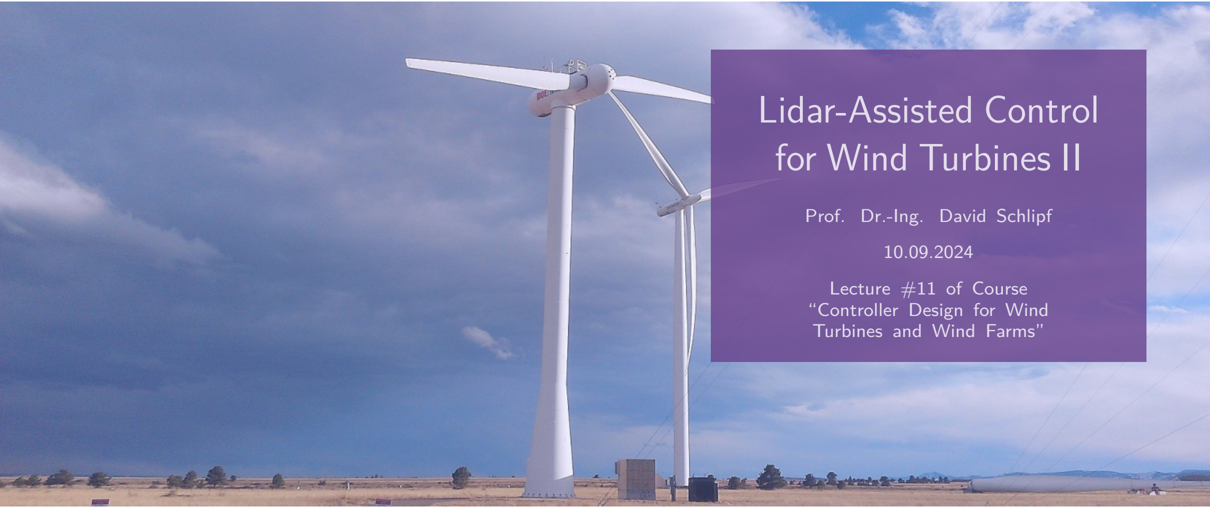


Lidar-Assisted Control for Wind Turbines II

Prof. Dr.-Ing. David Schlipf

10.09.2024

Lecture #11 of Course "Controller Design for Wind Turbines and Wind Farms"

Hochschule Flensburg University of Applied Sciences

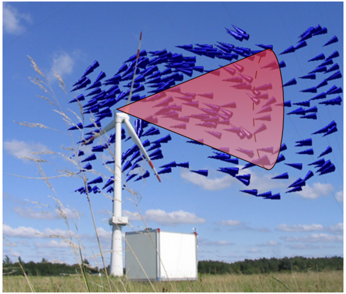
SWE Stuttgart Wind Energy @ Institute of Aircraft Design

Wind Energy Technology Institute

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.	7	Wind Field Generation
09.09.	10	Lidar-Assisted Control I
10.09.	11	Lidar-Assisted Control II
11.09.	5	Tower Damper
12.09.	6	Advanced Torque Controller
12.09.	8	Steady State Calculations
16.09.	9	Individual Pitch Control
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

Lidar-Assisted Control for Wind Turbines



Motivation

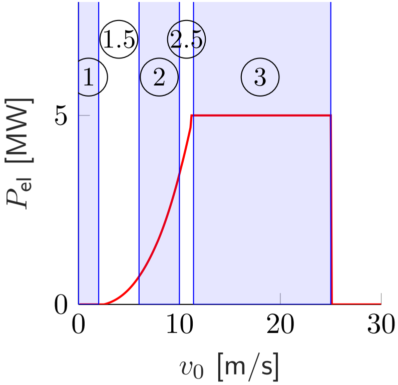
- wind is changing over space and time
- conventional control reacts after impact
- lidar technology provides wind preview
- better control performance is expected

Main questions

- How can useful wind preview signals be extracted from lidar data?
- How can these signals be used to improve wind turbine control?

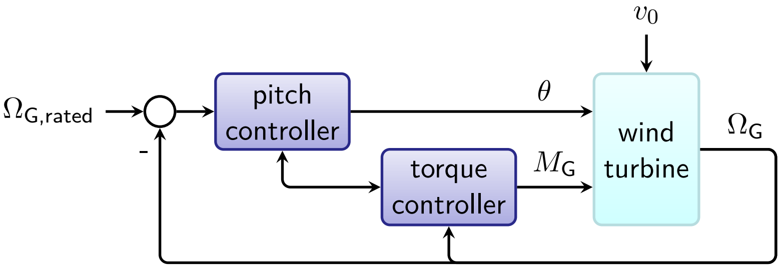
Contents

Wind Turbine Control Regions



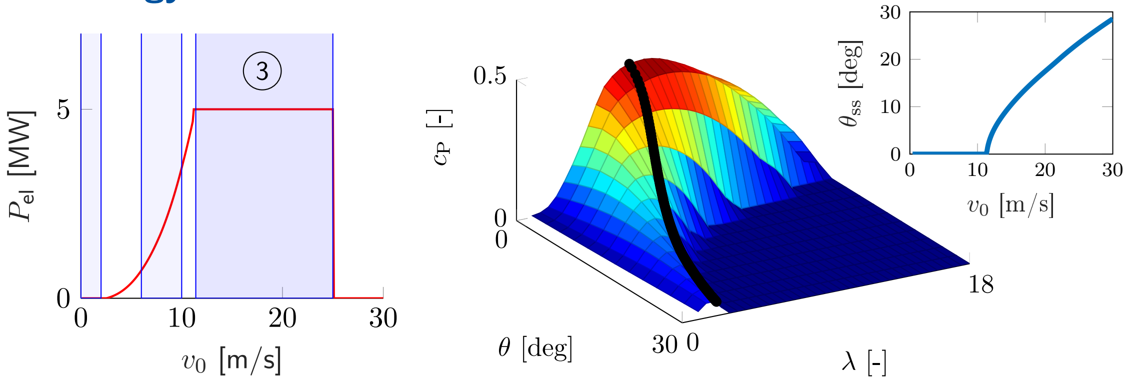
- Region 1: wind speed too low, no power generation.
- Region 2: control goal: maximize energy yield.
- Region 3: Maximum/rated power is reached. Control goal: maintain rated power and generator speed, reduce structural loads.
- Transition regions: 1.5 and 2.5.

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 $\Omega_{\mathrm{G,rated}}$ by adjusting blade pitch angle θ.
- Interactions for transition between above and below rated wind very important!

Strategy Baseline Pitch Controller



- Maximum power and rotor speed is reached $\rightarrow$ controller in region 3 aims to maintain $P_{\mathrm{el,rated}} = \frac{1}{2}\rho\pi R^2 c_\mathrm{P}(\lambda,\theta)v_0^3\ \eta_{\mathrm{el}}$ and rated rotor speed.
- This results in static pitch angle θ_{ss} over wind speed v_0 to reduce power coefficient c_P.

Dinámicamente

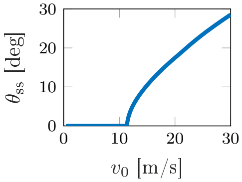
- Compromise between speed regulation, reduction of structural load, and pitch activity.

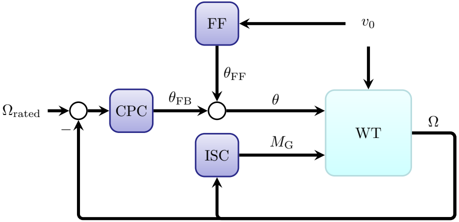
Collective Pitch Feedforward Controller Design

$$J\dot{\Omega} = M_{\mathsf{a}}(\theta, \Omega, v_0) - M_{\mathsf{G}} \overset{!}{=} 0$$

Objetivo, mantener el pitch en el valor deseado para que el sistema no se acelere

$$\theta_{\mathsf{FF}} = \theta_{\mathsf{ss}}(v_0)$$





Control in full load operation

- pitch controller (CPC) maintains rated speed
- torque controller (ISC) maintains rated power

Collective pitch feedforward [1]

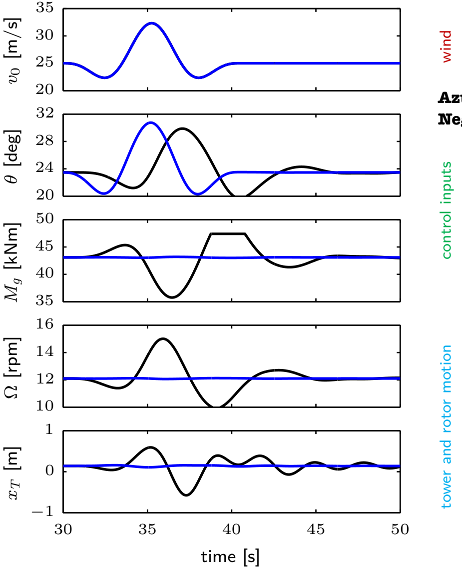
pitch follows static curve θ_{ss} to cancel out effects of changing wind speed v_0 in aerodynamics

Advantages

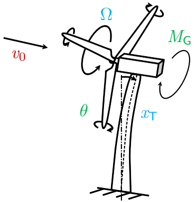
- simple update to conventional FB
- works over entire full load
- little model information
- guaranteed stability

Garantiza la estabilidad ya que si el control realimentado es estable el agregar un control anticipativo estable el sistema continua siendo estable.

Comparison with Perfect Wind Preview



Azul - Control Anticipativo
Negro - Control estandar



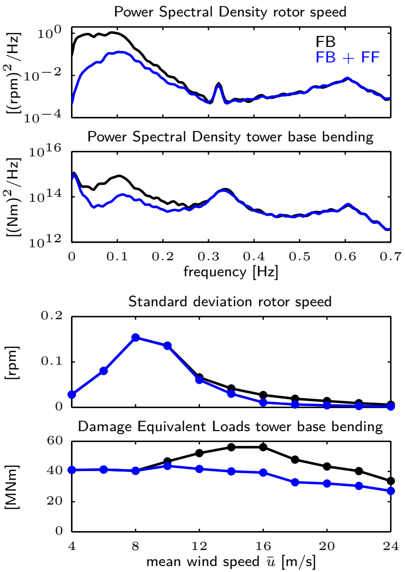
Environment

- FAST model + coherent wind
- EOG at $25\,\mathrm{m/s}$

Results

- pitch θ follows wind speed v_0
- constant generator torque M_{G}
- no variation in rotor speed Ω
- also less tower top motion x_{T}
- robust with respect to model uncertainties over large range

Comparison with Realistic Preview



Power Spectral Densities

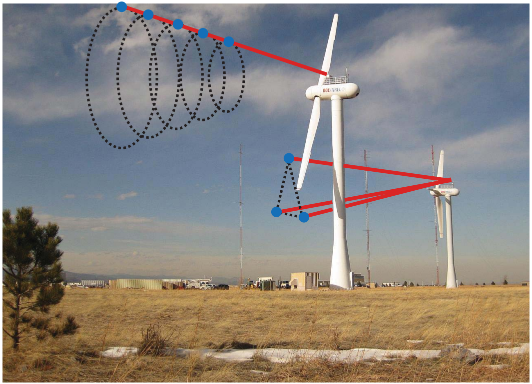
- FAST model + turbulent wind + lidar simulator
- reconstruction + adaptive filter
- reduction at low frequencies for rotor speed + tower bending

Life time analysis

- simulations over full range
- beneficial for high wind speeds
- DEL on tower reduced by $\approx 20\%$
- benefits for blade + shaft loads
- only marginal energy increase
- robust with respect to measurement uncertainties

Damage equivalent load

Field Testing 2012 - Setup



Control Advanced Research Turbines

- National Wind Technology Center
- 42 m rotor diameter
- 600 kW rated power
- heavily instrumented

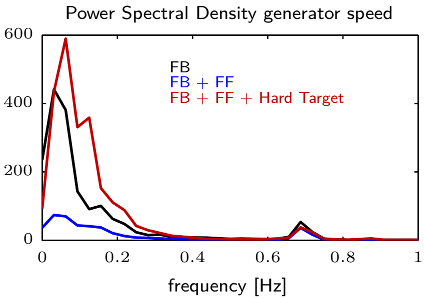
Lidar systems

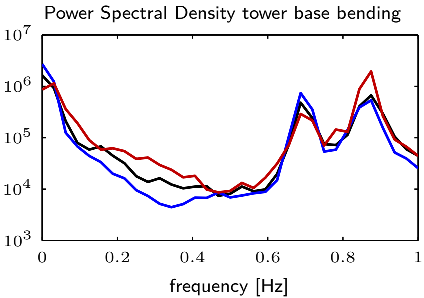
- commercial system on CART3
- SWE scanning lidar on CART2

Organization

- cooperation between SWE and NREL
- focus on rotor speed regulation

Field Testing 2012 - Results





Main results

- reduction standard deviation of generator speed of 30% at low frequencies
- but increase of 30% before solving a measurement problem due to met mast
- similar behavior for the tower base bending moment and other loads

$\rightarrow$ checking correlation online and more adaptivity necessary

Chain of Benefit for Lidar-Assisted Control

1. Improved speed regulation

- Adjusted lidar data processing
- Adding feedforward control

2. Load reduction

- Retuning feedback control
- Adaptive filter

3. More energy

- Uprating for higher AEP if possible
- life-time-extension for more production

Current Status of Lidar-Assisted Control

[Goldwind]

sowento

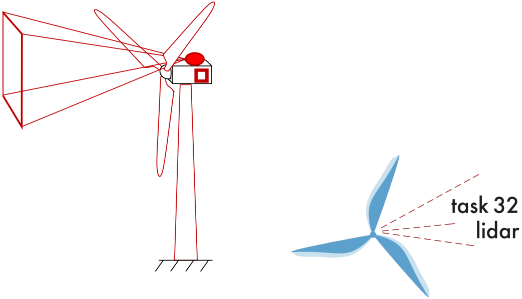
Status

- >2000 wind turbines (≈6 GW) running with LAC (Goldwind supported by sowento)
- Further industrial collaboration with SGRE, Movelaser etc.

Challenges

- complexity of economic benefit
- robustness / adaptivity
- certification

Systems Engineering



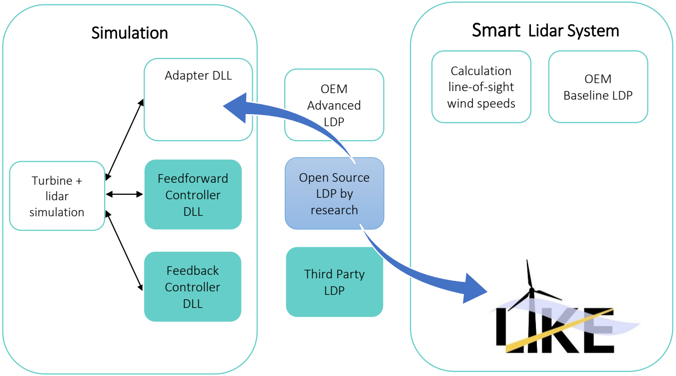
Systems Engineering

- used for multidisciplinary optimization
- challenge: set up optimization problem
- typically applied to aircraft design

Optimization Lidar-Assisted Control

- Which economic benefit can be obtained by LAC?
- IEA Wind Task 32 Workshop [2]

The “Smart Lidar” concept



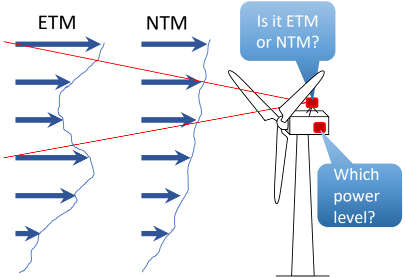
Main Idea

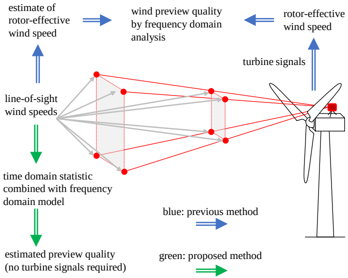
- enables cooperation
- algorithms can be adjusted for specific conditions
- algorithms can be tested in aero-elastic simulations
- LDP outside safety-relevant turbine controller
- great for certification

PhD Project in Flensburg

- Adaptive lidar systems for wind turbine control
- LIdar Knowledge Europe

Possible “Apps” for a Smart Lidar





Turbulence Intensity Estimation [3]

- provides estimate similar to point measurement
- uses a spectral model to relate variance of line-of-sight wind speeds to variance of longitudinal wind speed

Wind Preview Quality Estimation [4]

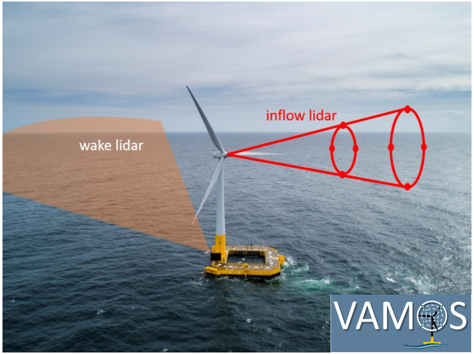
- provides a correlation coefficient or measurement coherence bandwidth
- uses a spectral model to relate covariance between line-of-sight measurements to correlation coefficient

Smart Lidar concept tested offshore!

Validation, **M**easurement and **O**ptimization of Floating Wind Energy **S**ystems

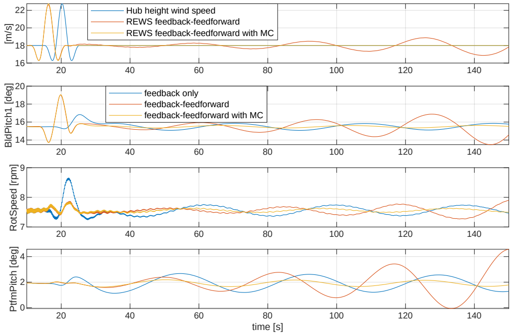
- German-French research project
- measurements on Floatgen demonstrator since summer 2020
- simultaneous measurement of inflow and wake on floating wind turbine with lidar
- power curve assessment
- monitoring with model-based observer
- real-time lidar data processing for feedforward control

→ DLL [5] runs on PC (gateway)



[Press release: www.uni-stuttgart.de/en/research/]

A Tutorial on LAC for Floating Offshore Wind Turbines



Open Source Tools of IEA Wind Task 52

- Detailed Lidar Simulator
- Source code of lidar data processing, feedback and feedforward controller
- Scripts to run examples

→ Used in LAC Summer Games

The LAC Summer Games 2024 – Participation is everything!

Motivation

- Share knowledge and make application easier!
- Share enthusiasm with students!

Three disciplines

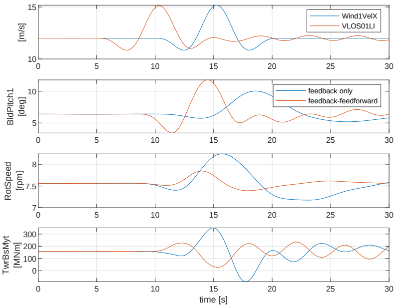
- The 30 s sprint Great for controls students!
- The 18 m/s hurdles
- The DLC 1.2 Marathon

How to participate?

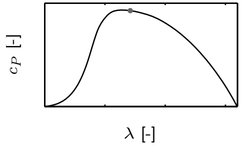
- Try the code on Github!
- Check details in the Announcement at Zenodo!
- Join the next webinar and discussion on github!
- Mobilize your students and colleagues!

iea wind Task 52

LAC Summer Games 2024



Other Ideas



Direct Speed Control

- tracking of optimal λ at partial load can be improved
- marginal energy gain, higher loads and power variation

Lidar-Assisted Yaw Control

- lidar-estimation of misalignment might be better as point measurement
- some energy gain, depends on inhomogeneity and control strategy

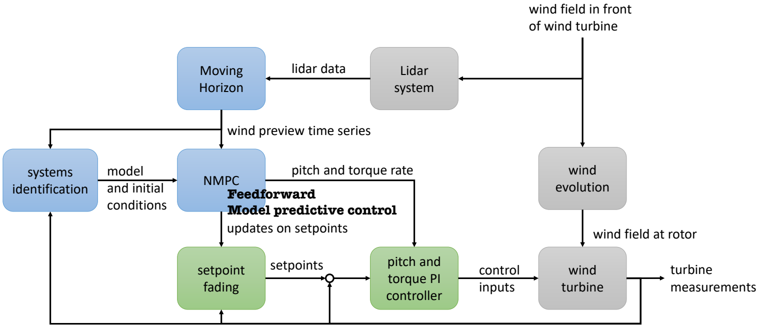
Multivariable Feedforward Control

- collective pitch and generator torque feedforward
- advantages between partial and full load
- can be realized as Model Predictive Control (optimizing control action over time horizon)

Lidar-Assisted Individual Pitch Control

- blade load reduction from shear or blade-effective wind speed measurement
- shear estimation critical, advantage over feedback questionable

Nonlinear Model Predictive Control Field

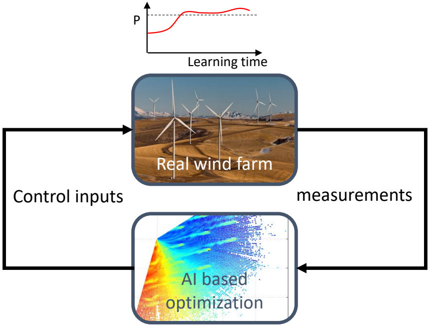


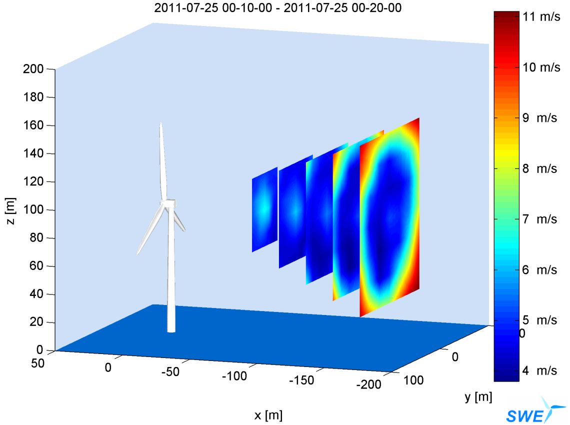
- Moving Horizon lidar data processing developed by sowento
- Provides Wiener-filtered wind speed over several seconds
- Currently tested at 6 MW wind turbine with NMPC from IAV
- Feedforward concept will be tested on 2 MW WETI research turbine

Lidar-Assisted Wind Farm Control

Lidar systems can be used for:

- wake model verification
- farm control monitoring
- track wind turbine wakes
- optimize wind farm operation



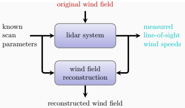


Conclusions

Main questions

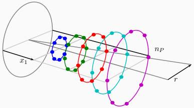
- How can useful wind preview signals be extracted from lidar data?

Nacelle-based lidar needs new model-based wind field reconstruction!



- Main problem: limitation to line-of-sight wind speeds.
- Good estimates can be provided with adequate wind models!
- For lidar-assisted control we can assume perfect alignment and the Frozen Turbulence Hypothesis to condense all line-of-sight to an estimate for the rotor-effective wind speed.

Correlation between lidar and rotor very important!



- Rotor-effective wind speed can be also estimated from turbine data.
- We can model spectra, transfer function and coherence based on Fourier transform of measurement equations and using turbulence models.
- Lidar data needs to be filtered according to the transfer function.
- We can use the correlation model for scan optimization and filter design.

Conclusions

Main questions

- How can these signals be used to improve wind turbine control?

Load reduction is possible, transformable into more energy!

- nonlinear feedforward controller as add-on to conventional feedback
- in region 3 collective pitch feedforward control based on static pitch curve
- design assuming perfect wind preview and then adding adaptive filter
- currently first commercial applications

References

[1] D. Schlipf and M. Kühn. "Prospects of a collective pitch control by means of predictive disturbance compensation assisted by wind speed measurements". In: *German Wind Energy Conference (DEWEK)*. Bremen, Germany, Nov. 2008. DOI: 10.18419/opus-3900.

[2] E. Simley, P. Bortolotti, A. Scholbrock, D. Schlipf, and K. Dykes. "IEA Wind Task 32 and Task 37: Optimizing Wind Turbines with Lidar-Assisted Control Using Systems Engineering". In: *Journal of Physics: Conference Series*. Vol. 1618. 4. The Science of Making Torque from Wind (TORQUE 2020). Sept. 2020, p. 042029. DOI: 10.1088/1742-6596/1618/4/042029.

[3] D. Schlipf, F. Guo, and S. Raach. "Lidar-based Estimation of Turbulence Intensity for Controller Scheduling". In: *Journal of Physics: Conference Series*. Vol. 1618. 3. The Science of Making Torque from Wind (TORQUE 2020). Sept. 2020, p. 032053. DOI: 10.1088/1742-6596/1618/3/032053.

[4] F. Guo and D. Schlipf. "Lidar Wind Preview Quality Estimation for Wind Turbine Control". In: *American Control Conference*. New Orleans, LA, USA, May 2021. DOI: 10.23919/ACC50511.2021.9483442.

[5] D. Schlipf, F. Lemmer, and S. Raach. "Multi-Variable Feedforward Control for Floating Wind Turbines Using Lidar". In: *International Ocean and Polar Engineering Conference*. Oct. 2020. DOI: 10.18419/opus-11067. URL: https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE20/All-ISOPE20/ISOPE-I-20-1174/446367.

Please let me know if you have further questions!

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