \sigma_{\theta,k} Q_{g,ref,k}^{full}$
$Q_{g,max,k} = (1-\sigma_{\theta,k}) Q_{g,max,k}^{part} + \sigma_{\theta,k} Q_{g,ref,k}^{full}$
First order low-pass filter
$\bar{\theta}_{m,k} = f_1(\tau_\theta; \bar{\theta}_{m,k-1}, \theta_{m,k}, \theta_{m,k-1})$
Torque limits in full load
$Q_{g,ref,k}^{full} = P_0/\Omega_k$ Constant power control
$Q_{g,ref,k}^{full} = P_0/\Omega_0$ Constant torque control
Gain scheduling factor
$\eta_{A,k} = \frac{1}{1+\bar{\theta}_{m,k}/K_1+\bar{\theta}_{m,k}^2/K_2}$
Total gain factor
$\eta_k = \eta_{A,k}\eta_{nl,k}$
Nonlinear gain factor
$\eta_{nl,k} = 1 + \frac{e_{\Omega,k}^2}{(\Omega_2-\Omega_0)^2}$
PID controller for collective pitch angle
Proportional term
$\theta_{P,k} = \eta_k\left(k_P \frac{1}{2}(\bar{e}_{\Omega,k} + \bar{e}_{\Omega,k-1}) + k_P^P \frac{1}{2}(\bar{e}_{P,k} + \bar{e}_{P,k-1})\right)$
Speed error
$e_{\Omega,k} = \bar{\Omega}_k - \Omega_0$
Second order notch filter
$\bar{e}_{\Omega,k} = f_n(\zeta_{n,1}, \zeta_{n,2}, \omega_n; \bar{e}_{\Omega,k-1}, \bar{e}_{\Omega,k-2}, e_{\Omega,k}, e_{\Omega,k-1}, e_{\Omega,k-2})$
Differential term
$\theta_{D,k} = \eta_k k_D(\bar{e}_{\Omega,k} - \bar{e}_{\Omega,k-1})/\Delta t$
PID feedback with minimum limit
$\theta_{ref,k} = \max(\theta_{min,k}, \theta_{P,k} + \theta_{I,k} + \theta_{D,k})$
$\theta_{ref,k}$
V_k
First order low-pass filter
$\bar{V}_k = f_1(\tau_V; \bar{V}_{k-1}, V_k, V_{k-1})$
Fine pitch adjustment
$\theta_{min,k} = \theta_{min}(\bar{V}_k)$
Integral term
$\theta_{I,k} = \theta_{I,k-1} + \eta_k\left(k_I \frac{\Delta t}{2}(\bar{e}_{\Omega,k} + \bar{e}_{\Omega,k-1}) + k_I^P \frac{\Delta t}{2}(\bar{e}_{P,k} + \bar{e}_{P,k-1})\right)$
Anti-windup of integral term
$\theta_{I,k} = \theta_{ref,k} - \theta_{P,k} - \theta_{D,k}$
Power error
$e_{P,k} = P_{ref,k} - P_0$
Second order notch filter
$\bar{e}_{P,k} = f_n(\zeta_{n,1}, \zeta_{n,2}, \omega_n; \bar{e}_{P,k-1}, \bar{e}_{P,k-2}, e_{P,k}, e_{P,k-1}, e_{P,k-2})$

Set-Point-Fading Overview



- close to industrial practice
- modified version of [2]
- $\Delta\Omega_G$ is low pass filtered
- input to torque PI controller and pitch PI controller
- developed at sowento, used at SWE, University of Stuttgart in several projects
- can be combined with multi-variable lidar-based feedfoward control [4]
- NREL now using sowento approach [5]

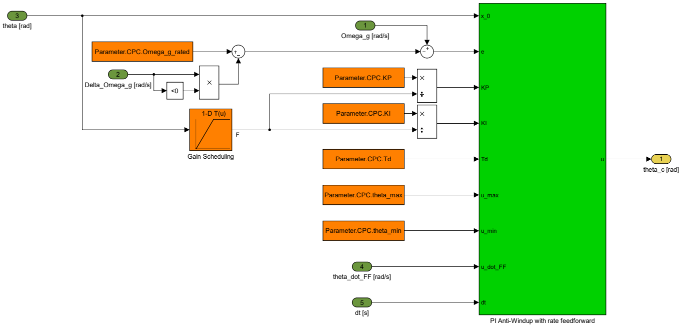
Switch Transition



Transition

- deviation from minimum pitch and deviation from rated power as proxy for deviation from rated wind
- normalized by $\Delta\theta$ and ΔP
- multiplied and saturated with maximum tolerated over-/under-speed $\Delta\Omega_{\mathrm{G,max}}$

Integration into Pitch/Torque Controller



Pitch Controller

If $\Delta\Omega_G < 0$ then

$\Omega_{G,\mathrm{ref}} = \Omega_{G,\mathrm{rated}} - \Delta\Omega_G$,

else

$\Omega_{G,\mathrm{ref}} = \Omega_{G,\mathrm{rated}}$

Torque Controller

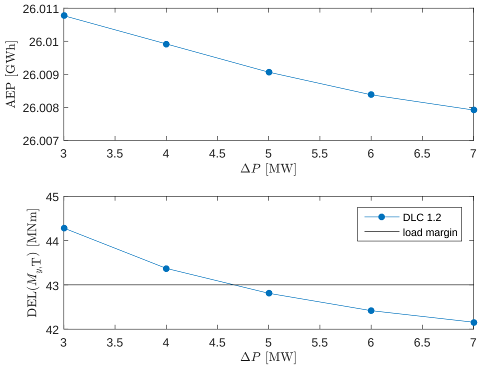
If $\Delta\Omega_G > 0$ then

$\Omega_{G,\mathrm{ref}} = \Omega_{G,\mathrm{rated}} - \Delta\Omega_G$,

else

$\Omega_{G,\mathrm{ref}} = \Omega_{G,\mathrm{rated}}$

Rule-of-thumb and Tuning



Rule-of-thumb

- $\Delta\Omega_{\text{G,max}}$ maximum allowed over-speed, e.g. 10 % of $\Omega_{\text{G,rated}}$
- ΔP close to rated power
- $\Delta\theta$ close to the pitch angle at cut-out wind speed (e.g. 25 deg)

Tuning

- ΔP and $\Delta\theta$ can be optimized by brute-force-optimization
- running a full DLC 1.2 [6] for fatigue load reduction
- useful objective: maximize AEP without exceeding the load margins

Conclusion

Main questions

- How can we design an advanced generator torque controller?
- How can we tune the advanced torque controller?

PI controller with Anti-windup

- Closed-loop shaping similar to pitch controller, usually no Gain Scheduling.
- Adjustments of reference values and bounds.
- Several methods for coupling with pitch PI controller available. Set-point fading helpful.

Linear and nonlinear tuning

- Closed-loop shaping with similar values compared to pitch PI controller.
- Coupling with pitch PI controller very nonlinear.

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[2] E. A. Bossanyi. "The Design of closed loop controllers for wind turbines". In: Wind Energy 3.3 (2000), pp. 149–163. ISSN: 1099-1824. DOI: 10.1002/we.34.

[3] M. Hansen and L. C. Henriksen. Basic DTU Wind Energy controller. E-Report 0028(E). DTU Wind Energy, 2013. URL: https://orbit.dtu.dk/en/publications/basic-dtu-wind-energy-controller.

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Please let me know if you have further questions!

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