Making nonlinear state estimation techniques ready for use in industrial wind turbine control systems

Session: Advanced control strategies for wind plants

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Motivation

output feedback controller

state feedback controller
Central contributions

1. Investigate **observability** and **identifiability** in detail (for a non-state of the art model)

2. Discuss **nonlinear filters and architecture** to address all relevant estimation sub-problems

3. Show that **state estimation is feasible**
   - with an advanced nonlinear model
   - with high estimation quality
   - in real-time.
Outline

1. Model analysis
2. State estimation
3. Simulation results
4. Conclusions
1. Model analysis

Prerequisites for wind turbine state estimation

- Hi-fidelity nonlinear wind turbine model catching the relevant system dynamics with few physical parameters (< 20)

\[
\begin{align*}
\dot{x}_T &= f_1(x, u, \theta, d) \\
\dot{y}_T &= f_2(x, u, \theta, d) \\
\ddot{\varphi}_g &= f_3(x, u, \theta, d) \\
\Delta \ddot{\varphi} &= f_4(x, u, \theta, d) \\
\ddot{x}_{B,1} &= f_5(x, u, \theta, d) \\
\ddot{x}_{B,2} &= f_6(x, u, \theta, d) \\
\ddot{x}_{B,3} &= f_7(x, u, \theta, d)
\end{align*}
\]

- What are the benefits from additional load measurements?
- How good can the desired quantities be estimated?
1. Model analysis
Local observability analysis

- Observability depends on external excitation, number of measurements & choice of sensors
- Investigated measurement configurations
  - **Standard**: Nacelle acceleration + generator speed
  - **Extended**: Standard + blade-root bending moments
  - **Advanced**: Extended + tower-base bending moments
- Blade-root sensors show **significant improvement** of observability of certain states and parameters

References
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2. State estimation

Algorithms to solve the estimation problem

- **Sigma-point Kalman filters** [2,3] among others [1]
  - Preferable alternative to Extended Kalman Filter (EKF)
  - Suitable for nonlinear systems with characteristic maps
  - Mature and industry-tested techniques

- **Implementation in Matlab/Simulink**
  - Efficient code generation for UKF, CDKF & CKF and their square-root realizations
  - Computational time <10ms with 28th order nonlinear model on Beckhoff Industrial Controller (monolithic filter)

References


2. State estimation
Composition of observer architecture for real-time application

- Several subproblems to manage (wind, state, parameter & load estimation)
- How to compose an observer with low computational cost and high accuracy?
- Distributed architecture allows for...
  - exploiting system properties explicitly to save computational time
  - employing different linear/nonlinear filter types, different sample times
  - selective filter adaptation & situational by-passing (triggered by observability measures)

Reference
Outline

1. Model analysis
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3. Simulation results
4. Conclusions
3. Simulation results
Illustrative application to 5-MW reference turbine using FASTv8

- Disturbance and control inputs
3. Simulation results
Illustrative application to 5-MW reference turbine using FASTv8

- Measurement outputs/observations

![Graphs of Nacelle fore-aft acceleration and Generator speed with Standard and Extended instrumentation for 1st and 3rd blade-root moment.]
3. Simulation results
Illustrative application to 5-MW reference turbine using FASTv8

- Unknown wind speed and dynamic state estimation (Standard vs. Extended)

Wind speed

Drive-train torsion

Nacelle fore-aft position

Blade tip deflection
Outline

1. Model analysis
2. State estimation
3. Simulation results
4. Conclusions
4. Conclusions

Central statements

• Sigma-point Kalman filters are fast, low-cost and powerful estimators (in contrast to error-prone and expensive load sensors)

• **Real-time** study shows feasibility in principle.

• **Distributed architecture** is preferable rather than a monolithic one.

• For basic estimation tasks the **standard instrumentation** is sufficient.

• Additional out-of-plane **blade-root measurements** increase estimate’s accuracy of blade dynamic response and certain related parameters.
4. Conclusions

Next steps

→ Incorporate filter adaptation rules to improve performance in the field

→ Explicit consideration of state and parameter constraints (i.e. by a moving horizon approach)

→ Field testing with real measurement data

Take-home messages

→ Nonlinear state estimation techniques are ready to use.

→ Since complete state information is on hand, advanced controllers with state-feedback are the right choice for future wind turbine control systems.
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