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Effective wind speed estimation: Comparison between Kalman Filter and Takagi–Sugeno observer techniques

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ABSTRACT

Advanced model-based control of wind turbines requires knowledge of the states and the wind speed. This paper benchmarks a nonlinear Takagi–Sugeno observer for wind speed estimation with enhanced Kalman Filter techniques: The performance and robustness towards model-structure uncertainties of the Takagi–Sugeno observer, a Linear, Extended and Unscented Kalman Filter are assessed. Hence the Takagi–Sugeno observer and enhanced Kalman Filter techniques are compared based on reduced-order models of a reference wind turbine with different modelling details. The objective is the systematic comparison with different design assumptions and requirements and the numerical evaluation of the reconstruction quality of the wind speed. Exemplified by a feedforward loop employing the reconstructed wind speed, the benefit of wind speed estimation within wind turbine control is illustrated.

1. Introduction

The worldwide installed wind turbine (WT) capacity increased up to 336 GW rated power until 2014 and grew with an annual rate of 5–10% since 2010 [24]. Nowadays WT with rated power up to 7.5 MW (ENERCON E126) and the maximum rotor diameter up to 171 m (SAMSUNG SHI 7MW) are available and on test, respectively.

To continue or even enlarge this market development, the cost of energy has to be reduced, e.g. by advanced control strategies like predictive or feedforward WT control [23]. Conventional WT control is based on rotational speed measurement with control signal feedback for gain scheduling [4,23,27]. This control strategy leads to high time constants resulting from drive train inertia causing elevated output signal (i.e. rotational speed) and dynamic loads (i.e. rotor thrust force). Therefore more advanced approaches use observers, like Linear Kalman or Extended Kalman Filter ([20,6] and [3], respectively) to reconstruct the *rotor effective free wind speed* from other measured variables lowering these time constants.

Within this paper the recently proposed [12,9] *Takagi–Sugeno (TS) observer* according to [31] is introduced as an alternative observer method to Kalman Filter techniques, because the TS method is more powerful, e.g. in terms of the integration of nonlinear characteristic maps, like the aero maps of wind turbine rotors.

To benchmark the proposed TS method for rotor effective mean wind speed reconstruction, the *reconstruction performance* and its *relative robustness* is analysed.

The *relative robustness* towards model structure uncertainties is assessed by comparing the TS observer reconstruction results with the results, achieved with a Linear, Extended and Unscented Kalman Filter. So within this paper the term *relative robustness* is used as a *performance criterion*, implying the *robustness towards stability*.

As the model structure uncertainties result from dynamic effects of the real wind turbine not considered in the observer and filter design models, the reference WT is described with a simplified four degree of freedom (DOF) model. This model is used as the basis for the TS observer and enhanced Kalman Filter design models and denoted as *baseline model*.

As the performance of a TS steady-state-controller is not directly related to its model-structure accuracy, i.e. high model accuracy does not correlate with better controller performance as shown in [11], it is expected, that the TS observer wind speed reconstruction performance is not related proportional to its model-structure accuracy, too. Therefore different types of reduced TS observer and enhanced Kalman Filter design models

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are deduced from the WT baseline model, denoted as *reduced (design) models*.

To assess the *reconstruction performance* and the *relative robustness* of the observer and filter techniques, three major influences are investigated by systematic variations of the simulation models, comprising the WT plant model, a gain scheduling controller and the reduced design models of the TS observer and enhanced Kalman Filters:

- *Design model order* (*DMO*): The design models, used for the TS observer and Linear, Extended and Unscented Kalman Filter designs, are varied regarding the reduced number of DOF.
- *Measurement signals* (*MS*): The TS observer and enhanced Kalman Filter design models comprise different combinations of the measurement signals *rotor angular speed* ω_r, *generator speed* ω_g and *blade tip deflection* y_B.
- *Aero map accuracy* (*AMA*): For the characteristic curves and aerodynamic maps, respectively, comprising the inflow depending aerodynamic efficiency of the WT rotor, the influence of two aero map data sets with different levels of accuracy is analysed.

The simulations presented in this paper base on a four DOF simplification of the *NREL 5MW reference WT* description by [15].

In addition to the TS observer approach, Linear, Extended and Unscented Kalman Filter as well as other methods have been applied for wind speed estimation in the literature. In [33] the aerodynamic torque is reconstructed from the torque balance and afterwards the wind speed is estimated, employing a numerical solution based on the implicit stationary relationship between aerodynamic torque and wind speed.

In [22] a state-observer for the rotor speed is combined with a PI controller to estimate the aerodynamic rotor torque. The effective wind speed is then reconstructed from the estimated torque signal via inversion of the aerodynamic model. A recent brief overview and comparison of several techniques for wind speed estimation can be found in [26]. Besides a Linear and an Extended Kalman Filter, a power balance estimator, a dynamic average consensus (DAC) estimator, an unknown input observer (UIO) (see also [21]) and an immersion and invariance estimator (I&I) are compared. While being able to yield good wind speed estimates, these methods are either rather specialised (DAC and I&I) or have other detriments. In [25] the estimation of the aerodynamic torque instead of the effective wind speed estimation is proposed. The strategy uses a proportional multiple integral observer (PMIO), whereby the effect of generator and/or rotor sensor fault on the TS fuzzy dynamic output feedback controller is additionally compensated by a second PMIO.

The paper is structured as follows: In Section 2, the wind turbine model structure with different degrees of freedom for filter and observer design is introduced. In Section 3 an introduction of both approaches (enhanced Kalman Filter and Takagi–Sugeno observer techniques) for wind speed reconstruction is given and the similarities and differences are described. In Section 4 the different approaches for wind speed reconstruction are compared for a given deterministic wind speed signal to analyse the wind speed reconstruction performance and robustness of a TS observer compared to enhanced Kalman Filters. Hereinafter in Section 5 the effect of wind speed reconstruction is illustrated: Rotational speed and thrust force resulting from the conventional feedback controller approach are compared with the results achieved with a feedback controller supplemented with a feedforward controller loop employing the observer based wind speed reconstruction. Finally conclusion and outlook is given in Section 6 and the detailed simulation results are presented in Appendix A.

2. Wind turbine modelling for filter and observer design

Within this section the control-oriented model of a wind turbine (WT) is presented. Starting with the aerodynamics and the mechanical model, a generalised state-space model is deduced. Based on this, the analysed design models for the TS observer and the enhanced Kalman Filter as well as the simulation models are described.

2.1. Aerodynamic model

According to the *stream tube theory* the wind power P_w of a free air flow along the stream tube of radius R with a cross section averaged wind speed v, the so-called *effective* (*mean*) *wind speed*, and air density ρ is defined by

$$P_w = \tfrac{1}{2}\rho v^2 \pi R^2 v. \tag{1}$$

If a WT rotor with blade length R is placed inside the stream tube the power gained with the rotor P_r from the wind power P_w depends on the aerodynamic efficiency of the rotor, the so-called *power coefficient* C_P resulting in

$$P_r = \tfrac{1}{2}\rho v^2 \pi R^2 v C_P(\lambda,\beta), \tag{2}$$

where v denotes the undisturbed and free, respectively wind speed v far in front of the WT, the so-called *rotor effective* (*free mean*) *wind speed*, β denotes the pitch angle and λ the *tip speed ratio*

$$\lambda = \frac{\omega_r R}{v} \tag{3}$$

with the angular rotor velocity ω_r. From the rotor power $P_r = T_r\omega_r$ also the rotor torque T_r can be deduced

$$T_r = \tfrac{1}{2}\rho v^2 \pi R^2 R C_Q(\lambda,\beta) \tag{4}$$

with the so-called *torque coefficient* $C_Q(\lambda,\beta) = \frac{C_P(\lambda,\beta)}{\lambda}$. Analogously to (4) the thrust force F_t with the *thrust coefficient* $C_T(\lambda,\beta)$ is defined as follows (see [8]):

$$F_t = \tfrac{1}{2}\rho v^2 \pi R^2 C_T(\lambda,\beta) \tag{5}$$

Within this paper two descriptions of the nonlinear dependency of the power coefficient $C_P(\lambda,\beta)$ and thrust coefficient $C_T(\lambda,\beta)$ for the same rotor of the reference wind turbine are used: tabulated values of high accuracy and an analytical approximation of these tabulated values (see [13]). A comparison of the tabulated and analytical aero map for the NREL 5MW reference wind turbine is shown in Fig. 1, illustrating the relative error, which is up to 35% (in full-load region).

Note: With the help of the aero maps the rotor torque T_r and thrust force F_t can be calculated analytically according to (4) and (5) for all current operational states.

2.2. Mechanical model

In this paper a WT model with four degrees of freedom (4-DOF) is used as *baseline model*. Hereby the tower top deflection, the drive train rotation and especially the blade tip deflection are assumed to be sensitive to wind speed variations.

Therefore the DOF of the model are the collective horizontal tip displacements of the rotor blade tips (in wind direction) y_B, the displacement of tower top in wind direction denoted with y_T and the rotor and generator rotational angle θ_r and θ_g. The drive train is modelled by two rigid bodies joined with a torsionally elastic coupling, as described in [2,13].

The equations of motion of the four DOF WT model yields four coupled differential equations (see [12]). The coupled differential equations are nonlinear, as the excitations resulting from thrust force F_t and rotor torque T_r depend nonlinearly from the wind

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