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Fault tolerant control of a simulated hydroelectric system ☆

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ABSTRACT

This paper analyses the application of two fault tolerant control schemes to a hydroelectric model developed in the Matlab and Simulink environments. The proposed fault tolerant controllers are exploited for regulating the speed of the Francis turbine included in the hydraulic system. The nonlinear behaviour of the hydraulic turbine and the inelastic water hammer effects are taken into account in order to develop a high-fidelity simulator of this dynamic plant. The first fault tolerant control solution relies on an adaptive control design, which exploits the recursive identification of a linear parametric time-varying model of the monitored system. The second scheme proposed uses the identification of a fuzzy model that is exploited for the reconstruction of the fault affecting the system under diagnosis. In this way, the fault estimation and its accommodation is possible. Note that these strategies, which are both based on identification approaches, are suggested for enhancing the application of the suggested fault tolerant control methodologies. These characteristics of the study represent key issues when on-line implementations are considered for a viable application of the proposed fault tolerant control schemes. The faults considered in this paper affect the electric servomotor used as a governor, the hydraulic turbine speed sensor, and the hydraulic turbine system, and are imposed both separately and simultaneously. Moreover, the complete drop of the rotational speed sensor is also analysed. Monte-Carlo simulations are also used for analysing the most important issues of the proposed schemes in the presence of parameter variations. Moreover, the performances achieved by means of the proposed solutions are compared to those of a standard PID controller already developed for the considered model. Finally, these strategies serve to highlight the potential application of the proposed control strategies to real hydraulic systems.

1. Introduction

Modern technological and technical processes are based on complex control systems that are designed to meet advanced performance and safety requirements. Conventional feedback control solutions may lead to unsatisfactory performances, or even to instability, when possible malfunctions in actuators, sensors or other system components are present. To overcome these problems, new strategies to control system design have been proposed in order to manage actuator, sensor and component faults, while maintaining desirable stability and performance properties. This class of control design is also known as Fault Tolerant Control (FTC) systems, which have the capability to accommodate the faults in an automatic way. The closed-loop control system is thus able to manage any malfunctions, while maintaining good control properties. The FTC system is based on adaptive strategies or active Fault Detection and Diagnosis (FDD) scheme, *i.e.* when the fault function is estimated and compensated. Regarding the latest issue, many FDD techniques have been developed, see for example the survey works (Chen & Patton, 1999; Ding, 2008).

In general, FTC solutions are divided into two strategies, namely Passive Fault Tolerant Control Scheme (PFTCS) and Active Fault Tolerant Control Scheme (AFTCS), as addressed *e.g.* in Blanke, Kinnaert, Lunze, and Staroswiecki (2006), Zhang and Jiang (2008), and Noura, Theilliol, Ponsart, and Chamseddine (2009). On one hand, in the case of PFTCS, the designed controllers are defined and designed to be robust with respect to a specific set of presumed faults. This scheme uses neither FDD methods nor controller reconfiguration, but it presents limited fault tolerant features (Zhang & Jiang, 2008). On the other hand, AFTCS reacts actively to the system fault by using a control accommodation approach, so that the stability and the final performance of the entire system are maintained. Concerning AFTCS, it was remarked that robust and reliable FDD are required (Chen & Patton, 1999; Ding, 2008).

FTC solutions can derive from the application of model-based and model-free designs, as described *e.g.* in Blanke et al. (2006)

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and Zhang and Jiang (2008). Different FTC methods have been addressed in the recent related literature. For example, Kim and Kim (2015) proposed stochastic petri nets exploited for designing process control system of a continuous casting plant. The work of Schuh, Zgorzelski, and Lunze (2015) presented deterministic input/output automata applied to a handling system. The paper by Fonod et al. (2015) developed a control system to detect, isolate and accommodate single faults affecting the thruster-based propulsion system of an autonomous spacecraft. Ubaid, Daley, and Pope (2015) described a control design procedure through its application to a laboratory scale slab floor. The study of Li, Liu, and Cao (2015) presented a robust H_∞ approach used to solve an optimal state-feedback-type controller parameter design for a HVDC/AC system. The paper by Kiltz, Join, Mboup, and Rudolph (2014) introduced a method based on algebraic derivative estimation that is applied on an example of electromagnetically supported plate. Finally, the work of Blesa, Rotondo, Puig, and Nejjari (2014) used interval observers oriented to the design of virtual sensors/actuators for wind turbines.

On the other hand, few works analysed the model-based fault tolerant control problem when applied to hydroelectric plants, as described in Hong, Guangda, and Weiyou (2008), Li et al. (1992), and Wei, Wei-bo, Gen-mao, and Jian-hua (2000). In fact, as a mathematical model is needed for the description of the system behaviour, precise modelling for these processes could be difficult to achieve in practice. There are several works that discuss the modelling of hydroelectric processes with their controller design, as in Mansoor, Jones, Bradley, Aris, and Jones (2000) and Weber, Prillwitz, Hladky, and Asal (2001). These works consider the elastic water effects, though the nonlinear dynamics are linearised at an operating point. Other papers (Eker, 2004; Hanmandlu & Goyal, 2008; Kishor, Saini, & Singh, 2007) considered different mathematical descriptions with the techniques to control the power systems. Moreover, linear and nonlinear plants with various water column effects and control solutions are also considered. Mahmoud, Dutton, and Denman (2005) and Kishor, Singh, and Raghuvanshi (2006) addressed complex control solutions for hydraulic processes.

In some cases, it could be impossible to describe the nonlinear systems in an analytical way; moreover, the system structure with its parameters and measurements can be almost unknown. Therefore, parametric model estimation can represent an alternative solution for deriving practical models of nonlinear dynamic processes systems for control design. Moreover, if nonlinear identification methods require a detailed knowledge of the model structure, fuzzy systems and neural networks can be obtained directly from measured data (Alvisi & Franchini, 2012; Asgari, Venturini, Chen, & Sainudiin, 2014; Nelles, 2001).

This paper proposes two fault-tolerant control approaches for the adjustment of a hydraulic turbine developed in the Matlab® and Simulink® environments. The development of the suggested solutions is particularly important from a practical point of view. In fact, the variable demand for electricity and changing conditions in the power system can lead to different demand of peak energy generation, with short response time and fast frequency changes. Hydroelectric power systems thus require to operate taking into account different variable load and demand conditions. In general, the operation of hydropower systems can frequently experience variations in the flow in both routine operations and abnormal conditions. In particular, turbine operations such as start-up, load acceptance, load rejection and shutdown can lead to hydraulic transients that can generate large pressure and sub-pressure oscillations, which must be carefully evaluated to avoid mechanical failures in the hydraulic systems. Therefore, the need for accurate simulation of transient flow in hydroelectric power plants is obvious. However, even if the basic technology in a hydraulic process has not changed much, powerful computers and software now can be used to provide virtual models and simulators of hydropower systems.

Therefore, this work proposes a first methodology based on the fuzzy theory, as it represents a suitable method to manage almost unknown situations and uncertain measurements (Babuška, 1998). In this way, instead of using purely nonlinear analytical description obtained via the first principle modelling approach, the paper proposes to exploit Takagi–Sugeno (TS) models (Babuška, 1998; Takagi & Sugeno, 1985), whose parameters are estimated via an identification methodology. In particular, the fuzzy fault tolerant scheme is obtained according to the following stages. The FDD model is firstly estimated using the fuzzy identification approach (Babuška, 1998). Secondly, the fault accommodation strategy uses the estimation of FDD module to compensate for the fault effect. The FDD model is obtained via a proper choice of the fuzzy model parameters. The Membership Functions (MFs) with their rules are also derived directly from the data of the monitored system. The fuzzy modelling and identification scheme is thus able to lead to the required fault tolerance features. Note that the proposed design approach exploited for the derivation of the fuzzy controller was already addressed in Simani and Castaldi (2013), but applied to a wind turbine system, and without fault tolerance capabilities.

Concerning the traditional controller design, classical linear control schemes, such as the PID solution could not lead to satisfactory behaviour for all operating points of the plant, due to nonlinearity, system ageing, environmental conditions, uncertain measurements, disturbance and possible faults. Due to this behaviour, possible solutions could exploit a multiple model approach, or gain-scheduled controllers that are derived to work in fixed operating points, as described *e.g.* in Fang, Chen, Dlakavu, and Shen (2008). In this case, it was assumed that the model parameters change slowly compared to the system dynamics, which is generally not satisfied. Moreover, classic gain-scheduling strategies could guarantee prescribed performance and stability requirements at different operating points, but with design procedures that sometimes are not direct and straightforward.

Under these considerations, the second FTC approach suggested in this paper uses a recursive identification mechanism in connection with model-based adaptive control design, which was addressed *e.g.* in Bobál, Böhm, Fessl, and Machácek (2005). Note that this alternative strategy suggested in this paper for the adaptive controller design was already proposed in Simani, Alvisi, and Venturini (2014), but without any fault tolerance properties. Therefore, the controller design problem is proposed here since the characteristics of the process under investigation can change over time. Moreover, in the perspective of the fault tolerant application, this paper suggests to exploit an *adaptive* solution based on a recursive or on-line estimation scheme relying on the on-line estimation of the controlled process, which is affected by faults. While the time-varying parameters of the plant are identified, which are the result of both disturbance and faults, the time-varying variables of the controller are computed on-line, in order to maintain fixed control performances.

The efficacy of the suggested FTC strategies are proved on different data sequences acquired from the hydraulic system under diagnosis. Several simulations provide the effectiveness of the proposed regulators also with respect to the baseline PID controller proposed in Fang et al. (2008), when both the fault tolerance and the reference tracking capabilities are considered. Moreover, as it fundamental to analyse the behaviour of the proposed control strategies with respect to modelling uncertainties, the suggested verification tool exploits extensive Monte-Carlo simulations. In fact, as the hydraulic plant uses a hydraulic turbine represented as two-dimensional map, the Monte-Carlo analysis represents a viable approach for assessing the performances of the