ARTICLE IN PRESS
JID: JARAP [m5G;October 16, 2015;18:6]

Annual Reviews in Control 000 (2015) 1–11

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Fault-tolerant control of wind turbines with hydrostatic transmission using Takagi–Sugeno and sliding mode techniques☆

Horst Schulte*, Eckhard Gauterin

HTW University of Applied Sciences Berlin, Department of Engineering I, Control Engineering Group, Wilhelminenhofstr. 75a, Berlin D-12459, Germany

ARTICLE INFO

Article history:
Received 15 June 2015
Accepted 2 August 2015
Available online xxx

Keywords:
Wind turbine control
Fault tolerant Control
Sliding-mode observer
Takagi–Sugeno systems

ABSTRACT

In this paper, a Takagi–Sugeno Sliding Mode Observer for actuator fault diagnosis and fault-tolerant control scheme of wind turbines with hydrostatic transmission are presented. It will be shown that sliding mode techniques have the advantages that several actuator faults of the wind turbine drive train can be simultaneously reconstructed with one and the same observer and directly applied for fault compensation. Furthermore, a simple compensation approach is implemented by subtracting the reconstructed faults obtained from the (faulty) inputs. These corrected inputs act on the system as virtual actuators, such that the originally designed controller for the nominal, i.e. fault-free situation, can still be used. The fault reconstruction and fault tolerant control strategy are tested in simulations with several faults of different types.

1. Introduction

Wind turbines with hydrostatic transmission are not yet available in commercial systems. Only recently, however, this drive train concept has been considered as an alternative to conventional wind turbines. There are several reasons for this: firstly over the rated power range between 1.5 and 10 MW, the existing gear-less direct-drive concepts cause an increase of weight around 25 percent and a cost increase of around 30 percent (Ragheb & Ragheb, 2010). Secondly, the conventional gearboxes of modern wind turbines at the Mega-Watt (MW) level of rated power are highly stressed by different load cases, where wind gusts and turbulence lead to misalignment of the drive train and a gradual failure of the gear components. This failure interval creates a significant increase in the capital and operating costs and downtime of a turbine, while greatly reducing its profitability and reliability (Ragheb & Ragheb, 2010).

In contrast, hydrostatic transmission allows mechanically decoupled operation of wind turbine rotor and generator over a wider range of wind speeds without the need of mechanical gearboxes and frequency converters. It permits the use of synchronous generators with low numbers of poles, which are cheaper than double fed induction generator for indirect drive (with gearbox) and multi-pole synchronous generators for direct drive (without gearboxes). Both drive-train configurations are commonly used in variable speed machines today. Furthermore, as a consequence of the omission of power electronics, the use of synchronous generator with an electrical voltage up to a range of 10 kV eliminates the need for voltage transformer. According to the investigation in Diepeveen and Laguna (2011), hydrostatic transmission also have a positive impact on power quality, since small rotor speed fluctuations due to wind gusts are absorbed.

Up to now, hydraulic transmissions are mainly used in construction and agricultural equipment. For these kinds of applications, condition monitoring, fault diagnosis and maintenance are easy to perform. However, for a reliable operation of hydrostatic transmission in wind turbines, fault diagnosis and fault tolerant control are indispensable especially for offshore applications. Only a few model-based fault-tolerant control approaches exist for wind turbines with conventional drive-trains. In Sloth, Esbensen, and Stoustrup (2011), passive and active fault-tolerant controllers are designed and considered with regard to accommodating altered actuator dynamics in the pitch system model. In Odgaard and Stoustrup (2012), a bank of unknown-input observers is used for fault diagnosis in the rotor and generator speed sensors of the fault detection isolation (FDI) benchmark model presented in Odgaard, Stoustrup, and Kinnaert (2009). In Sami and Patton (2012b), Sami and Patton (2014) active fault-tolerant control is achieved in the partial-load region of wind turbines by means of a sensor fault hiding approach. The fault-tolerant control (FTC) strategy uses a multiple integral observer and a fast adaptive fuzzy estimator, where the observer designs are based on a nonlinear Takagi–Sugeno (TS) model. In Sami and Patton (2012a), a passive sensor fault-tolerant control strategy is implemented using a sliding mode controller for the partial-load region that tolerates generator speed sensor faults and generator torque offset faults. In Rotondo, Puig, Valle, and Nejjari (2013), an FTC strategy using Linear Parameter Varying (LPV) virtual

☆ A shorter version of this paper was presented at the 19th IFAC World Congress, Cape Town, South Africa, August 24-29, 2014

* Corresponding author.
E-mail addresses: horst.schulte@htw-berlin.de (H. Schulte), eckhard.gauterin@htw-berlin.de (E. Gauterin).

http://dx.doi.org/10.1016/j.arcontrol.2015.08.003
1367-5788/

Please cite this article as: H. Schulte, E. Gauterin, Fault-tolerant control of wind turbines with hydrostatic transmission using Takagi–Sugeno and sliding mode techniques, Annual Reviews in Control (2015), http://dx.doi.org/10.1016/j.arcontrol.2015.08.003

sensors is proposed and applied to the benchmark model (Odgaard et al., 2009). Instead of hiding the fault, the virtual sensor is used to expand the set of available sensors before the state observer is designed. In Simani and Castaldi (2014), an FTC scheme based on adaptive filters obtained via the nonlinear geometric approach is applied to the actuator of a wind turbine benchmark model. It is shown that the proposed approach allows us to obtain an interesting decoupling property with respect to uncertainty affecting the wind turbine system. A fuzzy modeling and identification method for fault detection and FTC is applied in Badihi, Zhang, and Hong (2014). The proposed fuzzy gain-scheduled fault-tolerant control system is evaluated by a series of simulations on a wind turbine benchmark in the presence different fault scenarios. In Badihi, Zhang, and Hong (2015), the method of Badihi et al. (2014) is compared with a fuzzy model-reference adaptive control in which a fuzzy inference mechanism is used for parameter adaptation without any explicit knowledge of the system faults. In Georg and Schulte (2013), a Takagi–Sugeno sliding mode observer (TS SMO) is used to reconstruct actuator and sensor faults in wind turbines with conventional drive train. Here, the proposed FTC strategy is based on the modification of the control inputs in the presence of actuator faults and on the active-fault compensation of the sensor output signal in the presence of sensor faults. Both strategies serve a behavior similar to the fault-free case.

In this paper, a TS SMO for actuator fault diagnosis and fault-tolerant control scheme for wind turbines with hydrostatic transmission is presented. It will be shown that TS SMO has the advantages that several faults in the two different actuators (hydraulic pump and hydraulic motor) of the wind turbine drive train can be reconstructed with one and the same observer and directly applied for fault compensation. In this work, a simple compensation approach is implemented by subtracting the reconstructed faults obtained from the (faulty) inputs. These corrected inputs act on the system as virtual actuators, such that the originally designed controller for the nominal, i.e. fault-free situation, can still be used.

This paper is organized as follows: Section 2 presents a control-oriented nominal model in Takagi–Sugeno form as an exact representation of a holistic nonlinear physical model of a horizontal axes wind turbine with hydrostatic transmission. A nominal controller strategy is proposed in Section 3. The objective is a fixed, wind speed independent rated speed of the synchronous generator. For this, the rotor/generator speed ratio is continuously adjusted by a variable-displacement hydraulic pump and motor. In Section 4, the observer-based method for fault diagnosis is described. In particular, the TS SMO structure and design for directly reconstruction of faults is briefly introduced. After, the fault tolerant control strategy for actuator faults are introduced and tested in simulations. Finally, a conclusion and an overlook on possible future work are given in Section 5.

2. Control-oriented modeling

In the following the operation principle of hydrostatic transmission in wind turbines is briefly described and a holistic control-oriented model of the overall system in Takagi–Sugeno's form is proposed. A detailed derivation of the wind turbine model using TS model structure is given in Georg, Schulte, and Aschemann (2012). The novel drive train concept is described and published in the recent work (Schulte, 2014). It must be pointed out, that the collective pitch angle is not considered as a control input, because the focus is on the fault tolerant speed control of the generator and the optimal control in the partial load, such that the rotor is constantly running around the optimal tip speed ratio. Nevertheless, the pitch angle in the control-oriented model may considered as a measurable premise variable for the transition between partial and full load range.

2.1. Wind turbine with hydrostatic transmission

In contrast to wind turbines with conventional drive trains, the inertia power in hydrostatic transmissions is transmitted by static oil pressure and flow rate. One advantage is that the transmission ratio between rotor and generator is continuously adjustable. The entire drive train consists of the low speed shaft (LSS), the high speed shaft (HSS) and the hydrostatic transmission line. In its simplest form, the hydrostatic transmission consists of a hydraulic pump and motor, of which at least one must have a variable displacement. A configuration with a variable pump and a variable motor is illustrated in Fig. 1. Other configurations are investigated in Skaare, Nielsen, and Hörnsten (2013), with a variable displacement pump and fixed motor and in Dolan and Aschemann (2012) with a fixed pump and a variable displacement motor.

On the transmission input side, the torque and speed of the rotor are converted by the hydraulic pump into a pressurized oil flow q_P. On the output side, the pressurized flow q_M is converted back into mechanical torque and speed by the hydraulic motor. By varying the displacement of the hydraulic components, any desired transmission ratio can be adjusted. This can be illustrated by the following considerations: The fluid flow q_P produced by the pump is proportional to its rotational speed n_P and depends on the variable volume of the pump per revolution. Indeed, the volume is not constant and proportional to the normalized position $\tilde{x}_P$ of the displacement unit

$$q_P = V_P\,\tilde{x}_P\,n_P \quad \text{with} \quad \tilde{x}_P = x_P/x_{P_{max}} \le 1 \tag{1}$$

where V_P is the maximum volumetric displacement per revolution of the pump. Similarly, the volume flow through the hydraulic motor is given by

$$q_M = V_M\,\tilde{x}_M\,n_M \quad \text{with} \quad \tilde{x}_M = x_M/x_{M_{max}} \le 1 \tag{2}$$

where $\tilde{x}_M$ denotes the normalized position of the displacement unit, and n_M the rotational speed of the motor shaft. Fig. 1 shows that the pump feeds directly the motor. Neglecting the compressibility of the fluid and hydrostatic losses it holds that $q_P = q_M$ and with (1), (2) we obtain

$$r_{cv}(\tilde{x}_P, \tilde{x}_M) = \frac{n_M}{n_P} = \frac{V_P}{V_M}\,\frac{\tilde{x}_P}{\tilde{x}_M}\,. \tag{3}$$

That is, the continuously variable transmission ratio r_{cv} depends on the constant ratio $\frac{V_P}{V_M}$ of the maximum volumetric displacement of the pump/motor combination and the adjustable ratio of the position $\tilde{x}_P$ and $\tilde{x}_M$. Thereby the maximum transmission ratio $r_{cv,\,max}$ results from maximum normalized position of the pump displacement $\tilde{x}_P = 1$ and the minimum normalized position of the motor displacement with $\tilde{x}_M \ll 1$.

The necessary high transmission ratio for wind turbines of the Megawatt class up to 2.5 MW can easily be reached by a suitably large ratio of the maximum volumetric displacements V_P/V_M. By taking advantage of the second adjustable term $\tilde{x}_P/\tilde{x}_M$, the transmission ratio can be varied in such a way that the generator operates at constant speed directly connected to the electric grid.

2.2. Takagi–Sugeno model representation

In the next step a Takagi–Sugeno model of the entire wind turbine system will be derived using the sub-models of the wind turbine mechanics (Georg et al., 2012), the hydrostatic transmission (Schulte & Gerland, 2010), the aero map C_Q for rotor torque calculation T_r and the reduced model of the hydraulic pump and motor with a first order delay model of the displacement units. The nonlinear state space model of a wind turbine with hydrostatic transmission is thus given by

$$\dot{\omega}_r = \frac{1}{J_r}\Big(T_r(\lambda, \beta) - \tilde{V}_P\,\tilde{x}_P\,\Delta p\,\Big)$$