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Research article

Modeling and sliding mode predictive control of the ultra-supercritical boiler-turbine system with uncertainties and input constraints

Zhen Tian, Jingqi Yuan*, Xiang Zhang, Lei Kong, Jingcheng Wang

Department of Automation, Shanghai Jiao Tong University, and the Key Laboratory of System Control and Information Processing, Ministry of Education of China, Dongchuan Road 800, Minhang District, Shanghai 200240, China

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ABSTRACT

The coordinated control system (CCS) serves as an important role in load regulation, efficiency optimization and pollutant reduction for coal-fired power plants. The CCS faces with tough challenges, such as the wide-range load variation, various uncertainties and constraints. This paper aims to improve the load tacking ability and robustness for boiler-turbine units under wide-range operation. To capture the key dynamics of the ultra-supercritical boiler-turbine system, a nonlinear control-oriented model is developed based on mechanism analysis and model reduction techniques, which is validated with the history operation data of a real 1000 MW unit. To simultaneously address the issues of uncertainties and input constraints, a discrete-time sliding mode predictive controller (SMPC) is designed with the dual-mode control law. Moreover, the input-to-state stability and robustness of the closed-loop system are proved. Simulation results are presented to illustrate the effectiveness of the proposed control scheme, which achieves good tracking performance, disturbance rejection ability and compatibility to input constraints.

1. Introduction

With the increasing energy crisis and environmental concerns, ultra-supercritical coal-fired power plants have become prior electricity suppliers for their high thermal efficiency and relatively low pollutants emission [1]. To make full use of renewable energy, ultra-supercritical units are playing an increasingly important role in the peak load regulation [2]. Correspondingly, the load scheduling of power grid demands even faster load response of the units. Besides, the coordinated control system (CCS) faces with tougher challenges for the units under wide-range load operation. The main task of the CCS is to regulate the power output to meet the load demand of the power grid while maintaining other state variables, such as the main steam pressure and steam temperature, within their safe and economical ranges. However, conventional PID-based control approaches could hardly achieve satisfactory performance because of the nonlinearity, input constraints and uncertainties existing in practical operation [3].

One way to improve the performance of the model-based coordinated controllers is to establish an appropriate model of the boiler-turbine units. There has been extensive research on the modeling of the subcritical boiler-turbine system [3–7]. Nevertheless, many models of subcritical units cannot directly be applied to the ultra-supercritical units since their different dynamics under the supercritical working condition [8]. For the ultra-supercritical unit, some complicated models based on the general physical principles have been established for the purpose of process simulation [9,10]. A simplified model is developed for controller design, but which may overlook the turbine-side dynamics [11,12]. Intelligent methods are also found applications in the modeling of boiler-turbine units, such as the neural network [13,14], fuzzy neural network [15] and genetic algorithm [16], but which may bring to heavy computational burden and the model parameters have no explicit physical significance.

In addition, advanced control approaches have been studied to enhance the CCS of boiler-turbine units. Since their merit of explicitly handling the constraints, model predictive control (MPC) methods have been widely investigated, such as the multi-model

* Corresponding author.
E-mail addresses: tianzhen9032-@sjtu.edu.cn (Z. Tian), jqyuan@sjtu.edu.cn (J. Yuan), zhangxiangzi0071@163.com (X. Zhang), konglei@sjtu.edu.cn (L. Kong), jcwang@sjtu.edu.cn (J. Wang).

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predictive control [17], fuzzy predictive control [18] and nonlinear model predictive control (NMPC) [19,20]. For a practical ultra-supercritical unit, modeling errors and various disturbances need to be considered for controller design, such as the fuel composition fluctuations, the contamination of the boiler heat exchange surfaces, the soot blowing operation and model simplification errors [3]. To reject the external disturbances, a linear active disturbance rejection control method is proposed based on an extended state observer [21]. An adaptive sliding mode controller is designed to improve the robustness against with the bounded uncertainties [22]. However, these control methods could not simultaneously deal with the uncertainties and input constraints, which may deteriorate the control performance of CCS in practice. Among various robust control methods, sliding mode control (SMC) is advantageous for its fast response and inherent robustness [23]. To deal with the input constraints, the sliding mode predictive control approaches have been studied with the combination of SMC and MPC [24–27]. For instance, a predictive sliding mode controller is used for the control of the outlet oil temperature of a field of distributed solar collectors [24].

This paper is aimed at improving the CCS performance in the presence of both input constraints and uncertainties. To achieve excellent load tracking ability under wide-range operation, a novel sliding mode predictive controller (SMPC) is designed with the integration of model predictive control and sliding mode control approaches. The proposed control approach could simultaneously address the issues of uncertainties and input constraints, which is applicable for various industrial process.

The rest of this paper is organized as follows: Section 2 develops a control-oriented model of the ultra-supercritical boiler-turbine system. Section 3 presents the design of a sliding model predictive controller to improve the robustness against with the uncertainties and input constraints. Moreover, the input-to-state stability and robustness of the closed-loop system are proved in Section 4. Simulation results with three different control methods are discussed in Section 5 to illustrate the model accuracy and effectiveness of the proposed control scheme. Concluding remarks are given in Section 6.

2. Modeling of the ultra-supercritical boiler-turbine system

A simplified schematic diagram of an ultra-supercritical unit is depicted Fig. 1, where some auxiliary facilities are ignored. This paper is mainly focused on the integrated boiler-turbine system, which is simplified as a three-input three-output nonlinear system [11]. The input variables are the governor opening value of the steam turbine u_1, the mass flow rate of the feed coal u_2 and the mass flow rate of the feed water u_3; the output variables include the power output y_1, the main steam pressure y_2 and the specific enthalpy of the steam at the separator outlet (generally called intermediate point) y_3. To facilitate the modeling, several reasonable assumptions are introduced as follows:

(1) Without considering the mismatch between the feed coal and the combustion air;
(2) The time delay (roughly 200 ms) of the combustion process in the furnace is ignored;
(3) The slight sensible heat of the slag and flue ash is neglected;
(4) The main steam temperature is regarded as constant;
(5) The generator efficiency and the shaft efficiency of the turbine retain constant under various load conditions.

In this section, some common physical principles and public equations related with the modeling process are presented for the sake of completeness and ready reference and more details can be found in the cited references. According to the sequence of energy conversion, the system dynamics is typically divided into five parts, i.e., coal pulverizing system, economizer, evaporation system, superheaters and steam turbine system.

2.1. Coal pulverizing system model

For simplicity, the mass dynamic balance for the coal entering the furnace may be regarded as a first-order inertia process with time delay [28]:

$$T_f\frac{dD_f}{dt} = -D_f + \mu_B(t-\tau) \tag{1}$$

where μ_B and D_f are the mass flow rate of the feed coal and the coal entering into the furnace, respectively; T_f the time constant of the pulverizer; τ the pure time delay of the coal feeder.

2.2. Economizer model

Since this paper is mainly focused on the integrated boiler-turbine system, only a simplified economizer model is considered here. Considering the fact that the temperature of the subcooled feed water at the economizer outlet is almost constant, the specific enthalpy of the feed water h_{fw} may be regarded as the function of the intermediate-point steam pressure p_m, which is approximated with a polynomial function:

$$h_{fw} = \lambda_{20} + \lambda_{21}p_m + \lambda_{22}p_m^2 \tag{2}$$

which illustrates the parameters variation principle of the feed water at the economizer outlet.

2.3. Evaporation system model

The mass and energy balances for working fluid in the waterwall are represented as [11]:

$$c_{11}\frac{dp_m}{dt} = D_{fw}\left(h_{fw} - c_{12}\right) + Q_s - D_m(h_m - c_{12}) \tag{3}$$

$$c_{21}\frac{dh_m}{dt} = D_{fw}\left(h_{fw} - c_{22}\right) + Q_s - D_m(h_m - c_{22}) \tag{4}$$

where h_m and D_m denote the specific enthalpy and mass flow rate of the intermediate-point steam, respectively; D_{fw} is the mass flow rate of the feed water; c_{11}, c_{12}, c_{21}, and c_{22} are four time-variant parameters correlated with the thermal parameters of the working fluid, which could be obtained by identification [11]. Q_s is the heat absorption rate of the working fluid in the waterwall and calculated as [29]:

$$Q_s = D_f Q_{ar,net}(1-q_4) - Q_{fg} = k_1 D_f - Q_{fg}$$

where D_f denotes the mass flow rate of the coal entering into the furnace; $Q_{net,\ ar}$ the lower heating value (LHV) of the feed coal, which can be acquired by offline assay or online identification [29]; q_4 the heat loss rate due to the mechanical incomplete combustion; Q_{fg} the energy of the flue gas obtained from combustion in the furnace; k_1 the effective heating value of the coal.

According to the operation data, Q_{fg} is found highly associated with the power output N_e, and a linear polynomial function is used for approximation:

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