Controller Design Objectives and Modeling

Prof. Dr.-Ing. David Schlipf

02.09.2024

Lecture #1
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

Controller Design Objectives and Modeling

Motivation: Control is responsible for...

- optimizing the energy production
- avoiding over-speed and other constraints
- reducing structural loads

$\rightarrow$ and thus is very important!

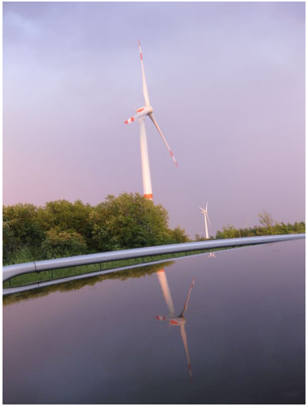
Main questions

- What are the basic layers and functions of a wind turbine controller?
- How can we model the main dynamics of a wind turbine for controller design?

Schedule

02.09. 1 Controller Design Objectives and Modeling
03.09. 2 Baseline Generator Torque Controller
04.09. 3 Collective Pitch Controller
05.09. 4 Filter Design
06.09. 5 Tower Damper
09.09. 6 Advanced Torque Controller
10.09. 7 Wind Field Generation
11.09. 8 Steady State Calculations
12.09. 9 Individual Pitch Control
13.09. 10 Lidar-Assisted Control I
16.09. 11 Lidar-Assisted Control II
17.09. 12 Wind Farm Effects
18.09. 13 Wind Farm Control
19.09. 14 Floating Wind Control I
20.09. 15 Floating Wind Control II

Contents



Typical hierarchy of wind turbine controllers

safety system

protection against

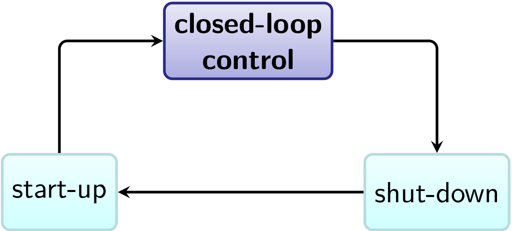
- over speed
- excessive vibrations
- over heating

emergency stop

. . .

supervisory control

state machine based on signals from temperature, anemometer, etc.



Based on [1]

Functions of hierarchy layers

Safety system

- Provides protection in unforeseeable situations.
- Usually overwrites the signals from the controller to stop the turbine's operation by pitching the blades to feathering position and disconnecting the generator from the grid.
- Emergency stop can be activated manually by an emergency button or triggered.

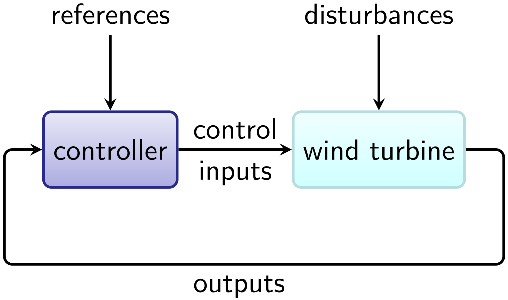
Supervisory control

- Is responsible to bring the wind turbine from one operational state to another.
- Includes supervision of system, state control, and set of controllers.
- Usually is responsible for the majority of the code within an industrial controller.

Closed-loop control

- Maximizes the energy capture over the turbine's lifetime during normal operations.
- Increase of energy capture is evaluated against higher structural loads.

Closed-loop control tasks



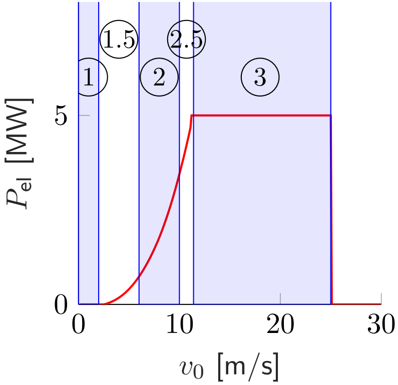
Past: disturbance rejection

- disturbances: changes in wind speed, direction, air density, grid loss...
- outputs: generator speed, tower top acceleration, pitch angles...
- control inputs: generator torque, yaw and pitch actuator...

New: reference signal tracking

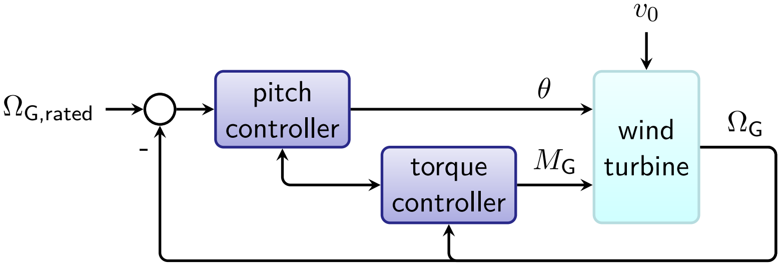
- for wind plant control or grid service
- reference: power set-point, yaw misalignment...

Wind turbine control regions



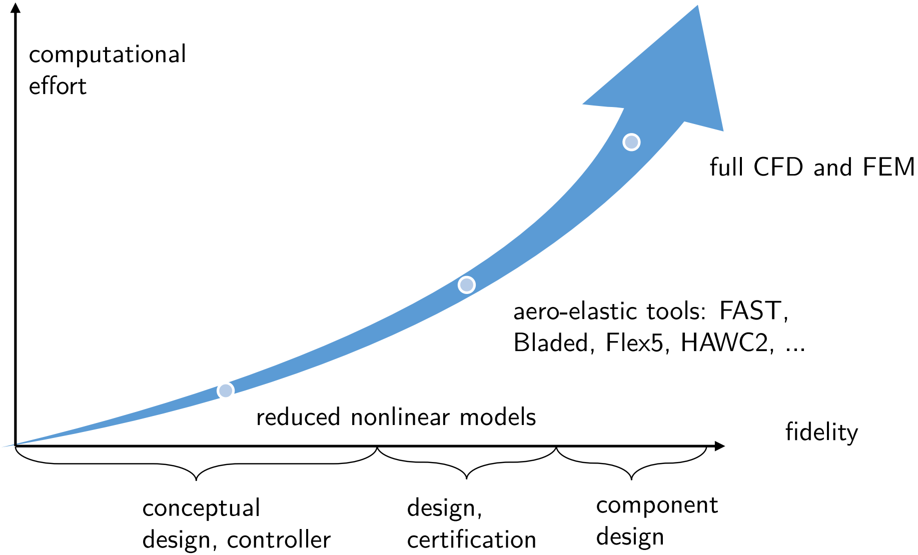
- region 1: wind speed too low, no power generation
- region 2: control goal: maximize energy yield
- region 3: maximum/rated power is reached, control goal: maintain rated power and generator speed, reduce structural loads
- transition regions: 1.5 and 2.5

Baseline wind turbine controller

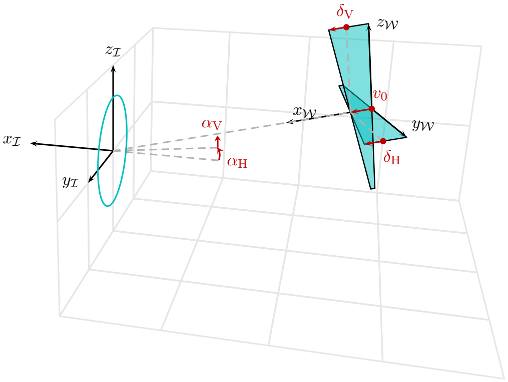


- Torque controller optimizes power below and maintains rated power above rated wind speed by adjusting generator torque M_{G} based on generator speed Ω_{G}.
- Pitch control maintains rated generator speed $\Omega_{\mathsf{G,rated}}$ by adjusting blade pitch angle θ.
- Interactions for transition between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

Fidelity of wind turbine models



Wind disturbance modeling



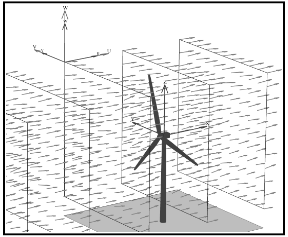
Realistic wind

- time variant 3D vector field
- turbulence defined along mean wind direction
- inflow angles α_{H}, α_{V}

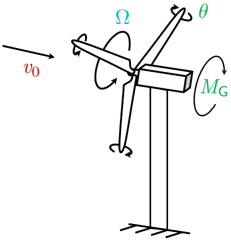
Reduced wind

- rotor effective wind speed v_0
- wind shears δ_{H}, δ_{V}
- Taylor's frozen turbulence hypothesis

Comparison of two wind turbine models



[2]



Fatigue, Aerodynamics, Structures, Turbulence (FAST) [3]

- tower, rotational and blade modes (4+2+3x3=15 DOFs)
- deterministic or stochastic wind field (TurbSim) [2]
- aerodynamics: blade element momentum theory

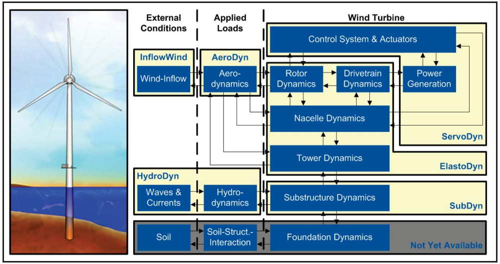
$\rightarrow$ sufficiently realistic model for load simulations

Simplified Low Order Wind turbine (SLOW)

- rotor motion Ω (1 DOF) [4], other DOFs can be added
- disturbance: rotor effective wind speed v_0
- inputs: blade pitch θ and generator torque M_G

$\rightarrow$ sufficiently accurate model for controller design

Fatigue, Aerodynamics, Structures, Turbulence (FAST)



[3]

$$\boldsymbol{M}(\boldsymbol{q},\boldsymbol{u})\ddot{q} = \boldsymbol{f}(\boldsymbol{q},\dot{\boldsymbol{q}},\boldsymbol{u},\boldsymbol{d})$$

$\boldsymbol{q}$	modal coordinates
$\boldsymbol{u}$	control inputs
$\boldsymbol{d}$	disturbance

Current Version: OpenFAST v3.5

- developed by National Renewable Energy Laboratory (NREL)
- certified simulation tool
- open source (Fortran) at github.com
- modular setup
- executable or Matlab sFunction
- https://openfast.readthedocs.io

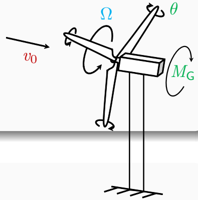
- Pre-Processing: wind input, ASCII files
- Processing: EXE or Matlab Simulink
- Post-Processing: Matlab or Python

Simplified Low Order Wind turbine (SLOW)

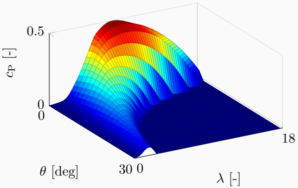
Structural dynamics

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

generator: $P_{\mathsf{el}} = M_{\mathsf{G}} \Omega r_{\mathsf{GB}} \eta_{\mathsf{el}}$



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 $\lambda = \frac{\Omega R}{v_0}$.

How can we get the parameters for the reduced model?

Scalar parameters usually direct from aero-elastic tools

- J sum of the moments of inertia about the rotation axis
- η_{el} generator efficiency
- r_{GB} gearbox ratio
- ρ air density
- R rotor radius

$$J\dot{\Omega} = M_{\text{a}} - M_{\text{G}} r_{\text{GB}}$$
$$P_{\text{el}} = M_{\text{G}} \Omega r_{\text{GB}} \eta_{\text{el}}$$
$$M_{\text{a}} = \frac{1}{2}\rho\pi R^2 \frac{c_{\text{P}}(\lambda,\theta)}{\Omega} v_0^3$$

Power coefficient $c_{\text{P}}(\lambda, \theta)$ from calculations or simulations

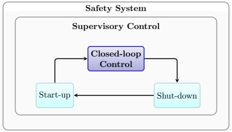
- Tricky part!
- Some tools provide calculations based on blade data. Blade bending is not considered, thus not very accurate for flexible (usually large) blades.
- If rotor motion can be fixed, simulations can be run with blade and tower modes enabled for a set of pitch angles θ and tip speed ratios λ. Adjusting the rotor speed and wind speed for each λ based on the steady states can be useful.

Conclusion

Main questions

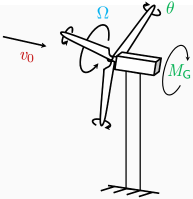
- What are the basic layers and functions of a wind turbine controller?
- How can we model the main dynamics of a wind turbine for controller design?

Safety system, supervisory control, and closed-loop control



- safety system provides protection in unforeseeable situations
- supervisory control responsible for operational state control
- closed-loop control responsible for normal operations (energy capture vs. load reduction)

We need a simplified sufficiently accurate model!



- only rotor effective wind speed as disturbance input
- collective pitch and generator torque as control input
- rotor motion via "Law of Conservation of Angular Momentum"
- parameters and power coefficient from aero-elastic tools

Quick check on learning objectives

After this lectures you should be able to...

- ...name the layers of a typical wind turbine controller and describe their main functions.
- ...name the main control regions and describe their control objectives.
- ...rank aero-elastic simulation tools against others in terms of effort and accuracy.
- ...describe, why a controller is crucial for wind turbines.
- ...model the basic dynamics of the rotor of a wind turbine.

References

[1] T. Burton, N. Jenkins, D. Sharpe, and E. Bossanyi. *Wind Energy Handbook*. New York, USA: John Wiley & Sons, 2011.

[2] B. J. Jonkman. *TurbSim User's Guide*. Tech. rep. TP-500-46198. NREL, 2009. URL: https://www.nrel.gov/docs/fy06osti/39797.pdf.

[3] J. Jonkman and L. M. Buhl. *FAST User's Guide*. Tech. rep. EL-500-38230. NREL, 2005. URL: https://www.nrel.gov/docs/fy06osti/38230.pdf.

[4] D. Schlipf. "Lidar-Assisted Control Concepts for Wind Turbines". PhD thesis. University of Stuttgart, 2015. DOI: 10.18419/opus-8796.

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

Disclaimer