Solving the problem of ill-conditioning
A data-enabled co-design approach for modern wind turbine control schemes

Boulder – August 31, 2022

Sebastiaan Mulders, Livia Brandetti,
Yichao Liu and Jan-Willem van Wingerden
Delft University of Technology

TU Delft

The team

Livia Brandetti
PhD candidate on HAWT/VAWT control systems (TU Delft)

Yichao Liu
Researcher at Electric Power Research Institute (EPRI)

Jan-Willem van Wingerden
Full professor (TU Delft)

On the ill-conditioning of the combined wind speed estimator and tip-speed ratio tracking control scheme

L Brandetti[1,2], Y Liu[2], SP Mulders[2], C Ferreira[1], S Watson[1], JW van Wingerden[2]
[1]AWEP Department, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands.
[2]DCSC Department, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands.
E-mail: l.brandetti@tudelft.nl

Abstract. In recent years, industrial controllers for modern wind turbines have been designed as a combined wind speed estimator and tip-speed ratio (WSE-TSR) tracking control scheme. In contrast to the conventional and widely used $K\omega^2$ torque control strategy, the WSE-TSR scheme provides flexibility in terms of controller responsiveness and potentially improves power extraction performance. However, both control schemes heavily rely on prior information about the aerodynamic properties of the turbine rotor. Using a control-oriented linear analysis framework, this paper shows that the WSE-TSR scheme is inherently ill-conditioned. The ill-conditioning is defined as the inability of the scheme to uniquely determine the wind speed from the product with other model parameters in the power balance equation. Uncertainty of the power coefficient contribution in the latter mentioned product inevitably leads to a biased effective wind speed estimate. As a consequence, in the presence of uncertainty, the real-world wind turbine deviates from the intended optimal operating point, while the controller believes that the turbine operates at the desired set-point. Simulation results confirm that inaccurate model parameters lead to biased estimates of the actual turbine operating point, causing sub-optimal power extraction efficiency.

1. Introduction
Wind energy plays a crucial role in the global energy mix as its installed power capacity continues to increase [1]. After the Glasgow climate summit, the net-zero emissions targets set for the middle of the century pose ambitious goals for the wind industry [2]. To efficiently achieve these goals, the sizes of wind turbines increase dramatically. Larger turbines together with a more flexible rotor assembly and support structure result in a rising demand for optimization of wind turbine controllers [3].

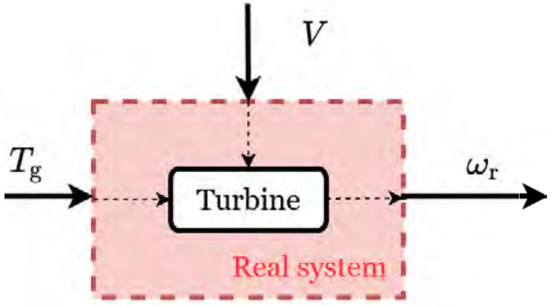
Modern wind turbines usually employ a variable-speed variable-pitch (VS-VP) operating strategy, and thereby use generator torque control to maximize energy capture in below-rated operating conditions [4, 5]. Until recently, the most common partial load wind turbine torque

L. Brandetti, Y. Liu, S.P. Mulders,
C. Ferreira, S. Watson, J.W. van Wingerden
“On the ill-conditioning of the combined wind speed estimator and tip-speed ratio tracking control scheme”
TORQUE 2022

TUDelft

Conventional torque control

The $K\omega^2$-controller

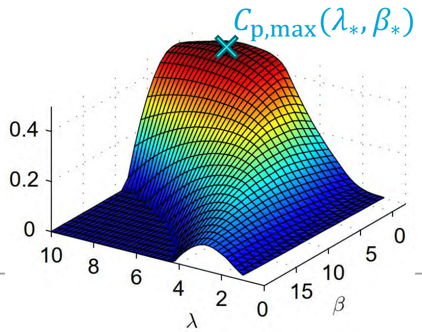


Advantages

- **Effective** and satisfactory performance
- **Easy** to understand
- **Simple** to implement

Disadvantages

- Highly dependent on **prior information**
- Predetermined (varying) **control bandwidth**
- **Inflexible** in controller design and tuning



$$K = \frac{\pi \rho R^5 C_{p,max}(\lambda^*, \beta^*)}{2(\lambda^*)^3}$$

The combined estimator-controller scheme

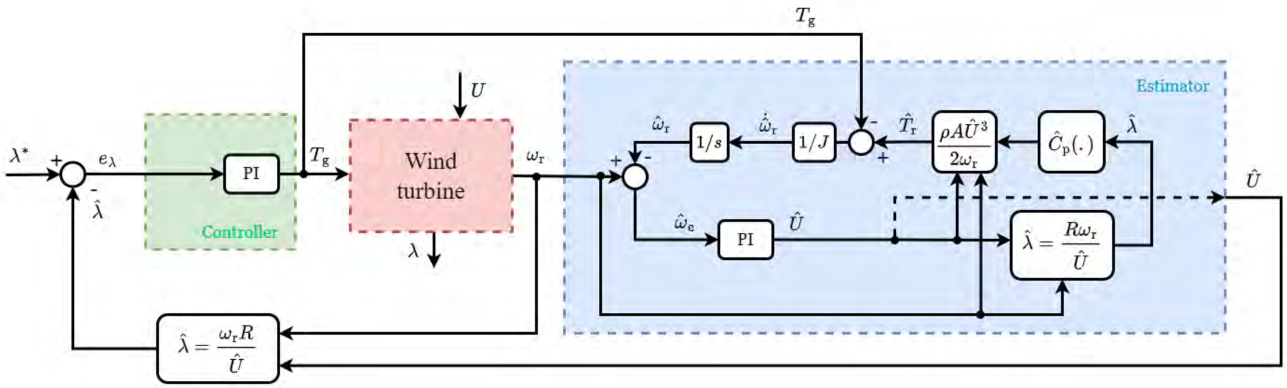
Tip-speed ratio set point and torque control

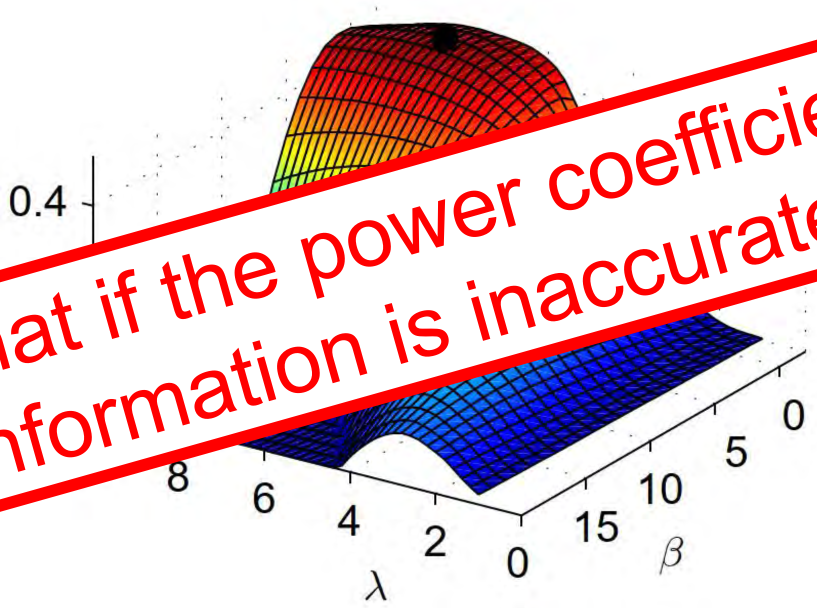
Advantages

- **Dynamic** controller
- **Tuneable**
- **Trade-off** between *energy capture* and *loads*

Disadvantages

- **Complex** implementation and calibration
- Still heavily relying on **prior information** in **Contr.** and **Est.**





What if the power coefficient information is inaccurate?

Problem definition

Aerodynamic
Estimator
Controller

The problem of ill-conditioning explained

Consider steady-state condition:

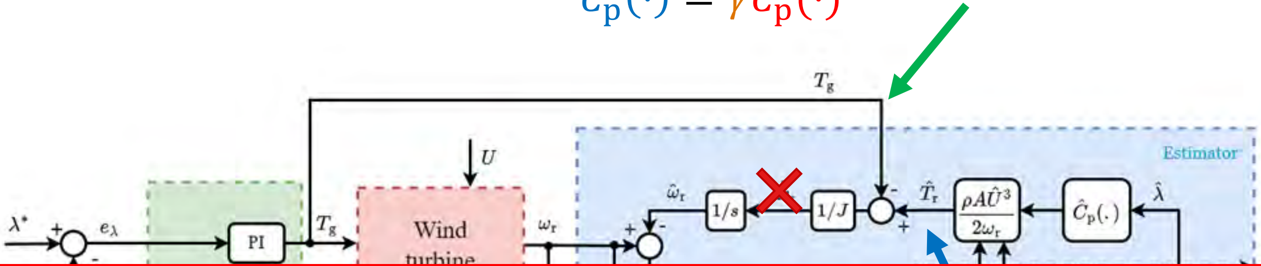
$$J\dot{\omega}_r = T_r - T_g = 0 \;\rightarrow\; \dot{\omega}_r = 0$$

$$\widehat{T}_r = T_g \text{ (no drivetrain losses)}$$

$$\widehat{U}^3 \hat{C}_p(\hat{\lambda}) = U^3 C_p(\lambda)$$

Having uncertain power coefficient information $(\gamma \neq 1)$:

$$\hat{C}_p(\cdot) = \gamma C_p(\cdot)$$



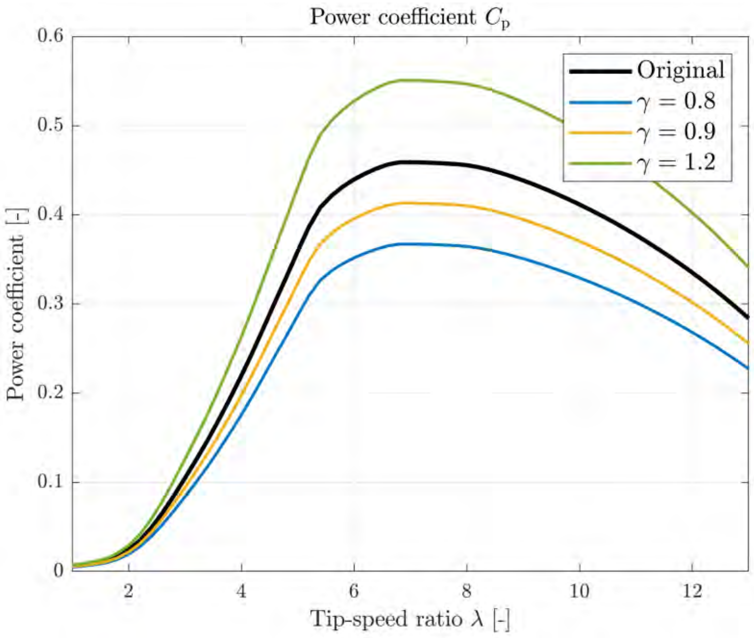
THE PROBLEM OF ILL-CONDITIONING

L. Brandetti, Y. Liu, S.P. Mulders, C. Ferreira, S. Watson, J.W. van Wingerden
"On the ill-conditioning of the combined wind speed estimator and tip-speed ratio tracking control scheme",
TORQUE 2022

TU Delft

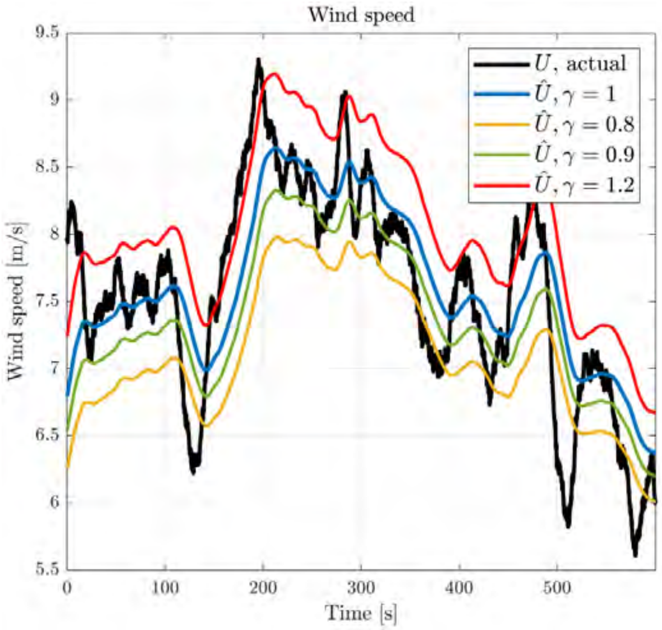
Definition of uncertainty

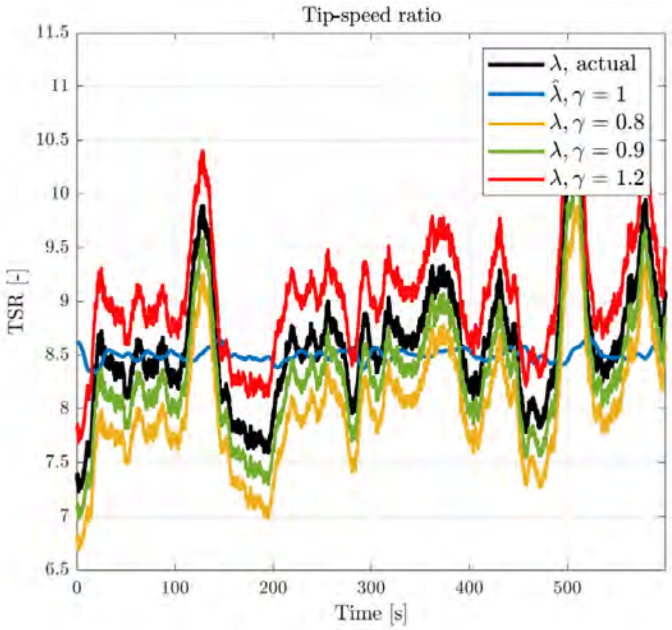
Uncertainty: $C_\mathrm{p}(\lambda) \neq \left(\hat{C}_\mathrm{p}(\lambda) = \gamma C_\mathrm{p}(\lambda)\right)$ when $\gamma \in \mathbb{R}^+ \neq 1$



Effect on operating point

Wind speed and tip-speed ratio





TU Delft

Industrial collaboration

Can we come up with a scheme to learn $\hat{C}_p \rightarrow C_p$?

The slides on the learning scheme cannot be shared at this time

For more info, please keep an eye on future publications of our group

Conclusions

Ill-conditioning

- There is not enough information to make a unique and unbiased wind speed estimate with model uncertainty $(\gamma \neq 1)$

$$U^3 C_\mathrm{p}(\lambda) = \hat{U}^3 \hat{C}_\mathrm{p}(\hat{\lambda})$$

- The controller always thinks **it's** doing the right thing, while the under uncertainty the turbine is doing something different

Learning scheme

- Correct controller internal model using readily available signals
- Exploiting the control scheme structure to learn

Vestas

TU Delft

Solving the problem of ill-conditioning
A data-enabled co-design approach for modern wind turbine control schemes

L. Brandetti, Y. Liu, S.P. Mulders, C. Ferreira, S. Watson, J.W. van Wingerden
"On the ill-conditioning of the combined wind speed estimator and tip-speed ratio tracking control scheme", *TORQUE 2022*

Vestas

TU Delft

Sebastiaan Mulders, Livia Brandetti,
Yichao Liu and Jan-Willem van Wingerden
Delft University of Technology