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Control-oriented modeling and analysis of direct energy balance in coal-fired boiler-turbine unit

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ABSTRACT

Direct energy balance (DEB) coordinated control scheme is widely used by field engineers in coal-fired power plants while attracting little attention in the academic community. This paper aims to derive a mathematical model that is suitable for DEB research. To balance the model's fidelity and simplicity, the power plant is divided into three transformation modules and, using conservation laws, a dynamic model is developed to describe each module. Within reasonable assumptions, numerous module equations are combined to yield a 6th-order nonlinear model. Time constants of the model are identified based on Pareto optimization. Model accuracy is confirmed using field measurements from a 300 MW coal-fired power plant. Based on the linearized model, the merits of the DEB control structure are analyzed. It is confirmed that the DEB control is sufficient to fulfill the fundamental goals of power plant regulation. An illustration of performance improvement is given by introducing gain scheduling techniques to the DEB structure. The proposed model can provide groundwork for future development of advanced control algorithms under the DEB structure.

1. Introduction

Despite the ever increasing role of renewable energy in the power grid, there still remains a large need for conventional power plants to promptly meet load demands. In China, the coal-fired power plant takes the most responsibility for the gird balance and is faced with increasing regulatory pressure.

Generally, the fundamental requirements of the fossil-fired power plant load control system, namely Coordinated Control System (CCS) (Wu, Shen, Li & Lee, 2014a), are

I. Electric power output should be adjusted timely as required by automatic dispatch system (ADS). The *tracking rate* of the power output in China is usually 1.5–2% of the full load per minute. Taking a 300 MW power plant as an example, it is required to generate 4.5–6 MW more power in one minute.
II. The reverse change of the throttle pressure when regulating the power output should be limited to a safety bound, e.g., $\pm$0.4 MPa, from the initial pressure.

The first requirement on load tracking is mandatory to guarantee the power grid stability and the second for the safety of the boiler itself. To achieve the fundamental requirements, various attempts have been made to build a reasonable dynamic model for the power plant so that an efficient control strategy can be designed. Among them, the model proposed in Bell and Åström (1987) is the most popular one, which represents a 160 MW oil-fired boiler-turbine unit as a third-order nonlinear model. Numerous advanced control strategies have been developed based on this model, such as the genetic algorithm based control (Dimeo & Lee, 1995), inverted decoupling (Garduno-Ramirez & Lee, 2005), robust control (Moradi, Alasty & Vossoughi, 2013; Tan, Marquez, Chen & Liu, 2005; Wu, Nguang, Shen, Liu & Li, 2010; Chen, 2013; Yu, Chan, Tong, Zhou & Li, 2010; Jalali & Golmohammad, 2012) and Model Predictive control (MPC) (Li, Shen, Lee & Liu, 2012; Wu, Shen, Li & Lee, 2014b, 2014c, 2013; Sarailoo, Rahmani & Rezaie, 2014; Liu, Guan & Chan, 2010; Liu & Kong, 2013).

Another widely-used model was proposed by De Mello (1991), which was extensively studied to develop numerous advanced control algorithms, such as multivariable decoupling PID (Tan, Liu, Fang & Chen, 2004), backstepping-based adaptive method (Fang & Wei, 2011) and sliding mode control (Ataei, Hooshmand & Samani, 2014). A linear transfer function model of a syncrude boiler (Moradi, Bakhtiari-Nejad & Saffar-Avval, 2009) also attracted some interests to design robust sliding mode controller (Moradi & Bakhtiari-Nejad, 2011).

Recently, a 'black-box' model of the coal-fired power plant was built based on the fuzzy neural network (Liu, Kong, Hou & Wang,

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2013), which can accurately imitate the characteristics of a power plant, but is difficult for controller design. Also, a neural network based model was proposed in Lee, Van Sickel, Hoffman, Jung and Kim (2010) by building 33 subsystems separately and combining them together. Such a complex model was, however, not suitable for direct controller design, and thus a Takagi–Sugeno (TS) fuzzy model (Wu, Shen, Li & Lee, 2014a) was established to approximate its behavior, based on which a stable MPC is developed to obtain robust offset-free tracking.

The advanced control algorithms developed from the above models can of course improve the control performance. However, most of them cannot be directly configured in the industrial Distributed Control System (DCS). Their complexity, compared with the decentralized PI controller, requires an additional high-performance computer, e.g., advanced Programmable Automation Controller (PAC), to the current DCS to compute the control signals. Inevitably, it brings more complexities and uncertainties into the system.

On the other hand, the field engineers, based on their empirical experiences, proposed a simple but efficient control structure, namely Direct Energy Balance (DEB) strategy. Currently, the DEB-based PI control, rather than advanced algorithms, is dominant in the coal-fired power plants. However, although the DEB strategy was widely used in industry, there is no suitable mathematical model to describe it and thus there were very few academic results reported about the DEB structure. To remedy the gap between the academic research and engineering application, this paper presents a control-oriented model for the DEB strategy so that i) the abilities and merits of DEB can be understood better from an academic point of view; ii) some potential problems can be identified by simulation; iii) some promising advanced solutions for performance improvement can be studied based on the model; and iv) it can provide a simulation platform before applying the advanced solution to field tests.

2. Mathematical modeling of coal-fired power plant

2.1. Plant description

Modeling of a plant is always related to a specific purpose of the model where it will be used. Variable selections and assumptions should be made with the application objective in mind. This section attempts to derive a model that can generate all required output signals in the coordinated control strategy. A 300 MW coal-fired drum-type boiler power plant in Guangdong Province, China, is selected for modeling purpose. Mathematical equations are derived based on the first law of thermodynamics and then simplifications are made. (Sun, Dong, Li, Zhang & Xue, 2014) previously revealed that the whole plant can be separated as three dominant transformation modules, i.e., the coal-steam module, steam-pressure module, and pressure-power module, as shown in Fig. 1, which can be modeled individually.

2.2. Assumptions

System dynamics can be roughly separated into two different time scales: Dynamics governing the coal and steam flows are relatively fast, whereas dynamics related to heat transfer are much slower. Therefore, heat transfer characteristics in steam and water circuits are ignored because the resulting inaccuracy can be effectively attenuated by feedback control. Another reason for this simplification is directed to the fact that there are no temperature or enthalpy variations needed in the DEB control system. For the purpose of simplification, the following assumptions are made in this paper:

(1) The temperature in steam and water circuits is controlled well, whose variation is very small and thus its effect on the pressure and power can be ignored.
(2) The coal quality variation is neglected.
(3) Drum level remains unchanged or can be regulated quickly.
(4) Fluid pressure is uniformly distributed in one lumped tube and frictional resistance is concentrated at the outlet of the tube.
(5) Pressure in the governing stage is proportional to the product of main steam pressure and valve opening.

2.3. Coal-steam transformation module

Control difficulties mainly come from the coal-steam module, where the large time-delay and inertia are present. The following equations are all derived from the fundamental mass and energy balance law.

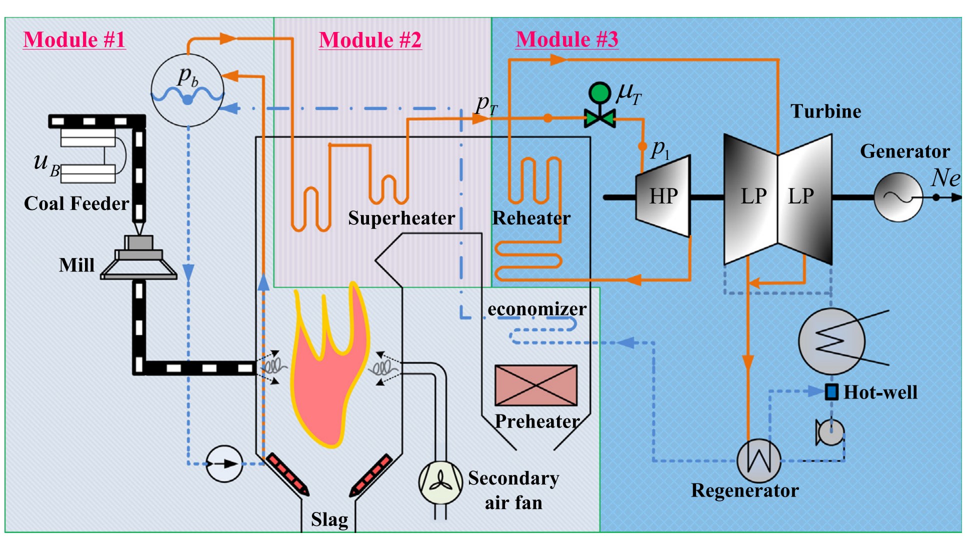

Fig. 1. A schematic view of a coal-fired power plant (blue dotted line: water flow; orange solid line: steam flow; three colored parts: model modules).(For interpretation of the references to color in this figure legend,the reader is referred to the web version of this article.)