ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISA Transactions

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

Practice article

Model-based adaptive sliding mode control of the subcritical boiler-turbine system with uncertainties

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ARTICLE INFO

Keywords:
Coal-fired power plant
Control-oriented modeling
Sliding mode control
Adaptive feedback linearization
Chattering reduction

ABSTRACT

As higher requirements are proposed for the load regulation and efficiency enhancement, the control performance of boiler-turbine systems has become much more important. In this paper, a novel robust control approach is proposed to improve the coordinated control performance for subcritical boiler-turbine units. To capture the key features of the boiler-turbine system, a nonlinear control-oriented model is established and validated with the history operation data of a 300 MW unit. To achieve system linearization and decoupling, an adaptive feedback linearization strategy is proposed, which could asymptotically eliminate the linearization error caused by the model uncertainties. Based on the linearized boiler-turbine system, a second-order sliding mode controller is designed with the super-twisting algorithm. Moreover, the closed-loop system is proved robustly stable with respect to uncertainties and disturbances. Simulation results are presented to illustrate the effectiveness of the proposed control scheme, which achieves excellent tracking performance, strong robustness and chattering reduction.

1. Introduction

In recent decades, renewable power generation technologies have been developed rapidly. However, coal-fired power plants are still playing the major electricity suppliers in most developing countries [1]. The control system performance is one of the most important factors related to the efficiency and safety of boiler-turbine units [2]. The objective of the coordinated control system (CCS) is to regulate the power output of the unit to meet the power demand. Specifically, the power output regulation is required as fast as 1.5%–2% of the full load per minute, and the main steam pressure needs to be stabilized within a limited range of $-0.4 \sim +0.4$ MPa around its set value [3]. For a practical boiler-turbine unit, various uncertainties and disturbances occurred in the operation need to be considered [4], such as the heating value variation of the feed coal, the contamination of the heat exchanger surfaces, the soot blowing operation, *etc*. Therefore, the robustness of the CCS is of great importance to achieve satisfactory control performance. In order to improve the CCS performance, two ways are commonly investigated. On the one hand, an appropriate control-oriented model with a balance between fidelity and simplicity needs to be built, which must cover the key features of the boiler-turbine system. On the other hand, the robust coordinated controller is studied to address the nonlinearity, intercoupling and uncertainties related to the boiler-turbine system.

Over past decades, several models have been established to describe the complex dynamics of the boiler-turbine system. In Refs. [5,6], full mechanism models are developed based on the basic mass and energy balance, which can only be applied for the detailed process simulation due to its complicated iterative calculation. Another typical model is built with the experimental operation data of a 160 MW oil-fired power plant [7]. However, the oil-fired power plants differ from large-scale coal-fired power plants in many aspects, *e.g.*, the time delay, the variance of the fuel heating value, the combustion system, *etc*. Similarly, a dynamic model is built for once-through boiler-turbine units [8]. Some improved models have also been found in the literature, such as the Takagi–Sugeno (TS) fuzzy model [9], piecewise affine model [10] and data-driven model [11]. However, the model parameters of these data-driven models are lack of explicit physical significance, which may lead to difficulty in dynamic analysis and model transplantation.

In recent years, various control approaches have been studied to improve the control performance of boiler-turbine units, which are summarized as follows:

(1) Linear control methods. So far, the conventional proportional

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https://doi.org/10.1016/j.isatra.2018.05.012
Received 11 October 2017; Received in revised form 27 April 2018; Accepted 16 May 2018

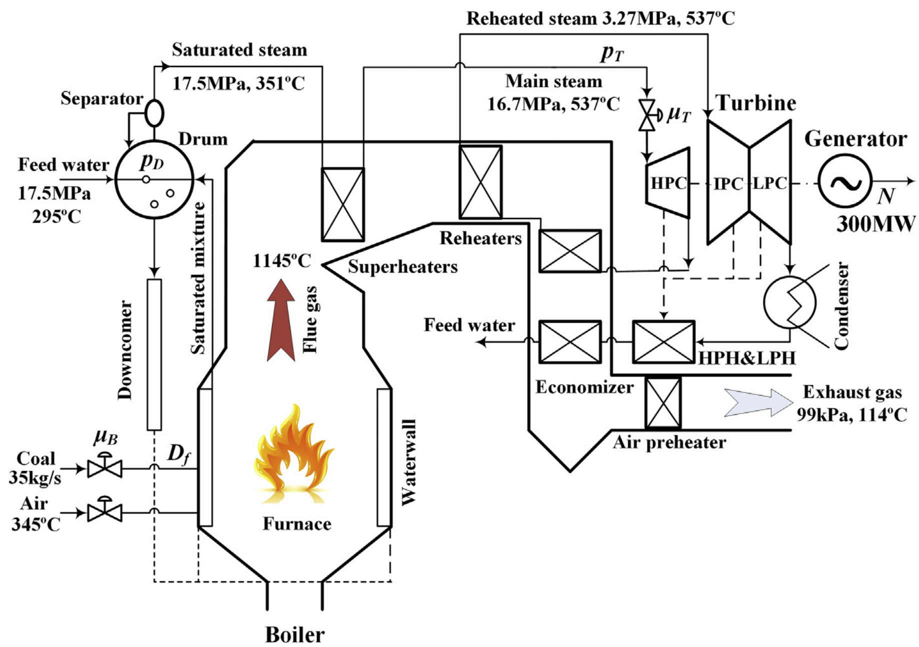

Fig. 1. Schematic of a 300 MW subcritical power plant (The data are corresponding to 100% BMCR working conditions approximately).

integral derivative (PID) control approaches are commonly adopted for boiler-turbine units, such as the cascade PID control [12], fuzzy PID control [13] and internal-mode-based PID control [14]. Based on a locally linearized model, an L_1 adaptive control strategy is proposed to address the nonlinearity and model uncertainties [15]. To achieve disturbance attenuation, a passivity-based H_∞ controller is designed with respect to a linear boiler-turbine model [16]. However, the performance of these linear control approaches may deteriorate for large-scale operating units due to the neglect of nonlinearity and intercoupling properties.

(2) Nonlinear control methods. Various nonlinear control methods have been applied to the nonlinear boiler-turbine model proposed in Ref. [7]. Feedback linearization based control methods are studied for the nonlinear boiler-turbine system [17,18]. With the successive on-line model linearization, a nonlinear predictive controller is designed to address the nonlinearity [19]. Some robust control approaches are proposed to achieve disturbance rejection, such as the active disturbance rejection control (ADRC) [3], sliding mode control [4] and backstepping control [20]. These nonlinear control methods may improve the CCS performance for the oil-fired units from different aspects. However, their effectiveness for practical boiler-turbine system needs to be further verified while considering the dynamics difference between the oil-fired units and coal-fired units.

(3) Model-free control methods. With the development of data-driven modeling, some model-free control approaches have been investigated. A predictive controller is designed based on the data-driven model by using fuzzy clustering and subspace methods [21]. To adapt to the load variation, a predictive controller is proposed based on the iterative learning principle [22]. Intelligent controllers are developed based on the neural network methods [23,24]. Even though these control approaches do not require mathematical models, they may encounter feasibility and reliability problem in practice for their complicated implementation.

Sliding mode control (SMC) approach is extensively studied for its merits of excellent performance and inherent robustness [25]. For nonlinear systems, several nonlinear SMC approaches have been studied [26,27], but most of them are limited to special structural constraints, such as the holomorphic and single-input conditions. Moreover, the reaching condition and stability analysis become much more complicated for nonlinear sliding mode controllers. With the help of feedback linearization technique, linear control methods could also be extended to nonlinear systems [17]. Thus, the linearization-based sliding mode control approach may facilitate the controller design for many nonlinear industrial processes [28].

In this paper, an adaptive sliding mode control approach is proposed for the boiler-turbine system to address the model uncertainties and external disturbances. Three attractive features may be found in this contribution. Firstly, an appropriate control-oriented model is built and validated, which covers the key dynamics of the subcritical boiler-turbine units under wide-range operation. Besides, an adaptive feedback linearization strategy is proposed to eliminate the linearization error caused by the model uncertainties. Last but not the least, a super-twisting sliding mode controller is designed to address the uncertainties and disturbances, which is free from the heavy computation and chattering trouble.

The rest of this paper is organized as follows: Section 2 develops a control-oriented model for the subcritical boiler-turbine system. In Section 3, an adaptive sliding mode controller is designed and the closed-loop stability is proved. Simulation results with three different control approaches are presented in Section 4. Section 5 gives the concluding remarks of this paper.

2. Modeling of the drum-type boiler-turbine system

A schematic diagram of the subcritical boiler-turbine system is shown in Fig. 1. As seen, the preheated feed water enters the boiler drum firstly, and then enters the waterwall through the downcomer. The working fluid absorbs heat from the waterwall and becomes saturated mixture of water and steam. Next, the mixture led to the drum is separated into saturated steam and water by the separator. The saturated steam leaves the drum and passes through multi-stage superheaters, becoming superheated steam or main steam for the high-pressure cylinder (HPC). The steam from the HPC exit is reheated in multi-stage reheaters and then fed into the intermediate-pressure cylinder (IPC). The steam from the IPC exit is fed into the low-pressure cylinder (LPC). Eventually, the steam working in the turbine drives the synchronous generator to produce electric power.

This paper mainly concerns the control-oriented modeling of the