ISA Transactions 52 (2013) 115–128

Contents lists available at SciVerse ScienceDirect

ISA Transactions

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

Multi-objective control of nonlinear boiler-turbine dynamics with actuator magnitude and rate constraints

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ARTICLE INFO

Article history:
Received 31 March 2012
Received in revised form
23 July 2012
Accepted 13 August 2012
Available online 5 September 2012
This paper was recommended for publication by Dr. Jeff Pieper.

Keywords:
Boiler-turbine dynamics
Actuator magnitude and rate saturations
Linear parameter varying system
Multi-objective performance
Linear matrix inequality

ABSTRACT

This paper investigates multi-objective controller design approaches for nonlinear boiler-turbine dynamics subject to actuator magnitude and rate constraints. System nonlinearity is handled by a suitable linear parameter varying system representation with drum pressure as the system varying parameter. Variation of the drum pressure is represented by suitable norm-bounded uncertainty and affine dependence on system matrices. Based on linear matrix inequality algorithms, the magnitude and rate constraints on the actuator and the deviations of fluid density and water level are formulated while the tracking abilities on the drum pressure and power output are optimized. Variation ranges of drum pressure and magnitude tracking commands are used as controller design parameters, determined according to the boiler-turbine's operation range.

1. Introduction

The primary function of boiler system control is to keep the mechanical energy output in balance with the electrical load demand while maintaining internal variables such as steam pressure, temperature and drum water level within their desired range. Typically, the temperature and drum water level are regulated tightly around designated levels over the full operating range of the boiler system. On the other hand, drum steam pressure must be controlled over a range of values according to varying operating conditions and load demand. Therefore, the performance of a boiler-turbine control system can be addressed to tracking varying load commands with regard to the power output and drum pressure, while regulating deviation of the drum water level. Moreover, the derived control signals need to satisfy any physical constraints imposed on actuators such as magnitude and rate saturation for the fuel flow, steam control and feedwater flow control valves.

Typically, boiler-turbine dynamics are highly nonlinear and are subject to actuator magnitude and rate constraints. The nonlinear boiler-turbine dynamics proposed in [1] were developed based on basic conservative laws which govern the boiler operation while maintaining an emphasis on simple structure. This model has been investigated for controller designs such as the intelligent control approaches [2,3]. In the work of [2], a genetic algorithm (GA) was utilised in cooperation with linearization of the nonlinear boiler-turbine dynamics in an attempt to extract the "fittest" feedback parameters for a proportional–integral (PI) controller as well as a state feedback control. However, it was shown that a large amount of oscillation or overshoot can occur, with duration of minutes, in drum pressure and power output responses when a step demand was issued. It was claimed in [2] that these overshoots can be attributed to saturation of the control valves during that period of time. In [3], an online self-organizing fuzzy logic controller was implemented for nonlinear boiler-turbine dynamics. Control rules and membership functions of the fuzzy logic controller were generated automatically, without using a plant model.

The nonlinear boiler-turbine dynamics proposed in [1] have been also utilized for model-based controller designs. In [4], a boiler controller design utilizing the H^{∞} methodology obtained a linear approximation of the nonlinear boiler dynamics. Although robustness against varying operation conditions was addressed, the problem of control saturation and rate limits was not handled. Performance degradation can be prominent in a multi-input system such as the boiler-turbine system. The work in [5] overcame the severe nonlinearity of boiler-turbine dynamics by

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0019-0578/$ - see front matter
http://dx.doi.org/10.1016/j.isatra.2012.08.002

carefully choosing the operating range. Then, a single linear controller was designed to work in such an operating range. In [6], nonlinear boiler-turbine dynamics were represented by the Takagi and Sugeno fuzzy model. Then, a fuzzy H^∞ state feedback control law was synthesized in terms of linear matrix inequalities (LMIs) [7].

Other work investigated the model predictive control (MPC) approach based on real-time system variables to handle the control of nonlinear boiler-turbine dynamics under various system constraints. In [8], a continuous-time MPC design was proposed for a nonlinear boiler-turbine system approximated by its Taylor series expansion. For the constraints on control input, the magnitude and rate saturations were satisfied, respectively, by increasing the predictive time and the tuning time constant of reference trajectories in a reference governor. In [9], a piecewise affine model was used to model nonlinear boiler-turbine dynamics. The MPC strategy in explicit form was then used to calculate the state-feedback control law as an affine function of the system states. In this method, the MPC computation is moved off-line, which in comparison with an on-line approach makes it easier to implement reduction to a look-up table. Recently in [10], an on-line MPC algorithm based on GA was proposed to find the optimal input sequence for boiler-turbine dynamics. Once the tracking error is within an error threshold for a certain duration, an H^∞ fuzzy controller is connected to achieve a fast transition to steady state.

In the work of [11], a gain-scheduled control approach via l^1-optimization was proposed for nonlinear boiler-turbine dynamics. The boiler-turbine dynamics were brought into a linear parameter varying (LPV) form which resembles a linear system with parameter-dependent state-space matrices. The resulting boiler-turbine LPV dynamics were first discretized, after which controller designs were performed by utilizing set-valued methods for l^1-optimization [12]. To calculate real-time control signals, linear programming [13] needs to be carefully implemented during practical operation.

As mentioned, boiler-turbine dynamics are highly nonlinear and subject to both the magnitude and rate constraints on the actuator. For the issue of nonlinearity, the intelligent control approaches as mentioned in [2,3] do not rely on modeling of the boiler-turbine dynamics. On the other hand, in the model-based control approaches, the nonlinearity (or modeled as uncertainty) is handled by robust design as in [4], direct nonlinear modeling as in [5–6], the MPC approach as in [8–10] or the gain-scheduled design via an LPV equivalence as in [11].

The issue of actuator magnitude saturation was addressed previously in [11]. The aim of that work was to further handle the issue of rate constraint on the actuator for controller design. Although some literature has discussed magnitude and rate saturation [14–17], scant work can be found on handling the rate constraints of the actuator for boiler-turbine dynamics. Although the work in [8] using an MPC approach can handle the actuator rate constraints for boiler-turbine dynamics, an intuitive tuning of suitable reference trajectories needs to be performed in real time. Recent works on controller design for LPV systems include [18–19], but the issue of rate constraints was not addressed.

In this present study, the nonlinearity of nonlinear boiler turbine dynamics is handled by a suitable LPV system formulation. To proceed with controller design, the variation property of drum pressure in the LPV system is represented by suitable norm-bounded uncertainty and affine dependence on system matrices. LMI conditions for controller construction are then parameterized by the system varying parameters and the drum pressure. Inclusion of the actuator dynamics as additional state variables of the plant enables the rate constraint to be explicitly addressed. By using the LMI algorithms, the magnitude and rate constraints on the actuator and the deviations of both fluid density and water level are formulated while the tracking capabilities on drum pressure and power output are optimized in terms of H^∞ optimization.

During controller construction, the variation ranges of the drum pressure and the magnitude tracking command are considered as design parameters, determined according to the boiler-turbine's operational range. The achieved performances consider the cases of full range operation conditions, one adjacent operating point and one-tenth of the full operating range. These are evaluated and compared so that a most suitable design can be suggested.

2. Boiler-turbine dynamics

The considered boiler-turbine dynamics were developed by Bell and Astrom [1] and can be described as

$$\begin{aligned}\dot{p} &= -0.0018u_2p^{9/8}+0.9u_1-0.15u_3,\\ \dot{P}_0 &= (0.073u_2-0.016)p^{9/8}-0.1P_0,\\ \dot{\rho}_f &= (141u_3-(1.1u_2-0.19)p)/85,\end{aligned} \tag{1}$$

where p denotes drum pressure (kg/cm^2), P_0 denotes power output (MW) and ρ_f denotes fluid density (kg/cm^3). Control inputs to the system are valve positions for fuel flow u_1, steam control u_2 and feedwater flow u_3. The control inputs are subject to normalized magnitude saturations

$$0 \le u_1,u_2,u_3 \le 1, \tag{2}$$

and rate constraints

$$\begin{aligned}-0.007 &\le \dot{u}_1 \le 0.007,\\ -2 &\le \dot{u}_2 \le 0.02,\\ -0.05 &\le \dot{u}_3 \le 0.05.\end{aligned} \tag{3}$$

It is noted that the rate constraint on the steam control u_2 is highly asymmetric. Decreased steam can be easily and quickly obtained by closing the valve; however, increased steam relies on the slow thermodynamic process of the boiler to obtain suitable responses for drum pressure p and fluid density ρ_f from the provided fuel flow u_1 and feedwater flow u_3.

Another quantity of interest is the water level χ_w, which is given by

$$\chi_w = 0.05(0.13073\rho_f+100\alpha_{cs}+q_e/9-67.975), \tag{4a}$$

where steam quantity α_{cs} and evaporation rate q_e are given by

$$\alpha_{cs} = \frac{(1-0.001538\rho_f)(0.8p-25.6)}{\rho_f(1.0394-0.0012304p)}, \tag{4b}$$

$$q_e = (0.854u_2-0.147)p+45.59u_1-2.514u_3-2.096. \tag{4c}$$

A schematic diagram of the boiler-turbine dynamics is shown in Fig. 1.

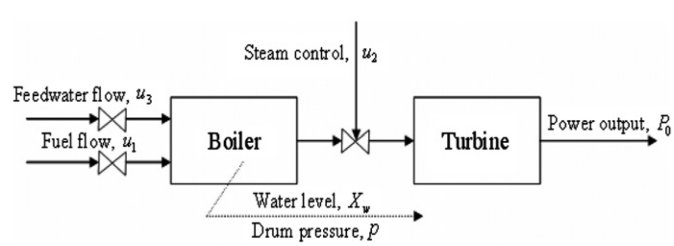

Fig. 1. Schematic diagram of the boiler-turbine dynamics.