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Active sensor fault tolerant output feedback tracking control for wind turbine systems via T–S model

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ABSTRACT

This paper presents a new approach to active sensor fault tolerant tracking control (FTTC) for offshore wind turbine (OWT) described via Takagi–Sugeno (T–S) multiple models. The FTTC strategy is designed in such way that aims to maintain nominal wind turbine controller without any change in both fault and fault-free cases. This is achieved by inserting T–S proportional state estimators augmented with proportional and integral feedback (PPI) fault estimators to be capable to estimate different generators and rotor speed sensors fault for compensation purposes. Due to the dependency of the FTTC strategy on the fault estimation the designed observer has the capability to estimate a wide range of time varying fault signals. Moreover, the robustness of the observer against the difference between the anemometer wind speed measurement and the immeasurable effective wind speed signal has been taken into account. The corrected measurements fed to a T–S fuzzy dynamic output feedback controller (TSDOFC) designed to track the desired trajectory. The stability proof with H_∞ performance and D-stability constraints is formulated as a Linear Matrix Inequality (LMI) problem. The strategy is illustrated using a non-linear benchmark system model of a wind turbine offered within a competition led by the companies Mathworks and KK-Electronic.

1. Introduction

Owing to inherent limitations in different kinds of the well-known fossil fuel and nuclear energy sources, e.g. carbon footprint, rapidly increasing fuel prices or probability of catastrophic effects of nuclear station malfunction, the last two decades have witnessed a rapid growth in the use of wind energy. Although, it is considered a promising source of energy, depending on naturally generated wind forces, there are several very significant challenges to efficient wind energy conversion for electrical power transformation (Marden et al., 2013; Odgaard et al., 2013).

Wind turbine systems demand a high degree of reliability and availability (sustainability) and at the same time are characterised by expensive and safety critical maintenance work (Verbruggen, 2003). The recently developed OWTs are foremost examples since OWT site accessibility and system availability are not always ensured during or soon after malfunctions, primarily due to changing weather conditions. Hence, the main challenges for the deployment of wind turbine systems are to maximise the amount of good quality electrical power extracted from wind energy over a significantly wide range of weather conditions and minimise both manufacturing and maintenance costs. To maximise the amount of the annual power production an increase in wind turbine size has been suggested, another opportunity is the development of a variable speed wind turbine which enhances both quality and the amount of the power production compared with the fixed speed wind turbines (Bianchi et al., 2007). Furthermore, to reduce the effects of obstacles and roughness of terrain that increase wind force turbulence, OWTs are currently being developed and installed (Stewart and Lackner, 2013).

In the last years, a number of publications consider the effect of wind turbines malfunction is noticed with focusing on designing fault tolerant control (FTC) (Sloth et al., 2011; Kamal et al., 2012; Sami and Patton, 2012b, 2012a; Badihi et al., 2013; Jain et al., 2013; Odgaard et al., 2013; Simani and Castaldi, 2013, 2014) and fault monitoring systems (Amirat et al., 2009; Hameed et al., 2009; Wei and Liu, 2010; Johnson and Fleming, 2011; Djurovic et al., 2012). In Sloth et al. (2011), the authors proposed linear parameter-varying FTC systems for pitch actuator faults occurring in the full load operation. In Kamal et al. (2012) a T–S fuzzy observer-based FTC design is proposed to achieve maximisation of the power extraction in the presence of generator sensor fault without taking into account the trade-off between the tracking of the optimal signal and the loads induced in the drive train due to exact tracking of optimal signal. Jain et al. (2013) present a real-time projection-

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based approach to tolerate faults occurring in a wind turbine system. In Sami and Patton (2012b, 2012a) the robustness of sliding mode control have been utilised to design FTC for OWT. Badihi et al. (2013)) present an approach for designing a fault detection and diagnosis (FDD) and FTC scheme for a wind turbine using fuzzy modelling and control. Simani and Castaldi (2014) proposed a fault tolerant controller to accommodate actuator fault using the on-line fault estimate signal generated by an adaptive filter. The fuzzy approach to wind turbine controller design in the presence of modelling and measurement errors has also been proposed in Simani and Castaldi (2013).

Generally, wind turbines have non-linear aerodynamics and this limits the use of a linear systems approach without due care to robustness issues. Furthermore, wind turbines have a stochastic and uncontrollable driving force as input in the form of wind speed. This, together with overall system nonlinearity limits the ability of linear control strategies to satisfy the control objectives. Hence, an increase in interest in controlling wind turbines through nonlinear control methods has been noticed in the last years to handle the nonlinearity of the turbine aerodynamics. This is achieved either through the use of nonlinear models directly in the design (Sami and Patton, 2012b, 2012a) or through the use of multiple-model approaches (Sloth et al., 2011; Kamal et al., 2012; Badihi et al., 2013).

This paper focuses on the design of FTTC dedicated to optimise the captured wind energy. Based on the wind turbine T–S fuzzy model, a TSDOFC is designed to achieve the required tracking of the optimal rotor speed ($\omega_{r\ opt}$) and the reduction of loads affecting the drive-train through minimising the L_2 norm of the wind variation on the torsion angle of the drive train. The FTTC is achieved by hiding the effects of different generators and rotor sensors fault from the controller inputs through the insertion of the PPI observer (PPIO) capable of handling the case of time-varying fault signals. The proposed strategy overcomes the dependence and limitation of requiring full state measurements. The technique also focuses on minimising the difficulties of designing observer based control systems that require special pole placement conditions since these conditions cannot hold perfectly in the multiple model framework due to global stability constraints. The design also locates the controller and observer poles of each T–S model system to lie within a disc region of the complex plane. Finally, the design is formulated as a linear matrix inequality problem that can be solved easily using MATLAB software. The simulation results are based using a non-linear benchmark system model of a wind turbine offered within a competition led by the companies Mathworks and KK-Electronic (Odgaard et al., 2009, 2013).

2. The proposed active FTTC

Generally, active FTC (AFTC) systems are designed to handle the occurrence of system faults on-line by using fault estimation/compensation methods, adaptive control or controller reconfiguration mechanisms. All AFTC methods involve some advantages and disadvantages. The operation philosophy of adaptive control fits very well with the AFTC approach. This is due to the ability of adaptive control systems to adjust controller parameters on-line based on measured signals. Clearly, the use of adaptive control methods as an approach to AFTC obviates the need for fault detection and diagnosis (FDD) unit. However, in this method, sensor faults represent the most challenging fault scenario for AFTC and have rarely been considered in fault tolerant adaptive control methods. For example, output feedback adaptive tracking control can tolerate actuator and/or system faults, whereas, if sensor faults have occurred the adaptation will force the faulty output to follow the reference signals and hence the control signal will no longer be suitable for the system under control. The controller reconfiguration approach can handle more general faults and/or failure cases through either off-line or on-line variation of the structure and/or the parameters of the controller based on the information delivered from an FDD unit. However, the main challenge of this method is that the time required to reconfigure the control system must be as low as possible. In fact, this is very important in practice where the time windows during which the system remains stabilisable in the presence of a fault are very short. This is especially the case for unstable open-loop systems, e.g. the unstable double inverted pendulum example (Niemann and Stoustrup, 2005). On the other hand, as an extension to the use of FDD base control reconfiguration, the estimation and compensation approach to FTC is based on the computation of fault estimates and a mechanism to compensate these fault effects by the addition of a new compensating signal to the nominal control input or faulty measured output. Clearly, this approach obviates the need for residual evaluation and parameter identification steps that are required for FDD based FTC and hence requires no time consuming algorithms for maintaining the performance of the nominal system control law. Moreover, the inability of the adaptive control-based FTC to tolerate sensor faults means that fault estimation and compensation represents the all round most appropriate method for the sensor fault case of FTC.

Within the framework of estimation and compensation, this section presents the structure of the proposed FTTC strategy for OWT control problems based on robust fault estimation and compensation of rotor rotational speed sensor faults $\hat{f}_{sr}$ and/or generator rotational speed sensor faults $\hat{f}_{sg}$ whilst maintaining the performance and stability of the nominal control system during both faulty and fault-free cases. It is clear from the architecture shown in Fig. 1, the proposed FTTC scheme is based on the combination of (a) robust TSDOFC and (b) estimates of the $\hat{f}_{sr}$ and/or $\hat{f}_{sg}$ via the T–S fuzzy PPIO. This strategy can be considered as a "fault-hiding" approach to FTC where the main aim of fault-hiding is to maintain the same controller in both faulty and fault-free system cases. Specifically, the T–S fuzzy PPIO will hide sensor faults through fault estimation and compensation so that the TSDOFC always receives the fault free measurements.

It should be noted that the T–S fuzzy model consists of local linear input–output relations of the nonlinear system. The overall fuzzy model is achieved by connecting the local linear models by membership functions yielding the global model of the system. It is important to note that a T–S fuzzy controller is a model-based control approach. The procedure of designing T–S fuzzy controller and/or T–S fuzzy observer should start from deriving the T–S fuzzy model. Hence, the next section presents the nonlinear model of the wind turbine and the derivation of its corresponding T–S model.

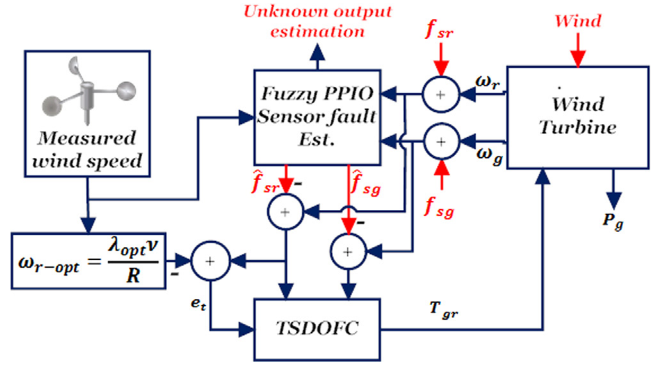

Fig. 1. Active sensor FTTC scheme.