Baseline Generator Torque Controller

Prof. Dr.-Ing. David Schlipf

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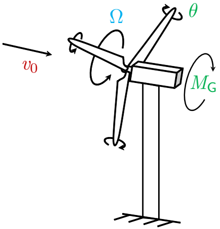
Lecture #2
Controller Design for Wind Turbines and Wind Farms

Hochschule Flensburg
University of Applied Sciences

SWE Stuttgart Wind Energy
@ Institute of Aircraft Design

Wind Energy Technology
Institute

Baseline Generator Torque Controller



Motivation

- Generator torque is one of the two main control inputs.
- Generator toque controller is enabled most of the time.
- Can be implemented in a quite simple form (baseline).

$\rightarrow$ Good point to get started with our controller!

Main questions

- How can we design a baseline generator torque controller?
- How can we and how should we evaluate a controller?

Schedule

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03.09.	2	Baseline Generator Torque Controller
04.09.	3	Collective Pitch Controller
05.09.	4	Filter Design
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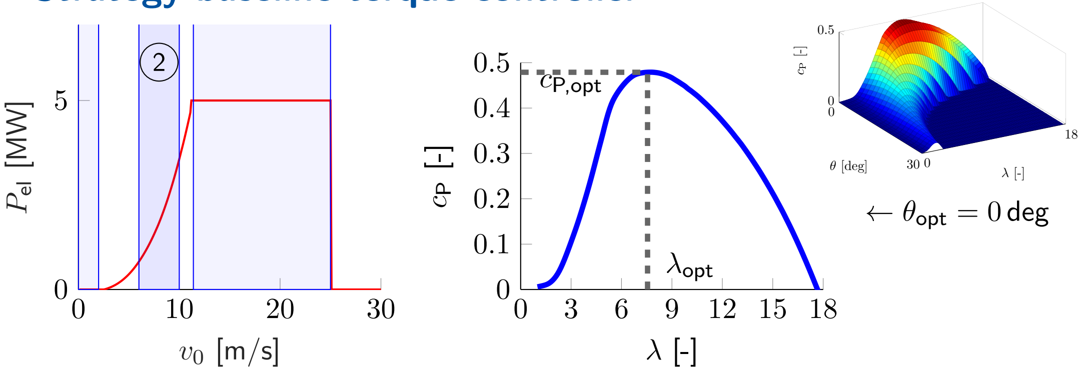
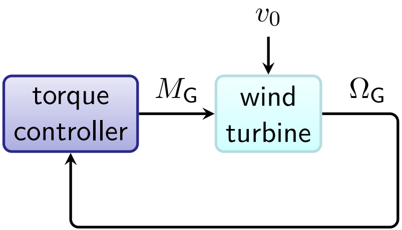
Contents

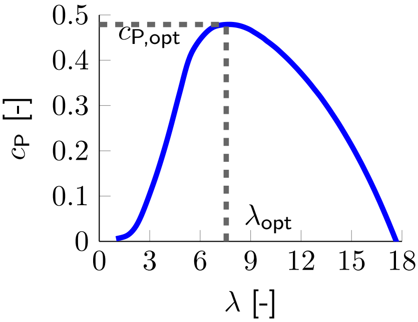
Strategy baseline torque controller



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

Optimal torque control





Optimal feedback

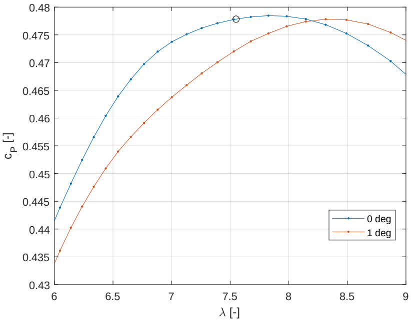
$$J\dot{\Omega} = M_a - M_G r_{GB} \overset{!}{=} 0$$

$$M_a = \frac{1}{2}\rho\pi R^2 \frac{c_{P,opt}}{\Omega} v_0^3, \qquad \Omega = \frac{\Omega_G}{r_{GB}}, \qquad v_0 = \frac{\Omega R}{\lambda_{opt}}$$

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

Proof of convergence and stability, see [1].

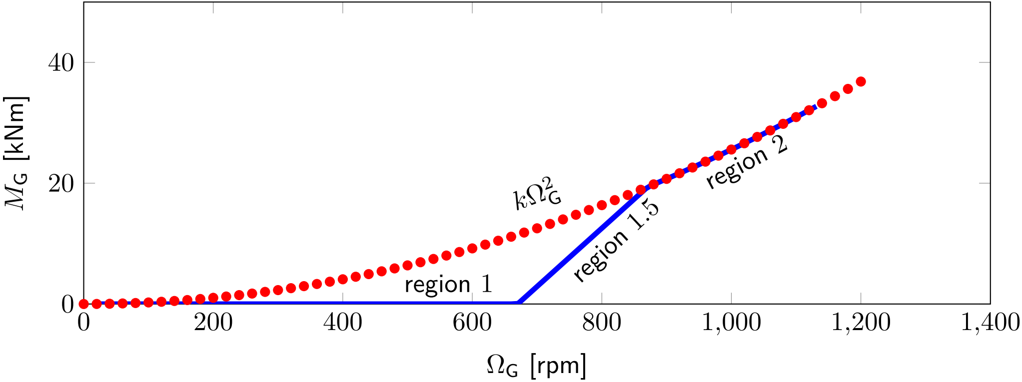
Practical considerations



How to pick θ_{opt}, $c_{\text{P,opt}}$ and λ_{opt}?

- Should fit together!
- Since λ varies, a θ_{opt} with slightly lower, but flat c_{P} can be beneficial.
- Depending on the shape of the c_{P} curve, a slightly off-peak value for λ_{opt} can be beneficial.
- Lower λ_{opt} can be chosen to reduce noise in region 2.
- The values can be chosen to have a better transition to full load.
- Other practical considerations might apply.

Nonlinear state feedback I

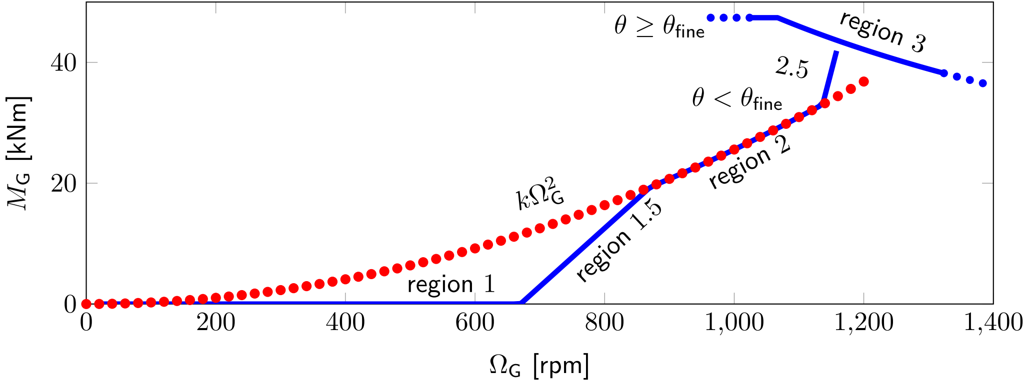


Region 1:
$\Omega_G < \Omega_{G,1to1.5}$
$M_G = 0$

Region 1.5:
$\Omega_{G,1to1.5} \leq \Omega_G < \Omega_{G,1.5to2}$
$M_G = a_{1.5}\ \Omega_G + b_{1.5}$

Region 2:
$\Omega_{G,1.5to2} \leq \Omega_G < \Omega_{G,2to2.5}$
$M_G = k\ \Omega_G^2$

Nonlinear state feedback II



Region 2.5:
$\Omega_{\text{G,2to2.5}} \leq \Omega_{\text{G}}$ and $\theta < \theta_{\text{fine}}$

$$M_{\text{G}} = a_{2.5}\ \Omega_{\text{G}} + b_{2.5}$$

Region 3:
$\theta \geq \theta_{\text{fine}}$

$$M_{\text{G}} = \min(M_{\text{G,rated}}\Omega_{\text{G,rated}}/\Omega_{\text{G}}, M_{\text{G,max}}) \text{ or } = M_{\text{G,rated}}$$

Transition regions

Region 1.5

Necessary to reach region 2 from region 1. Usually $\Omega_{\mathrm{G,1to1.5}}$ and $\Omega_{\mathrm{G,1.5to2}}$ are given:

$$
\begin{aligned}
0 &= a_{1.5}\ \Omega_{\mathrm{G,1to1.5}} + b_{1.5} \\
k\ \Omega^2_{\mathrm{G,1.5to2}} &= a_{1.5}\ \Omega_{\mathrm{G,1.5to2}} + b_{1.5}
\end{aligned}
$$

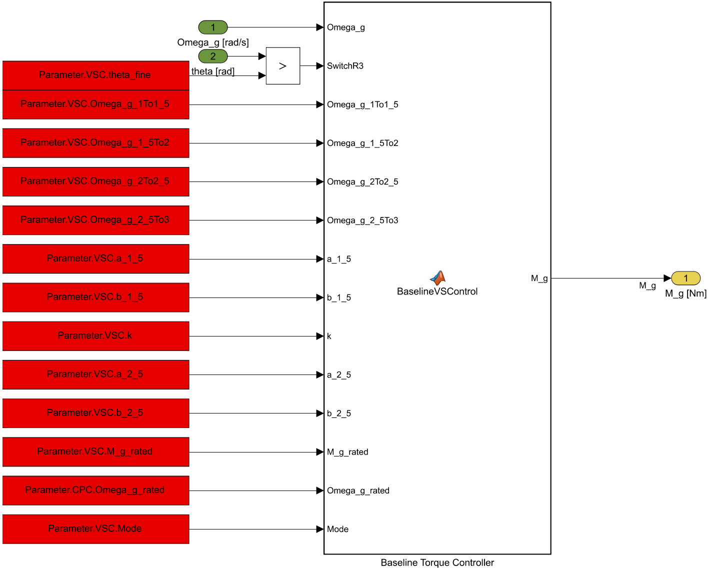
Region 2.5

Necessary to reach region 3, if rated generator speed is reached before rated torque is reached. Otherwise torque is held constant. If $\Omega_{\mathrm{G,2to2.5}}$ and $\Omega_{\mathrm{G,2.5to3}} = \Omega_{\mathrm{G,rated}}$ are given:

$$
\begin{aligned}
M_{\mathrm{G,rated}} &= a_{2.5}\ \Omega_{\mathrm{G,rated}} + b_{2.5} \\
k\ \Omega^2_{\mathrm{G,2to2.5}} &= a_{2.5}\ \Omega_{\mathrm{G,2to2.5}} + b_{2.5}
\end{aligned}
$$

Alternatively, $\Omega_{\mathrm{G,2.5to3}}$ slightly below $\Omega_{\mathrm{G,rated}}$ with given generator-slip percentage [2].

Implementation in Matlab Simulink I



Implementation in Matlab Simulink II

```
    Omega_g_1To1_5,Omega_g_1_5To2,...
    Omega_g_2To2_5,Omega_g_2_5To3,...                    % region limits
    a_1_5,b_1_5,...                                      % Region 1.5 parameters
    k,...                                                % Region   2 parameters
    a_2_5,b_2_5,...                                      % Region 2.5 parameters
    M_g_rated,Omega_g_rated,Mode)                        % Region   3 parameters

if  Mode == 1   % Power constant
    M_g_3       = M_g_rated*Omega_g_rated/Omega_g;
else            % Torque constant
    M_g_3       = M_g_rated;
end

if      Omega_g_2_5To3  <   Omega_g                      % Region 3
    M_g     = M_g_3;

elseif  Omega_g_2To2_5  <   Omega_g                      % Region 2.5
    M_g_2_5 = a_2_5 * Omega_g + b_2_5;
    M_g     = SwitchR3*M_g_3+(1-SwitchR3)*M_g_2_5;

elseif  Omega_g_1_5To2  <   Omega_g                      % Region 2
    M_g_2   = k * Omega_g^2;
    M_g     = SwitchR3*M_g_3+(1-SwitchR3)*M_g_2;

elseif  Omega_g_1To1_5  <   Omega_g                      % Region 1.5
    M_g = a_1_5 * Omega_g + b_1_5;

else                                                     % Region 1
    M_g = 0;
end
```

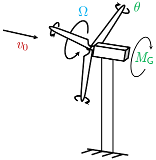
Evaluation steps and purpose

1. Step response of controller design model (e.g. Simulink):
   Does the controller exactly what it should or is there an implementation error?
2. Step response of aero-elastic tool (DLL: Dynamic Link Library):
   How does model uncertainties impact the behavior?
3. Load simulations following standards (DLL):
   How does the controller perform over a wide range of conditions?
4. Software/Hardware-in-the-loop tests (PLC: Programmable Logic Controller):
   How does the controller perform under realistic conditions?
5. Field Testing (PLC):
   How does the controller perform in reality?

- Controller should be initialized with current states to avoid long settling times (simulations) and bump-free switching (reality).
- If possible use one source code for all steps, e.g. libraries to avoid translation errors.

Why do we need load simulations?

Simulation



Reality

Load simulations help during all design phases:

- Which tower height should be used? $\rightarrow$ Conceptual design
- Which loads affect the components? $\rightarrow$ Design
- Are the loads within design limits? $\rightarrow$ Certification
- How can the system be optimized? $\rightarrow$ Optimization

Benefits over real tests

- simulations have low costs
- simulations are often fast
- simulations allow us to study easily many configuration
- simulations are reproducible
- however: models and tools need to be validated

Simulation process in general

Pre-Processing

- specification of all model, controller and simulation parameters
- specification of all external input signals (wind and sea states)
- performing calculations, which are needed as input for simulations

→

Processing

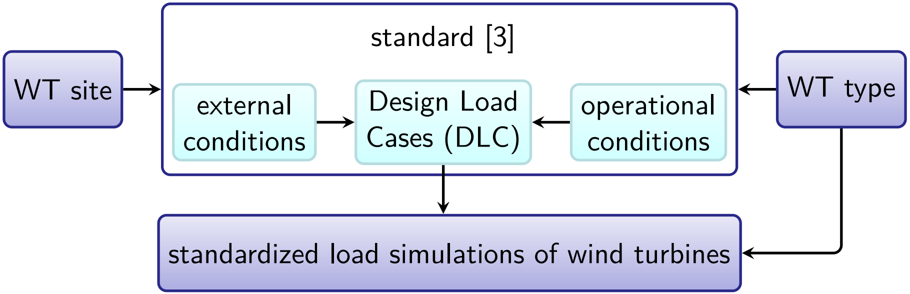
performing simulations using the defined algorithms, parameters and input signals

→

Post-Processing

- calculation of statistics and fatigue loads
- calculation of spectra
- plotting results etc.

Standardized load simulations for wind turbines



External conditions

- wind conditions
- other environmental inputs
- electrical power network

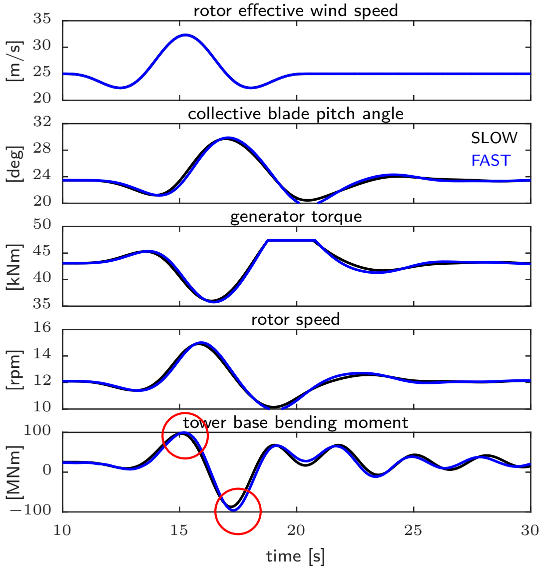
Operational conditions

- power production (+ fault)
- start up, shut down
- parked, transport

Type of analysis

- fatigue load analysis
- ultimate load analysis

Example: ultimate load simulation



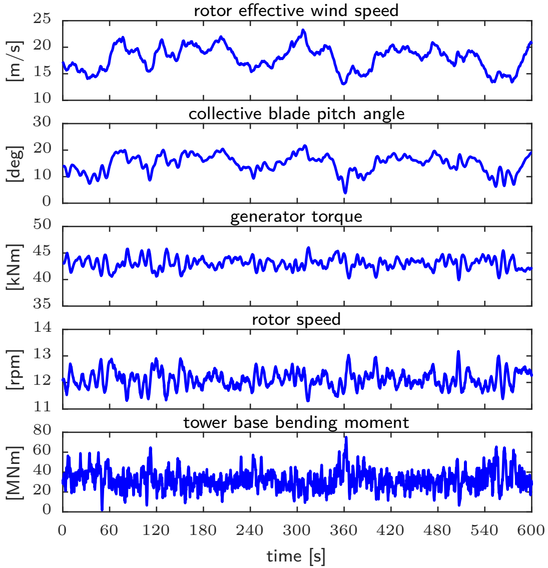
Extreme Operating Gust (EOG)

- coherent at cut-out wind speed
- often used for controller testing
- here NREL 5 MW reference wind turbine
- over speed and tower motion
- absolute values count

SLOW to FAST comparision

- main dynamic well captured
- differences mainly due to unmodeled blades and dynamic inflow / stall

Example: fatigue load simulation 1/2



Normal operation: DLC 1.2

- 6×10 min per mean wind speed
- from cut-in to cut-out, 2 m/s steps
- turbulence according to turbine class

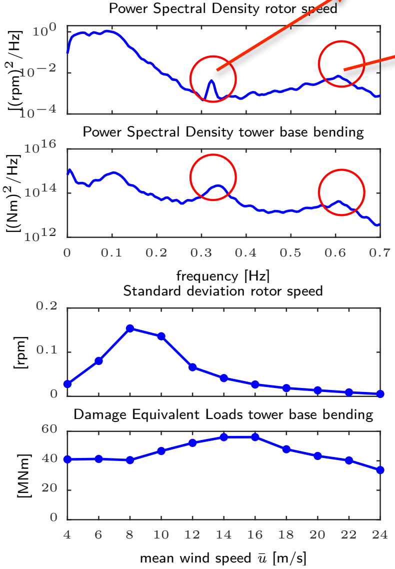
Damage Equivalent Loads (DEL)

DEL is an equivalent periodic load with constant amplitude and a predefined number of cycles which causes the same damage as stochastic loads.

Example: fatigue load simulation 2/2

1 periodo asociada a la frecuencia de la torre

3 periodo asociada a la frecuencia de las palas



Power Spectral Density (PSD)

- distribution of energy content over frequency
- tower resonance and 3P excitation visible
- useful to identify vibration issues at certain frequencies

Si el rotor trabaja en 6 vueltas por minuto las dos frecuencias se sincronizan y trabajamos en una resonancis de mayor pico.

Lifetime weighted load distribution

- weighting of values from each wind bin according to their relative frequency of occurrence over the lifetime
- useful to identify issues at certain operation points

Conclusion

Main questions

- How can we design a baseline generator torque controller?
- How can we and how should we evaluate a controller?

Nonlinear-state feedback controller $M_\mathsf{G} = f(\Omega_\mathsf{G}, \theta)$

- Region 2: $k\ \Omega_\mathsf{G}^2$ brings turbine to chosen power coefficient
- Region 1.5 and 2.5: linear functions for transition
- Region 3: onshore usually constant power
- pitch limit θ_fine to determine, whether Region 3 or 2.5 should be applied

- Various steps to focus on specific questions starting with nominal model.
- Use same source code and initialize controller.

Quick check on learning objectives

After this lectures you should be able to...

- ...describe the main tasks of a generator torque controller.
- ...design a baseline torque controller for all control regions.
- ...describe how the interaction with the pitch controller works.
- ...name useful steps to evaluate a controller.
- ...name conditions and type of analyses for standardized load simulations.

References

[1] K. Johnson, L. Pao, M. Balas, and L. Fingersh. "Control of Variable-Speed Wind Turbines". In: *IEEE Control Systems Magazine* 06 (2006), pp. 70–81.

[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] IEC 61400-1. *Wind turbines - Part 1: Design requirements*. International Electrotechnical Commission, 2005.

Please let me know if you have further questions!

Prof. Dr.-Ing. David Schlipf
David.Schlipf@HS-Flensburg.de
www.hs-flensburg.de/go/WETI

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