Control Engineering Practice 63 (2017) 69–80

Contents lists available at ScienceDirect

Control Engineering Practice

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

Optimization control of a pulverizing system on the basis of the estimation of the outlet coal powder flow of a coal mill

Yaokui Gao[a], Deliang Zeng[b,*], Jizhen Liu[b], Yifan Jian[b]

[a] Key Laboratory of Measurement & Control New Technology and System for Industrial Process, North China Electric Power University, Changping District, 102206 Beijing, China

[b] State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Changping District, 102206 Beijing, China

ARTICLE INFO

Keywords:
Pulverizing system
Coal powder flow
Nonlinear dynamic model
Predictive control

ABSTRACT

This study aimed to master the operating characteristics of a pulverizing system, improve the output control precision of the system, and reduce the fluctuation amplitude of the main operating parameters of coal-fired units. A nonlinear dynamic model of a direct-fired pulverizing system that considers the effect of coal moisture on the energy balance of a coal mill was established. Then, an estimated signal of the outlet coal powder flow of the coal mill was constructed as a new output control target of the pulverizing system. Finally, an output control optimization method for the pulverizing system was designed on the basis of this signal. Simulation results showed that the model effectively reflects the dynamic characteristics of a pulverizing system. In addition, the results of simulation were concordant with those of online measurements. The control scheme reduced the internal disturbances in the coal feed rate, thereby improving the tracking capability and control precision of the pulverizing system's output and enhancing the disturbance suppression capability of the mill outlet temperature. Thus, the designed control scheme can ensure the safe and stable operation of coal-fired units.

1. Introduction

Positive-pressure, direct-fired pulverizing systems with medium-speed mills are widely used in coal-fired power plants in China; these systems are typical three-input, three-output, nonlinear, and time-varying systems with a large inertia and time delay in the milling process. In general, the control loop of such a pulverizing system is composed of three independent single loops. The output of the pulverizing system is often indirectly controlled by a coal feeder, resulting in poor control precision. Establishing a three-input, three-output, and nonlinear model of the pulverizing system, constructing state estimation signals of key parameters of the pulverizing system (which are difficult or impossible to measure), and realizing the decoupling control of the pulverizing system by using a model-based advanced control algorithm are necessary to overcome perturbation and delay of the coal feed rate, reduce the coupling intensity among control variables, and improve the output control precision of the pulverizing system. Therefore, modeling and control optimization of medium-speed mill, positive-pressure, and direct-fired pulverizing systems are significant.

The coal mill is an independent link in the pulverizing system that allows the analysis of the interactions between variables and the construction of state estimation signals of key parameters through modeling. Results of these processes lay the foundation for the control optimization of pulverizing systems. Recent studies have extensively focused on modeling coal mills. Tian, Zeng, and Liu, X. et al. (2004); Tian, Zeng, and Liu, J. et al. (2004) regarded the milling process as a first-order inertia link with pure delay and established a fuel dynamic model of a pulverizing system; however, this model is a single-input, single-output model that ignores the effect of primary air and is unsuitable for the control optimization of a pulverizing system. Mercangoez and Poland (2011) proposed a coal mill model based on a gray-box approach and identified parameters via least squares fitting; however, this model is limited and is unsuitable for designing a model-based control system. Odgaard and Mataji (2006) developed an effective method for estimating moisture content in coal mills based on an energy balance model. However, the primary air model and the coal content model in the coal mill were not established. As a result, this model is not conducive to optimize the control of the pulverizing system. Considering the starting and stopping processes in coal mills, Wei, Wang, and Wu (2007) established a multi-stage non-linear model for Mill Parter Ship (MPS) medium-speed coal mills. Despite its high precision during the start and termination of the coal mill, the model requires the identification of numerous parameters and

* Corresponding author.
E-mail address: zdl@ncepu.edu.cn (D. Zeng).

http://dx.doi.org/10.1016/j.conengprac.2017.03.015
Received 30 November 2016; Received in revised form 27 March 2017; Accepted 29 March 2017

Nomenclature

C_{dc}	specific heat capacity of dry-basis coal, kJ/(kg °C)
C_H	specific heat capacity of hot air, kJ/(kg °C)
C_{H_2O}	specific heat capacity of water, kJ/(kg °C)
C'_{H_2O}	average specific heat capacity of vapor at a constant pressure, kJ/(kg·°C)
C_{in}	specific heat capacity of primary air, kJ/(kg °C)
C_L	specific heat capacity of cold air, kJ/(kg °C)
C_{mix}	average specific heat capacity of raw coal, coal powder, and the metal involved in heat transfer, kJ/(kg °C)
C_{out}	specific heat capacity of wet air at T_{out}, kJ/(kg °C)
C_{pf}	specific heat capacity of coal powder, kJ/(kg °C)
C_{rc}	specific heat capacity of raw coal, kJ/(kg °C)
K_c	proportion coefficient between the coal feed flow and the coal feeder speed, rpm
K_{conv}	conversion coefficient of raw coal to pulverize coal per unit time, 1/s
K_i	model parameters that need to be identified, i=1,2,3
K_{loss}	coefficient of heat loss through equipment
K_{mac}	coefficient of heat generation in milling process
K_{pf}	proportion coefficient of coal powder flow
K_{seal}	leakage coefficient of sealed air for medium speed coal mill
M_{ar}	raw coal moisture, %
M_c	raw coal content in coal mill, kg
M_{metal}	amount of metal involved in the heat exchange, kg
M_{pc}	moisture content in coal powder, %
M_{pf}	coal powder content in coal mill, kg
ΔM	amount of moisture evaporated in the coal mill, %
ΔP_{pa}	differential pressure of primary air, mbar
Q_{air}	physical heat input into the coal mill by the primary air per unit time, kJ/s
$Q_{air\&seal}$	physical heat output from the coal mill by primary air and sealing air per unit time, kJ/s
Q_{in}	total heat input into the coal mill per unit time, kJ/s
Q_{le}	physical heat input into the coal mill by leaking cold air per unit time, kJ/s
Q_{loss}	heat loss through the equipment per unit time, kJ/s
Q_{mac}	heat produced by the grinding process per unit time, kJ/s
$Q_{\Delta M}$	heat consumed for evaporating raw coal moisture per unit time, kJ/s
Q_{out}	total heat output from the coal mill per unit time, kJ/s
Q_{pf}	heat consumed for heating fuel per unit time, kJ/s
Q_{rc}	physical heat input into the coal mill by raw coal per unit time, kJ/s
Q_{seal}	physical heat input into the coal mill by sealing air per unit time, kJ/s
R_{90}	coal fineness, %
T_1	inertia time from the air door to the primary air flow, s
T_2	inertia time from the air door to the primary air temperature, s
u_H	valve opening of hot air, %
u_L	valve opening of cold air, %
W_{air}	primary air flow, kg/s
W_c	coal feed flow, kg/s
W_H^{max}	max-flow of hot air, kg/s
W_L^{max}	max-flow of cold air, kg/s
W_{pf}	amount of coal powder blown out of the coal mill per unit time, kg/s
θ_H	temperature of hot air, °C
θ_{in}	primary air temperature, kg/s
θ_L	temperature of cold air, °C
θ_{out}	coal mill outlet temperature, °C
θ_{rc}	temperature of raw coal, °C

neglects the effect of coal moisture on the outlet temperature of the coal mill. Basing on the above model, Zeng, Hu, and Gao et al. (2015) proposed a nonlinear dynamic model of coal mills that considers the effect of raw coal moisture on the energy balance of the coal mill. Although the model output and the actual output are consistent, the model has many parameters to be identified. The coal mill is assumed to be a lumped parameter object, and a calculation method based on the static heat balance of the coal mill calculates all heat input into or output from the coal mill quantitatively; however, a model of the coal mill has yet to be established on this basis (Feng, Shen, & Yang, 1997; Ganapathy, 2002; Magdalinović, 1989). Basing on the static heat balance of the coal mill, some researchers proposed a quadratic equation of the raw coal moisture (Zeng, Hu, & Liu et al., 2015). Their results indicate that the calculation method of coal moisture is highly accurate when the coal mill operates under stable conditions.

Pulverizing system is a typical multivariable, nonlinear, time-varying system with strong coupling, large inertia, and time delay. People usually have no choice but to sacrifice the economy and efficiency of the system to ensure its safe and reliable operation. Hence, the conventional controller designed in this case cannot achieve decoupling control of the system, resulting in a poor control effect. Therefore, advanced, model-based control algorithms have been applied to the design of pulverizing control systems in recent years. Fei and Zhang (2007) proposed a tracking control scheme based on a T-S fuzzy model of medium-speed pulverizing systems. This scheme considers important performance indices for tracking control systems with a guarantee of their real-time characteristics. Simulation results showed that the control scheme can make the output variables of continuous nonlinear systems with uncertainties track the desired trajectories asymptotically and can maintain the internal stability of closed-loop systems; however, this control scheme cannot achieve the decoupling control of pulverizing systems. Mohamed, Wang, and Al-Duri et al. (2012) developed a control strategy to predict the future demand for fuel input and implement control actions at the earliest possible time for a supercritical coal-fired power plant. Their simulation results suggest that the control strategy is effective; however, this control strategy cannot effectively overcome the internal disturbance of the coal feed rate, rendering the precise control of the output of a pulverizing system impossible. Zeng, Hu, and Gao et al. (2015) designed a generalized predictive control scheme based on state equations for MPS medium-speed coal mill pulverizing systems. This scheme considers both the safety of the milling equipment and the optimum coal mill outlet temperature for energy saving. Their results indicated that the control method can improve the coal mill outlet temperature as much as possible within the safe operation of the coal mill equipment.

Using the above-stated literature (Feng et al., 1997; Ganapathy, 2002; Magdalinović, 1989; Wei et al., 2007; Zeng, Hu, & Gao et al., 2015; Zeng, Hu, & Liu et al., 2015), the researchers present a dynamic model of the pulverizing system in the current study on the basis of its mass and energy balance. The effect of raw coal moisture on the energy balance of the coal mill is considered to improve the accuracy of the model, and all heat inputs into or outputs from the coal mill are calculated quantitatively to reduce the number of parameters that need to be identified. Basing on the established model, the researchers constructed an estimated signal of outlet coal powder flow of the coal mill and proposed that this signal is the new control target of the pulverizing system's output. An optimized output control scheme of the pulverizing system was then designed on the basis of the estimation of outlet coal powder flow of the coal mill. This scheme considers the