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Practice article

Direct energy balance based active disturbance rejection control for coal-fired power plant

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ABSTRACT

The conventional direct energy balance (DEB) based PI control can fulfill the fundamental tracking requirements of the coal-fired power plant. However, it is challenging to deal with the cases when the coal quality variation is present. To this end, this paper introduces the active disturbance rejection control (ADRC) to the DEB structure, where the coal quality variation is deemed as a kind of unknown disturbance that can be estimated and mitigated promptly. Firstly, the nonlinearity of a recent power plant model is analyzed based on the gap metric, which provides guidance on how to set the pressure setpoint in line with the power demand. Secondly, the approximate decoupling effect of the DEB structure is analyzed based on the relative gain analysis in frequency domain. Finally, the synthesis of the DEB based ADRC control system is carried out based on multi-objective optimization. The optimized ADRC results show that the integrated absolute error (IAE) indices of the tracking performances in both loops can be simultaneously improved, in comparison with the DEB based PI control and H_∞ control system. The regulation performance in the presence of the coal quality variation is significantly improved under the ADRC control scheme. Moreover, the robustness of the proposed strategy is shown comparable with the H_∞ control.

1. Introduction

Faced with the ever-growing resource scarcity and environmental regulations, the recent 30 years has witnessed the rapid development of the renewable power sources, such as the wind power, tidal power and the solar power generation. However, the intermittent nature of such resources, as is well-known, is disadvantageous for the stability of the power grid. Till now there are few available commercial methods to accommodate the deficiency. There is, therefore, a growing requirement of the load regulation placed on the conventional power generation. Especially in China, the coal-fired power plant is faced with the unprecedented pressure to participate in the load regulation.

Generally, the fundamental requirements of the power plant load control system, which is usually named Coordinated Control System (CCS) [1], are listed as follows:

I. Electric output can be adjusted timely as required by automatic dispatch system (ADS). The tracking rate in China is usually 1.5%-2% of full load per minute.
II. The reverse change of the throttle pressure when regulating the power output should be limited to a safety bound, e.g., ± 0.4 MPa compared with the initial pressure.

These two requirements are mandatory because the first one is responsible for the power grid stability and the second one for the safety of the boiler itself. It is theoretically shown in [2] that the direct energy balance (DEB) based PI control structure can well fulfill the above requirements. However, it may be faced with some problems when the coal quality varies. The PI control system cannot haul the output power and throttle pressure back to the desired values promptly in face of the variation of the heat value. Actually this is a common intractable difficulty which is frequently encountered by most of the in-service power plants. A possible explanation for this phenomenon will be given in this paper.

In the past decade, Model Predictive Control (MPC) [3–9] received extensive attention in academia to improve the operational performance of the power plant. However, the commission of MPC usually requires an additional high-performance computer for calculation and then to communicate with the Distributed Control System (DCS). This additional hardware complexity limits its wide application in power plant since the safety and ease of use are of the prominent concern in power plant [10].

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In a recent survey [11], it is shown that the conventional single-loop PID controller accounts for 98.1% of all the feedback controllers utilized in power plants of Guangdong Province, China. Moreover, most of the controllers are simply of PI form to avoid the fluctuation caused by derivative action.

On the other hand, the emerging active disturbance rejection control (ADRC) [12] reached a reasonable trade-off between the performance and simplicity, which has thus received many successful applications in motion controls [13–16] as well as a pilot power plant application in [17]. Recently, it is revealed in [18] that the first-order ADRC can be bridged to PI by slightly modifying the integrator as extended state observer (ESO) which can estimate the 'total disturbance' and cancel it in real time. The variation of the coal heat value is deemed as an external disturbance to the system, which is expected to be mitigated in a much quicker way under the DEB-based ADRC control system.

While the previous paper [2] is focused on the modelling of the boiler-turbine unit and building the conventional DEB control system, this paper aims at the advanced control analysis and synthesis, with the main contributions as follows:

I. The nonlinearity of the power plant model, which was built and validated in [2], is analyzed in detail to provide reasonable set-point values so that the effect of the nonlinearity to the control performance can be reduced.
II. The DEB control structure, which was initially introduced by the field engineers, is first analyzed in detail from a theoretical point of view.
III. The outstanding problem in terms of coal quality variation is tackled by employing ADRC as the controller under the DEB structure, depicting ADRC is a promising solution that can simultaneously fulfill the objectives of power tracking, coal disturbance rejection and ease of use.

2. Problem formulaton

2.1. System description

A typical schematic of the subcritical power plant is shown in Fig. 1. The primary controlled variable is the power output, Ne, and the other controlled variable is the throttle pressure p_T. The manipulated variables are the fuel feed u_B and the valve opening μ_T. Other intermediate variables are the boiler pressure p_b and the governing stage pressure p_1.

With reasonable assumptions, recently a dynamic model was proposed in [2] based on the mass and energy balance law to describe the whole energy conversion process.

Denote the process outputs as $\mathbf{y} = \left[Ne \quad p_T \right]^T$, control inputs as $\mathbf{u} = [u_B \quad \mu_T]$ and the intermediate states as $\mathbf{x} = \left[q_f \ D_b \ p_b \ p_T \ p_1 \ D_T \right]^T$. Moreover, the normalization coefficient k_c is introduced to represent the influence of the coal quality, which should equal 100% under normal condition. Therefore, the process can be described by the following state-space model:

$$
\begin{aligned}
\dot{x}_1 &= \frac{1}{22}\left[u_1(t-43) - x_1 \right] \\
\dot{x}_2 &= \frac{1}{380}\left(2.46 k_c x_1^{1.230} - x_2 \right) \\
\dot{x}_3 &= \frac{1}{4057}\left(x_2 - 42.51 x_3^{0.956}\sqrt{x_3 - x_4} \right) \\
\dot{x}_4 &= \frac{1}{5101}\left(42.51 x_3^{0.956}\sqrt{x_3 - x_4} - x_6 \right) \\
\dot{x}_5 &= \frac{1}{5}\left(0.0083 u_2 x_4 - x_5 \right) \\
\dot{x}_6 &= \frac{1}{5}(74.74 x_5 - x_6)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
y_1 &= 0.86 x_6^{0.852} \\
y_2 &= x_4
\end{aligned} \tag{2}
$$

Subject to the actuator constraints:

$$
\begin{aligned}
0 &\le u_1 \le 150 \\
0 &\le u_2 \le 100 \\
0 &\le \dot{u}_1 \le 0.1 \\
0 &\le \dot{u}_2 \le 0.1
\end{aligned} \tag{3}
$$

The accuracy of the model has been verified by the field measurements from a power plant in Guangdong Province, China. Note that the valve action u_2 can produce much quicker effects to the outputs than the fuel feed u_1, which poses significant difficulty for control.

2.2. Problem formulation and proposed solutions

The fundamental control objective is to achieve a fast power tracking while limiting the variation of the throttle pressure within an acceptable range. Moreover, the process outputs are required to be as insensitive as possible to the heat value variation of the coal.

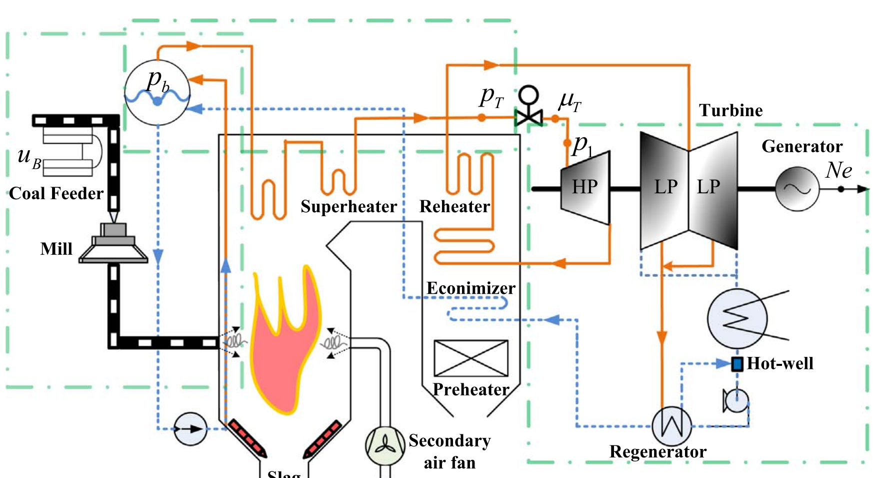

Fig. 1. A schematic view of a coal-fired power plant (blue dotted line: water flow; orange solid line: steam flow).

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