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Optimal operation of coal conveying systems assembled with crushers using model predictive control methodology

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HIGHLIGHTS

- Belt conveyors and crushers are taken as a whole for energy efficiency improvement.
- Feed rate, belt speeds and crusher rotational speed are used as optimization variables.
- MPC can resist the disturbances from forecasting, execution, and feeding particle size.
- Strategies are verified with a coal conveying system in a coal-fired power plant.

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ABSTRACT

Belt conveyors and crushers are always assembled in series to form coal conveying systems; reasonably, this paper takes them as a whole for energy efficiency optimization. The energy models of the key energy consuming devices, belt conveyors and crushers, are firstly constructed. They are then employed to formulate an open loop energy efficiency optimization problem for the studied coal conveying systems. The coal feed rate, belt speed and crusher rotational speed are taken as the optimization variables; and, the energy cost, with consideration of time-of-use (TOU) tariff, is formulated as the objective function. Next, basing on the above open loop optimization problem, a closed-loop model predictive control (MPC) strategy is constructed. The MPC strategy has the ability to deal with various disturbances with its feedback correction and receding horizon optimization mechanisms. A coal conveying system in a coal-fired power plant is taken as a case study for verification of the two strategies. The open loop optimization and MPC strategies are investigated respectively for comparison studies. The results show that, unlike the open loop optimization, the MPC strategy can deal with the disturbances of coal consumption forecasting, the disturbances of belt feeding rate and the disturbances of mean particle size of feeding coal effectively. The MPC strategy can considerably improve the energy efficiency of the whole coal conveying system while satisfying all the constraints. Its robustness and adaptability are verified through the comparison studies.

1. Introduction

Coal conveying systems are the critical auxiliary systems for coal dependent industries, like steelworks, cement plants, coking plants and coal-fired power plants. They shoulder the tasks of unloading, depositing, transferring and allocating the raw coal or coal products. China is the largest coal consumption country in the world. Since 2011, coal consumption in China has accounted for more than half of the global market [1]. Accordingly, the coal handling systems have been expanding continuously during the last few decades in China; and they are consuming energy heavily. For example, the coal conveying systems in coal-fired power plants are identified to contribute a considerable part to the total auxiliary power. Hence, it is of great importance to focus on the energy efficiency of coal conveying systems. A coal conveying system is an energy conversion system from electrical energy to mechanical energy, where crushers are usually assembled with conveyors to form the transferring routes. In a coal conveying system, the conveyors and crushers are the key energy consuming devices. Its energy efficiency can be divided into four components as performance efficiency, operation efficiency, equipment efficiency and technology efficiency, POET in short, according to the POET framework [2]. For most coal conveying systems, currently, their energy efficiency improvements are mainly achieved at operational or equipment levels [3]. At operational level, the

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Nomenclature

$f_p(V,T)$	power of belt conveyor (W)
V	belt speed (m/s)
T	feed rate (t/h)
Q_G	unit mass of the material along the belt (kg/m)
η_B	efficiency of the belt conveyor system
E	specific net energy of the crusher (J/kg)
R	rotor radius of the crusher (m)
ω	rotor angular velocity of crusher (rad/s)
T_R	mass feed rate of the crusher (t/h)
n	rotational speed of the crusher (rpm)
η_C	drive efficiency of ring hammer crusher
P_m	power of the crusher (W)
$P_{m,0}$	no-load mechanical power consumption of the crusher (W)
λ	constant coefficient (–)
$p(t)$	TOU tariff (¥/kW h)
p^j	electricity price at jth sample time (¥/kW h)
V_i^j	belt speed of the ith belt conveyor at jth sample time (m/s)
T_i^j	feed rate of ith belt conveyor at jth sample time (t/h)
n^j	rotational speed of ring hammer crusher at jth sample time (rpm)
t_s	sample time (h)
ϖ	weight (–)
IRC	remaining coal in the bins at the beginning of each control interval (t)
R_C	remaining coal in the bins (t)
L_U	upper limit of remaining coal in the bins (t)
L_L	lower limit of remaining coal in the bins (t)
C_C^k	coal consumption rate at the kth sample time (t/h)
d_p	mean particle size of the product (mm)
d_F	mean particle size of the fed coal (mm)
ρ	material density (kg/m^3)
Kl_c	fracture toughness of the object material (MPa m$^{0.5}$)
V_p	propagation velocity of the longitudinal elastic waves in the material (m/s)
p_0, p_1, p_2	off-peak, standard and peak energy tariff (¥/kW h)
L_d	load assignment of the generation units (MW)
a, b, c	coefficients (–)

energy efficiency of a coal conveying system is usually improved through the coordination of its sub-systems or components. In [4], an adaptive observer based energy model of belt conveyors is presented. Ref. [5] aims at downhill conveyors (DHCs). An optimal scheduling model and three drive configuration options are proposed to improve the energy efficiency of conveyor belt systems. In [6], an Estimation-Calculation-Optimization method is proposed to achieve green operation of belt conveyors while keeping belt in good dynamic behaviors in transient operations. Crushers are energy consuming devices of conveying systems as well. In [7], an optimal control model for vertical shaft impact (VSI) crushing processes is proposed for energy efficiency improvement. In [8], an optimization was made on how to operate a jaw crusher most energy-efficiently with evolutionary algorithm.

Concerning the assembly of belt conveyors and crushers, this paper takes them as a whole for energy efficiency optimization. An open loop optimal control is firstly proposed to improve the energy efficiency of coal conveying systems assembled with crushers at operational level. From the control theory perspective, the open loop optimization cannot deal with certain disturbances and unexpected reactions of the coal conveying system components. Unfortunately, the disturbances and inaccuracy always exist in practical applications. It makes the solutions of the open loop optimization inapplicable in some field application cases. Usually, a closed-loop control strategy is expected to better handle uncertainties and disturbances. In this paper, model predictive control (MPC) is employed to improve the energy efficiency of coal conveying systems. MPC is an effective way to deal with the constrained optimal control problems. It is capable of handling the constraints, nonlinear processes and multivariable cases easily [9–12].

MPC uses a process model to predict the future response of a plant. In fact, MPC is based on a sliding-window strategy in which an objective function is optimized over a moving time-horizon. Therefore, it allows for real-time optimization to be applied. The feedback mechanism provides MPC control with robustness subject to uncertainties [13,14]. With a prediction model, MPC can take control actions before a change to the output actually occurs [15]. Particularly, MPC has been successfully applied in the process industries. Ref. [16] proposes a model-based predictive control approach for optimal scheduling in concentrated solar power (CSP) plants towards a dual purpose. A model predictive controller based on reduced order model is proposed to control belt conveyor system in [17]. In our previous works, optimal control and MPC are applied to belt conveyor systems for energy efficiency improvement, respectively [18,25]. But the crushers were not considered in the optimization problems for simplicity purpose. In many conveying systems, crushers are assembled with belt conveyors. Thus, the two kinds of energy-intensive devices are deeply coupled. In this paper, we will combine belt conveyors and crushers together for efficiency improvement. Consequently, the optimization problems are extended and become more complex. Meanwhile, the presented results will be more comprehensive and practical.

The layout of the paper is as follows: In Section 2, the energy models of belt conveyors and ring hammer crushers are investigated. Section 3 applies the open loop optimization and MPC strategies to coal conveying systems for energy efficiency improvement. In Section 4, the results of the two control strategies for a coal conveying system in a coal-fired power plant are presented. The last section is conclusion.

2. Energy models of coal conveying systems

The models of the energy-intensive devices, belt conveyors and crushers, are needed prior to formulating the energy efficiency optimization problem.

2.1. Energy model of belt conveyors

In [19,24], an analytic energy calculation model of belt conveyors is proposed. It lumps all the parameters, defined in ISO 5048, into four coefficients, $\theta_1 - \theta_4$, to make itself suitable for optimization calculation. And the coefficients can be derived from the design parameters or identified through parameter identification [24]. This analytic energy calculation model of belt conveyors is as follows

$$f_p(V,T) = \frac{1}{\eta_B}\left(\theta_1 VT^2 + \theta_2 V + \theta_3 \frac{T^2}{V} + \theta_4 T + \frac{V^2 T}{3.6}\right), \quad (1)$$

where $f_p(V,T)$ is the power of belt conveyor (W), V is the belt speed (m/s), T is the feed rate (t/h) and $\theta_1 - \theta_4$ are the coefficients. η_B is