Wind Turbines: Innovative Concepts

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Wind Energy Theme Day for Industry: Control

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Outline

• Model-based control
  – Basics: State estimation, LQ/MPC control
  – Control Design Model
    • Example: Dynamic Inflow
• Trailing edge flaps
  – The concept
  – Combining trailing edge flaps and IPC
• LiDAR enhanced control
  – Load alleviation
  – Power optimization
• Passive vs. active control
  – Bend-twist couplings
• Floating wind turbines
  – Using an Extended Kalman Filter for state estimation
Model-based Control
Model-based Control

Control Methods applied on Wind Turbines

• **Classic Control Methods**
  - PI Control
  - Interconnected PI Controllers and Bandpass Filters
  - ...

• **Modern Control Methods**
  - Linear Quadratic Control (LQ)
  - Linear Parameter Varying Control (LPV)
  - Robust Control ($H_2, H_\infty$)
  - Model Predictive Control (MPC)
  - Misc. Nonlinear Control Methods
  - ...

• **Individual Pitch**
  - Coleman/Multi-blade Coordinate Transformation
  - Decoupling of control loops
  - ...

• **Trailing edge flaps**
  - Decoupling of control loops
  - ...

• **LiDAR**
  - Feed forward of measure wind
  - ...
Model-based Control

Control Theory in Time Discrete Form

State space model

\[ x(t_{k+1}) = f(x(t_k), u(t_k)) + w(t_k) \]
\[ y(t_k) = g(x(t_k), u(t_k)) + v(t_k) \]

State estimator

\[ x(t_k|t_k) = x(t_k|t_{k-1}) + L[y(t_k) - g(x(t_k|t_{k-1}), u(t_k))] \]
\[ x(t_{k+1}|t_k) = f(x(t_k|t_k), u(t_k)) \]

State space controller

\[ u(t_k) = K \cdot x(t_k|t_k) \]
or
\[ u(t_k) = K \cdot x(t_k|t_{k-1}) \]
or
\[ u(t_k) = k(x(t_k|t_{k-1})) \]
or
\[ ... \]

Disturbances: \( w \) and \( v \)
(Turbulent Wind, Wave forces, ...)

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Model-based Control
Control Design Model

• The control design model is a set of linear/nonlinear ordinary differential equations (in state space form), which are “adequately” describing the system to be controlled.

  – “Adequately” means including phenomena of interest (tower DOFs, blade DOFs etc.) in a frequency range of interest.

• The control design model can be obtained from first-principles modeling, system identification (black box), a combination of the two (gray box).

  – A first-principles model of a wind turbine can be obtained from aero-elastic software codes such as Bladed, FAST, HAWCStab2 etc.
Model-based Control

Control Design Model

- Bode plots – From collective blade pitch to generator speed

8 m/s

16 m/s
Model-based Control
Dynamic Inflow
Trailing Edge Flaps
Trailing Edge Flaps
The CRTEF Development

Comsol 2D analyses
two different inflow sensors
Trailing Edge Flaps
Comparison of measurements and model

\[ \alpha = \text{8deg} \]

\[ \beta \text{ [deg]} \]

\[ C_L \text{ [-]} \]

\[ \text{time [s]} \]
Trailing Edge Flaps

Test rig

Test rig based on a 100 kW turbine.
Rotation of a 10m long tube with an airfoil section of about 2x1m

Pressure measurements

Pitch actuator
Trailing Edge Flaps
Simulation Test Case

• Reference NREL 5 MW turbine

• Adaptive Trailing Edge Flaps
  – All flaps on one blade moved as one

• Sensors:
  – Shaft sp., Blade root b.mom, Tower top acc.

• Simulations with HAWC2
  – Multibody dynamics, includes torsion
  – Unsteady BEM aerodynamics

• IEC conditions: class A. Iref:0.16 (wsp: 18 m/s)

• Focus on blade load alleviation
Trailing Edge Flaps
Combined IPC and Trailing Edge Flap Control

Δ DEL Mx.Bl.Rt [-]

Flap act. [deg/s]

Pitch act. [deg/s]

PI 0.3

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LiDAR Enhanced Control
LiDAR Enhanced Control
Types and objectives

- Load alleviation
  - Collective pitch control (CPC)
  - Individual pitch control (IPC)
- Power optimization
  - Tracking optimal operation point
  - Reducing yaw misalignment

- Nacelle mounted (mounted on top of nacelle)
- Spinner/hub mounted
- Blade mounted (instead of pitot-tubes)
LiDAR Enhanced Control
Uncertainties and Limitations

- LiDAR uncertainties
  - Validity of Taylors hypothesis of frozen turbulence
  - Volume average of wind speed measurements
  - Projection error
  - Measurement availability and system reliability
LiDAR Enhanced Control
Collective Pitch Control

• D. Schlipf et al., 2012.
  - Experimental results shows that fatigue loads of CART2 turbine can be lowered by introducing LiDAR based feed-forward collective pitch control
• E. Bossanyi et al., 2012

Figure 11: Lifetime fatigue load reductions
LiDAR Enhanced Control
Individual Pitch Control

- K. A. Kragh et al., 2013
  - LiDAR based feed-forward IPC is mainly beneficial in situations with rapid, small scale variations (e.g. changing wind shear).
  - Very sensitive to uncertainties relating to the inflow estimation
Passive vs. Active Control
Passive vs. Active Control
Overview

- Passive control methods
  - Swept blades
  - Bend-twist couplings

- Active control methods
  - Individual pitch control
  - Trailing edge flap control

Figure 2.1: Torsion of a traditional design (left) and bend-twist coupled design (right) wind turbine blade sections
Passive vs. Active Control

Issues

- Many aero-elastic tools need further development to handle complex beam models.

- Can the blades be fabricated such that they behave as predicted by the aero-elastic tools.

- Further development of control methods is needed.

- Developed control methods should be adopted by industry.
Floating Wind Turbines
Floating Wind Turbines
The Hywind Concept
Floating Wind Turbines
Simulations of the Hywind Concept (I)

**Wind turbine states**
- 1 or 2 tower fore-aft DOF
- 1 or 2 tower side-side DOF
- 2 blade edge-wise DOF pr. blade
- 2 blade flap-wise DOF pr. Blade
- 1 induced wind speed state pr. blade

**Disturbance states**
- 1 wind speed (2nd order) pr. blade
- 1 fore-aft hydrodynamic force (2nd order)
- 1 side-side hydrodynamic force (2nd order)

**Sensors used by the EKF**
- Pitch angles of each blade
- Electro magnetic generator torque
- Generator power
- Generator speed
- Rotor speed
- Tower top fore-aft acceleration
- Tower top side-side acceleration
- Flap-wise blade root bending moment at each blade
- Edge-wise blade root bending moment at each blade
Floating Wind Turbines
Simulations of the Hywind Concept (II)

Col. pitch ref. to tower top fore-aft at 8 m/s

Magnitude [dB]

Phase [deg]

Frequency [Hz]
Floating Wind Turbines
Simulations of the Hywind Concept (III)

Wind speed 12 m/s, wave dir. 0 deg.

Wind speed 12 m/s, wave dir. 90 deg.
Floating Wind Turbines
The WindFloat Concept

Levelized Cost of Energy (€*/MWh) evolution per number of built platforms

- 3 MW
- 5 MW
- 7 MW
- 10 MW

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Industrial/academic Cooperation
Industrial/academic Cooperation

- Foundations for offshore wind turbines (incl. floating concepts)
- Trailing edge flaps
- LiDARs
- Pitch gears
- Drive train gears
- Aerodynamic blade design
- Structural blade design

- Materials research both composites and alloys/metals
- Wind Recourse Assessments

- Measurement campaigns for wind turbines

- High altitude wind energy converters (Kites and lighter than air devices)
Conclusions

• Good mathematical models of systems and components are required both for control design purposes but also for evaluation of performance/behavior.

• Many innovative concepts have been and will be tested and developed, some will mature for commercial success and some will be forgotten, only to be presented as innovations a decade later.

• Cost-of-energy (COE) is ultimately the main driver determining whether or not an innovation will reach a commercial state.

• Academic cooperation is good way to test some of the innovative ideas before spending too much time and money on the idea.
Thank you for your attention!