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Modeling and control of ball mill system considering coal moisture

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ABSTRACT

This study analyzes the dynamic characteristics of duplex inlet and outlet ball mill direct firing pulverizing system. A mass and energy balance-based model is built by thermodynamic analysis. As a critical parameter in pulverized coal humidity control, coal moisture is considered in the mechanism model, and an extended Kalman filter is designed to estimate the coal moisture. A multivariable control system is designed using extended state space predictive controller. The dynamic characteristic of the mill can be effectively forecasted using the established model. The system can rapidly track unit load changes while reducing the disturbance caused by coal moisture and other outlets.

1. Introduction

Duplex inlet and outlet ball mills are widely used in 200–300 MW coal-fired generating units. This pulverizing system is easily adaptable to multiple coal type and is simple to operate, thus it is suitable for pulverizing coal with low grindability, high abrasiveness and required degree of fineness. However, the system has the characteristics of multivariable, strong coupling, long-time delay and time-varying, which prevents duplex inlet and outlet ball mill from being automatically controlled for long periods. In addition, the security and economy of generating units have setbacks, such as waste of auxiliary power. Thus, research on modeling and control of the pulverizing system can improve its operation reliability and adaptability to unit load. The result can also improve boiler combustion stability and efficiency, which can reduce consumption, lower production costs and improve economic benefits.

Cui et al. [1] established a model for the duplex inlet and outlet ball mill based on a fuzzy neural network. The model has good stability and reliability, but it cannot reflect the dynamic characteristics of whole working condition under the restriction of data size and data range. Chai et al. [2] developed an intelligent decoupling control method and applied it to the ball mill coal pulverizing system. In the method the effects of nonlinearities are dealt with by neural network compensations and coupling effects are handled by specifically designed decoupling compensators. However it failed to consider coal moisture, which could influence the accuracy of the model to a certain extent. As for online measurement of coal moisture, the methods can be divided into hardware measurement and soft sensing methods. Kim et al. [3] and Tanno et al. [4] applied near infrared spectrum and reflective terahertz spectrum respectively in coal moisture measurement, but these methods require expensive equipment. Odgaard and Mataji [5] presented a method for estimating moisture content of coal based on a simple dynamic energy model of a MPS coal mill, which is used to handle faults and operation under special conditions. Other researchers [6–9] used neural network, multivariate regression, state estimation and Kalman filtering to estimate coal moisture online, thereby establishing a solid foundation on coal moisture measurement's application in control optimization and fault diagnosis.

In the presented study, a nonlinear duplex inlet and outlet ball mill model with four inputs and four outputs is established. The dynamic characteristics of coal moisture, fill level and outlet temperature of the mill are considered in the model. The parameters of the model are identified and verified by operating data and the prediction error minimum method (PEM). An extended Kalman filter (EKF) is designed to estimate coal moisture, and obtain the simplified nonlinear model under current working conditions. Based on the EKF, a new extended state space predictive control method is used to control the established model. The results demonstrate the accuracy of the model and the validity of the control method.

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Nomenclature

L_w	fill level of coal mill (Pa)	u_R	valve position of load air (%)
W_c	inlet coal flow of coal mill (kg/s)	u_p	valve position of bypass air (%)
W_{pf}	outlet pulverized coal flow of coal mill (kg/s)	u_L	valve position of cold air (%)
W_{air}	inlet primary air flow of coal mill (kg/s)	u_H	valve position of hot air (%)
W_{pf0}	calculation value of pulverized coal flow (kg/s)	R_{air}^{max}	maximum flow of load air (kg/s)
L_{W0}	optimal fill level (Pa)	P_{air}^{max}	maximum flow of bypass air (kg/s)
R_{air0}	optimal load air flow (kg/s)	W_L^{max}	maximum flow of cold air (kg/s)
R_{air}	flow of load air (kg/s)	W_H^{max}	maximum flow of hot air (kg/s)
P_{air}	flow of bypass air (kg/s)	T_{out}	outlet temperature of coal mill (°C)
W_L	flow of cold primary air (kg/s)	P	current of coal mill (A)
W_H	flow of hot primary air (kg/s)	θ_{CM}	coal moisture (%)
T_{in}	inlet primary air temperature of coal mill (°C)	W_{free}^{water}	evaporation of coal moisture (kg/s)
T_L	temperature of cold air (°C)	K_i	parameters of the model; $i = 1, 2, \ldots 18$
T_H	temperature of hot air (°C)		
$C_{p,a}$	specific heat capacity of air [kJ/(kg °C)]		

2. Simplified nonlinear model of duplex inlet and outlet ball mill

2.1. Operating principle of the coal mill

Fig. 1 shows the structure of a duplex inlet and outlet ball mill. The system is equivalent to two parallel cylinders joined together in one ball mill to achieve high milling efficiency. Milling work is carried out by the collision, squeezing and grinding of the steel balls inside the mill. The working principle described as follows [10]. When the cylinder rotates, the steel balls are subjected to centrifugal and frictional forces. They fall at parabola direction after rotating to a certain height and proceed to pulverize raw coal. The pulverized coal is transferred from the cylinder body into coarse separator by primary air. The unqualified pulverized coal falls back into coal chute for further grinding and the qualified pulverized coal is sent to the boiler for combustion.

In duplex inlet and outlet ball mill pulverizing system, pulverized coal flow must meet the needs of unit load command. However, the cylinder buffer capacity causes long time delays in the system, and pulverized coal flow can be influenced by fill level and primary air flow. Therefore the system is characterized by strong non-linearity and coupling. On the other hand, nowadays the source and composition of coal for electricity generation is complex. To reduce fuel costs, a number of power plants have opted to mix large proportions of inferior coal in blending and combustion, which results in considerable variations in the index parameters of fuel. However, changes of coal moisture have significant effects on coal calorific value and fluidity of pulverized coal. Thus the establishment of an effective dynamic mathematical model that considers coal moisture and the design of a control system will be beneficial for the economic and safe operation of generation units.

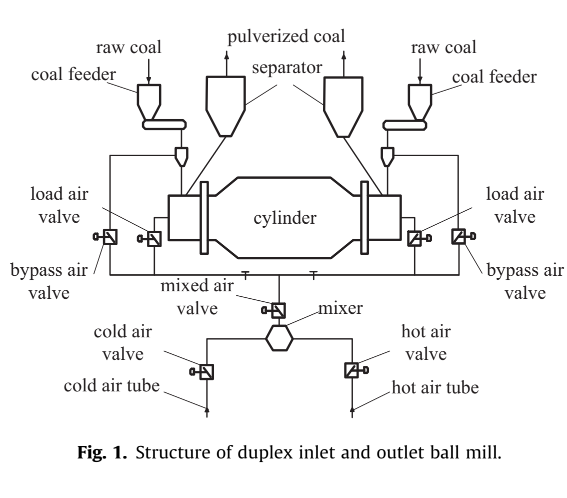

Fig. 1. Structure of duplex inlet and outlet ball mill.

2.2. Nonlinear model of the coal mill and identification of parameters

The established coal mill model is based on the following assumptions: (1) the process of coal grinding is simplified by disregarding the separation of coal particles; (2) the grinding and delivery of pulverized coal are divided into two stages in the mill; and (3) pulverized coal sizes at the outlet is neglected in the model, and only raw coal and pulverized coal exist in the mill. The mill model can be described by the following equations under stable operating conditions [11–13].

According to the mass balance inside coal mill, the differential equation of fill level is established as Eq. (1).

$$\dot{L}_W = K_1(W_C - W_{pf}) \tag{1}$$

where outlet pulverized coal flow W_{pf} is equal to the mass of pulverized coal brought out by primary air from the mill, and is influenced by outlet temperature, fill level, load air flow and position of coarse separator valve. The influences are represented by k_T, k_{Wm}, k_{tf} and k_{cf}, and the relationship is shown in Eq. (2)[12].

$$\begin{aligned} W_{pf} &= W_{pf_0} k_T k_{Wm} k_{tf} k_{cf} \\ k_T &= \frac{2.1}{1+e^{-\left(\frac{T-5}{30}\right)^2}} - 1.091 \\ k_{Wm} &= 1 - \frac{|L_W - L_{W0}|}{L_{W0}} \\ k_{tf} &= \frac{1}{0.7 + \frac{0.3R_{air0}}{R_{air}}} \end{aligned} \tag{2}$$

When outlet temperature is above 70 °C, k_T approximately equals to 1. Under stable operating conditions it is assumed that the position of coarse separator valve k_{cf} is constant. So Eq. (2) can be transformed into:

$$W_{pf} = K_2\left(1 - \frac{|L_W - K_3|}{K_3}\right)\frac{1}{0.7 + \frac{K_4}{R_{air}}} \tag{3}$$

We assume that primary air is ideal gas, and specific heat capacity of air $C_{p,a}$, as well as temperature of cold air T_L and hot air T_H are constant. Based on the balance of mass and energy, inlet primary air flow W_{air} and inlet primary air temperature T_{in} of coal mill are defined in Eqs. (4) and (5):

$$W_{air} = R_{air} + P_{air} = W_L + W_H \tag{4}$$