Wind Turbine Model and Observer in Takagi-Sugeno Model Structure

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Outline

1. Motivation

2. Wind Turbine Model

3. Takagi-Sugeno (TS) Model Structure

4. TS Observer for Wind Speed Estimation

5. Simulation Results

6. Conclusion and Outlook
1. Motivation

- The Takagi-Sugeno (TS) model structure provides a useful and uniform framework for nonlinear control design.
- TS models are weighted combinations of linear submodels.
- TS models are an ideal starting point for fault-tolerant control (FTC) concepts.
- A Reliable Wind Speed Estimate is important for FTC schemes.
1. Motivation

• Other methods for wind speed estimation have been applied in the literature (Kalman filter, extended Kalman filter, Newton-Raphson method)

• Advantages of a TS observer:

  → can be designed for the whole operating range of a wind turbine (nonlinear)

  → Methods based on solving linear matrix inequalities (LMIs) allow for implicit stable controller/observer design
2. Wind Turbine Model

Only drivetrain dynamics included

\[ \dot{\theta}_s = \omega_r - \omega_g \]
\[ \dot{\omega}_r = -\frac{1}{J_r} \left( d_S (\omega_r - \omega_g) + k_S \theta_s \right) + \frac{1}{J_r} T_a \]
\[ \dot{\omega}_g = \frac{1}{J_g} \left( d_S (\omega_r - \omega_g) + k_S \theta_s \right) - \frac{1}{J_g} T_g \]

\( \theta_s \) \hspace{1cm} \text{Torsion angle}
\( \omega_r, \omega_g \) \hspace{1cm} \text{Rotor/generator speed}
\( k_S, d_S \) \hspace{1cm} \text{Torsional stiffness/damping}
\( J_r, J_g \) \hspace{1cm} \text{Rotor/generator inertia}
\( T_a, T_g \) \hspace{1cm} \text{Generator torque}

Aerodynamic rotor torque \( T_a = \frac{\rho \pi R^3}{2} C_Q(\lambda, \beta) v^2 \)

Wind model \( \dot{v} = -\frac{1}{\tau_v} (v - \bar{v}) \)

\( \tau_v \) \hspace{1cm} \text{Delay time constant}
\( \bar{v} \) \hspace{1cm} \text{Mean wind speed}

\( \dot{v} \) \hspace{1cm} \text{Needed for observer}

Different model configurations were tested for the observer design (including also tower and blade degrees of freedom). The above model proved to be suitable for the reconstruction of the wind speed.
2. Wind Turbine Model

System of dynamic equations ...

\[
\begin{align*}
\dot{\theta}_s &= \omega_r - \omega_g \\
\dot{\omega}_r &= -\frac{1}{J_r} \left( d_S (\omega_r - \omega_g) + k_S \theta_s \right) + \frac{1}{J_r} T_a \\
\dot{\omega}_g &= \frac{1}{J_g} \left( d_S (\omega_r - \omega_g) + k_S \theta_s \right) - \frac{1}{J_g} T_g
\end{align*}
\]

... can be written in state-space form

\[
\dot{x} = Ax + Bu + g(x, v)
\]

with a nonlinear system vector

\[
g(x, v) = \begin{pmatrix} 0 \\ \frac{1}{J_r} T_a (x, v) \\ 0_{2 \times 1} \end{pmatrix}
\]

will be written as

\[
\dot{x} = \sum_{i=1}^{N_r} h_i(z) \left( A_i x + B_i u \right)
\]

Weighted combination of linear submodels

\[\Rightarrow\text{This is a Takagi-Sugeno (TS) model}\]
3. Takagi-Sugeno (TS) Model Structure

**TS model: Weighted combination of linear submodels**

\[
\dot{x} = \sum_{i=1}^{N_r} h_i(z) \left( A_i x + B_i u \right), \quad y = \sum_{i=1}^{N_r} h_i(z) C_i x \quad / \quad y = Cx
\]

**TS model can be derived from the nonlinear model using**

- Local Taylor linearisation and fuzzy blending of linear submodels

- **Sector nonlinearity approach** \(\rightarrow\) yields exact representation of nonlinear model [5]
3. Takagi-Sugeno (TS) Model Structure

Illustrating Example for a TS model using sector nonlinearities

Pendulum
\[ \ddot{\varphi} = -\frac{g}{l} \sin \varphi + \frac{1}{ml^2} M \]
\[ \mathbf{x} = (\varphi \quad \dot{\varphi})^T \quad u = M \]

State-space form
\[ \dot{\mathbf{x}} = \begin{pmatrix} 0 & 1 \\ -\frac{g}{l} \frac{\sin x_1}{x_1} & 0 \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ \frac{1}{ml^2} \end{pmatrix} u = A(\mathbf{x}) \mathbf{x} + B u \]

Nonlinear function
\[ f(x_1) = -\frac{g}{l} \frac{\sin x_1}{x_1} = w_1(x_1) \bar{f} + w_2(x_1) \underline{f} \]
\[ \bar{f}, \underline{f} : \text{max/min values of } f \]

Sector functions
\[ w_1(x_1) := \frac{f(x_1) - \underline{f}}{\bar{f} - \underline{f}} \quad w_2(x_1) := \frac{\bar{f} - f(x_1)}{\bar{f} - \underline{f}} \]
3. Takagi-Sugeno (TS) Model Structure

Nonlinear system matrix can be written as

\[
\begin{pmatrix}
0 & 1 \\
-g \frac{\sin x_1}{x_1} & 0
\end{pmatrix}
= \begin{pmatrix}
0 & w_1 + w_2 \\
w_1 f + w_2 f & 0
\end{pmatrix}
\]

\[
= w_1 \begin{pmatrix}
0 & 1 \\
f & 0
\end{pmatrix} + w_2 \begin{pmatrix}
0 & 1 \\
0 & 0
\end{pmatrix}
= w_1 A_1 + w_2 A_2
\]

and the whole state-space model as

\[
\dot{x} = \begin{pmatrix}
0 & 1 \\
-g \frac{\sin x_1}{x_1} & 0
\end{pmatrix} x + \begin{pmatrix}
0 \\
1/m t^2
\end{pmatrix} u = \sum_{i=1}^{N_r=2} w_i (x_1) (A_i x + B u)
\]

The Nonlinearity has been shifted from the system matrix to the membership functions.
4. TS Observer for Wind Speed Estimation

Effective wind speed

Virtual single point wind speed signal that causes the same variations in the aerodynamic rotor torque as the corresponding 3D turbulent wind field [4]

Luenberg Observer (linear)

\[ \dot{x} = A\hat{x} + Bu + L(y - \hat{y}) , \quad \hat{y} = Cx \]

cannot be used in the whole (nonlinear) operating range of a wind turbine.

Instead, a TS observer is used:

\[ \dot{x} = \sum_{i=1}^{N_r=2} h_i(z) (A_i\hat{x} + Bu + L_i(y - \hat{y})) , \quad \hat{y} = Cx \]
4. TS Observer for Wind Speed Estimation

TS observer obtained using the sector nonlinearity approach

\[
\dot{\hat{x}} = \sum_{i=1}^{N_r=2} h_i(\hat{z}) (A_i \hat{x} + B u + L_i (y - \hat{y})) , \quad \hat{y} = C \hat{x}
\]

Membership functions

\[
h_1(\hat{z}) = \frac{f(\hat{x}, \beta) - \underline{f}}{\overline{f} - \underline{f}} \quad h_2(\hat{z}) = \frac{\overline{f} - f(\hat{x}, \beta)}{\overline{f} - \underline{f}}
\]

Nonlinear function

\[
f(\hat{x}, \beta) = \frac{1}{2J_r} \rho \pi R^3 \hat{v} C_Q \left( \hat{\lambda}, \beta \right)
\]

Estimated state vector

\[
\hat{x} = \left( \hat{\theta}_s, \hat{\omega}_r, \hat{\omega}_g, \hat{v} \right)^T
\]

Measurable states: \( \theta_s, \omega_r, \omega_g \) \quad Premise variables \( \hat{z} = (\hat{\omega}_r, \hat{v}, \beta)^T \)

The observer gain matrices \( L_i \) are determined using an LMI-based design approach [5,6]

(LMI: Linear Matrix Inequality)
5. Simulation Results


1. IEC wind gust

Blue: Output from FAST; Red: Estimated states
5. Simulation Results


2. Turbulent wind

Blue: Output from FAST; Red: Estimated states

The FAST output wind speed signal is not the effective wind speed!
6. Conclusion and Outlook

• A nonlinear observer in Takagi-Sugeno structure was designed to estimate the effective wind speed

• The observer shows a stable behaviour in FAST simulations, although formal stability using LMI conditions could not be obtained.

• The TS observer is intended to be part of a fault-tolerant control scheme for wind turbines in future work
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