Applied Energy 87 (2010) 1929–1937

Contents lists available at ScienceDirect

Applied Energy

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

Optimal control of operation efficiency of belt conveyor systems

Shirong Zhang [a], Xiaohua Xia [b,*]

[a] Department of Automation, Wuhan University, Wuhan 430072, China
[b] Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

ARTICLE INFO

Article history:
Received 13 October 2009
Received in revised form 10 January 2010
Accepted 16 January 2010
Available online 9 February 2010

Keywords:
Belt conveyor system
Operation efficiency
Optimal switching control
Time-of-use tariff
Variable speed drive based optimal control

ABSTRACT

The improvement of the energy efficiency of belt conveyor systems can be achieved at equipment or operation levels. Switching control and variable speed control are proposed in literature to improve energy efficiency of belt conveyors. The current implementations mostly focus on lower level control loops or an individual belt conveyor without operational considerations at the system level. In this paper, an optimal switching control and a variable speed drive (VSD) based optimal control are proposed to improve the energy efficiency of belt conveyor systems at the operational level, where time-of-use (TOU) tariff, ramp rate of belt speed and other system constraints are considered. A coal conveying system in a coal-fired power plant is taken as a case study, where great saving of energy cost is achieved by the two optimal control strategies. Moreover, considerable energy saving resulting from VSD based optimal control is also proved by the case study.

1. Introduction

Belt conveyors are widely used for handling bulk material over short to medium conveying distances because of their high efficiency of transportation as compared to other transport methods. Energy cost forms a large part of the operational cost (up to 40% according to [1]) of belt conveyor systems. As a whole, the material handling is consuming a considerable proportion of the total power supply, for instance, 10% of the electricity supply is consumed by the material handling sector in South Africa [2]. Hence, it is significant to improve energy efficiency of belt conveyors to reduce the energy consumption or the energy cost of material handling, which is one of the development focuses of the belt conveyor technology [3].

A belt conveyor is a typical energy conversion system from electrical energy to mechanical energy. Its energy efficiency can be divided into four components: performance efficiency, operation efficiency, equipment efficiency, and technology efficiency. The improvement of energy efficiency can easily put to the operation efficiency and equipment efficiency for most energy systems. It holds true for belt conveyors. It is also noted that equipment efficiency, and consequently operation efficiency, decides performance efficiency which is usually reflected by various external indicators, such as energy consumption, energy cost, or emission of greenhouse gas. On the other hand, a performance indicator can drive an operation in the optimal efficiency mode.

The equipment efficiency of belt conveyor is improved either by introducing highly efficient equipment or improving the efficiency of the existing equipment. The idler, belt and drive system are the main targets for equipment efficiency. All the longitudinal main resistances are transferred via the idlers, hence the idlers have a great impact on the efficiency of belt conveyors. The influence from idler design, assembly, lubrication, bearing seals, and maintenance is reviewed in [4]. The energy consumption of long distance conveyors is reduced by improving the arrangement of the idlers [5]. An energy saving idler is proposed and tested in [6]. The performance of the belt is crucially influenced by the flexure resistance, which is the most important contributing factor to total resistance. Energy optimized belts are developed in [7] by improving the structure and rubber compounds of the belts. Energy-efficient motors and variable speed drives (VSDs) are recommended in [8]. Soft starters are commonly used to reduce belt tension during startup, furthermore, they reduce energy consumption as well [9]. Generally, the equipment efficiency oriented scenarios need extra investment and the efficiency improvement opportunities are limited to certain equipment.

The improvement of energy efficiency of belt conveyors can also be achieved at the operation level. Operation efficiency of an energy system is improved through the coordination of two or more internal sub-systems, or through the coordination of the system components and time, or through the coordination of the system and human operators. Two methods are proposed for load shifting of belt conveyors in [11,12,10]. They coordinate the on/off status of the belt conveyors and time to achieve higher operation efficiency, and consequently higher performance efficiency. However, these methods are designed to save cost instead of energy because they

* Corresponding author. Tel.: +27 12 420 2165; fax: +27 12 362 5000.
E-mail address: xxia@postino.up.ac.za (X. Xia).

0306-2619/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2010.01.006

just shift the work to different period of time according to the time-of-use (TOU) tariff. In the literature, speed control is recommended for energy efficiency of belt conveyor systems. The aim is to control the belt speed to keep a constantly high amount of material along the whole belt. The proper coordination of feed rate and belt speed is believed to have high operation efficiency in the majority of the literature, even though this belief is occasionally challenged, e.g., in [13] in two special circumstances. Further investigations on VSDs of belt conveyors are carried out in [14]. The theoretical analysis along with experimental validation on a VSD based conveying and loading system is shown in [15], where the great saving in energy consumption (15–30%) and maintenance cost (10–30%) along with the great reduction in dynamic belt tension (30%) are proved. The closed-loop control for belt speed is employed in [16,17]. The load dependent control strategy is also applied to a passenger conveyor for energy optimization in [18]. Nowadays, the idea of speed control has been adopted by industry and successfully applied to some practical projects [15,16,19,20]. The current strategy of speed control employs lower level control loops or multi-speed drive to improve the operation efficiency of an individual belt conveyor [16,17]. Extra instruments, such as the laser scanner [16] and the radiation density measuring device [17], are needed to measure the loading level, which is the control variable of the current control strategy. Furthermore, the current control strategy cannot be used to deal with the system constraints and external constraints, such as TOU tariff and storage capacities, especially in cases when there is a need to coordinate multiple belt conveyors of a conveying system.

The main purpose of this paper is to introduce optimal control to belt conveyor systems to improve the energy efficiency. An optimal switching control strategy and a VSD based optimal control strategy will be proposed. We start with energy calculation model of belt conveyors. Then the optimal switching control problem and the VSD based optimal control problem for operation efficiency of belt conveyor systems are formulated. They take the TOU tariff into account and consider other relevant constraints to achieve the minimization of energy cost. This economic indicator of performance efficiency is employed by the two optimal control strategies to drive the operation of the belt conveyor system in its optimal efficiency. We use a coal conveying system, including five belt conveyors, in a coal-fired power plant as a case study. The optimal switching control strategy, the VSD based optimal control strategy and the current control strategy will be applied to this coal conveying system, respectively. The simulation results will be presented.

The layout of the paper is as follows: In Section 2, the energy calculation model of belt conveyor is reviewed. In Section 3, the two optimal control strategies are formulated. Section 4 take the coal conveying system in a coal-fired power plant as a case study. The simulation results are presented in Section 5. The last section is the conclusion.

2. Energy calculation model

For the VSD based optimal control strategy of belt conveyors, a practical energy calculation model is needed. There exist several energy calculation models for the drive system design of belt conveyors [21–25]. These models originate from well-known standards or specifications, such as ISO 5048, DIN 22101, JIS B 8805, and Conveyor Equipment Manufacturers Association (CEMA). They employ many complicated equations for individual parts of the energy consumption. Moreover, they require many detailed parameters for calculation. These models are suitable for the design purpose and can hardly be used for optimization.

In [26], an analytic energy calculation model is proposed. It lumps all the parameters into four coefficients which can be derived from the design parameters or identified through the technique of parameter identification. This analytic energy calculation model of belt conveyors, proposed in [26], is as follows

$$f_P(V,T) = \theta_1 VT^2 + \theta_2 V + \theta_3 \frac{T^2}{V} + \theta_4 T + \frac{V^2 T}{3.6}, \tag{1}$$

where $f_P(V,T)$ is the power of the belt conveyor (kW), V is the belt speed (m/s), T is the feed rate (t/h) and θ_1–θ_4 are the coefficients which come from the design parameters or are identified by parameter identification. V and T also obey the following relation

$$T = 3.6 Q_G V, \tag{2}$$

where Q_G is the unit mass of the material along the belt (kg/m). The maximum value of Q_G,Q_{G_MAX}, is determined by the characteristics of the belt and the bulk material being transferred [21,22]. Energy model (1) calculates the mechanical energy of a belt conveyor. Incorporated with the efficiency of the drive system, model (1) is rewritten as follows

$$f_P(V,T) = \frac{1}{\eta}\left(\theta_1 VT^2 + \theta_2 V + \theta_3 \frac{T^2}{V} + \theta_4 T + \frac{V^2 T}{3.6}\right), \tag{3}$$

where η is the efficiency of the entire drive system. $\eta = \eta_d \cdot \eta_m$, where η_m is the efficiency of motor and η_d is the efficiency of the drive. In the next section, the energy model (3) will be integrated into the VSD based optimal control problem to improve the operation efficiency of the belt conveyor system through variable-speed control.

3. Optimal control of belt conveyors

The improvement of operation efficiency of a belt conveyor brings better performance efficiency. Specifically, the improvement of operation efficiency by coordinating the on/off status of belt conveyors and time (TOU tariff), as shown in [10], achieves great saving of energy cost. On the other hand, the improvement of operation efficiency through coordinating the belt speeds and feed rates also saves energy, consequently energy cost [15]. To consider optimal operation efficiency of belt conveying systems, we introduce optimal control to the above two methods with the objective to minimize energy cost. We take energy cost, a typical indicator to measure performance efficiency, as the objective of the optimization instead of a direct indicator of operation efficiency because the performance efficiency can drive the operation in its optimal efficiency and possibly balance the energy cost and a technical specification.

For a conveying system with n belt conveyors, the total electricity cost within a time period is related to the TOU tariff, the power of the conveyors, the time period and the number of belt conveyors. It can be expressed as an integration between t_0 and t_f as follows

$$J = \int_{t_0}^{t_f} \sum_{i=1}^{n} P_i(t) p(t) dt, \tag{4}$$

where $[t_0,t_f]$ is the time period for total cost calculation, $P_i(t)$ the power function of the ith belt conveyor and $p(t)$ is the TOU tariff function. For ease of discrete-time numerical analysis, the cost function (4) is discretized. Let the sample time $T_s = \frac{t_f - t_0}{N}$, we can obtain the discrete form of the cost function, J, as follows

$$J = \sum_{i=1}^{n} \sum_{j=1}^{N} P_i^j p^j T_s, \tag{5}$$

where P_i^j is the power of the ith belt conveyor at the jth sample time, $P_i^j = P_i(jT_s)$, and p^j is the electricity price at the jth sample time, $p^j = p(jT_s)$.

3.1. Optimal switching control problem

The optimal switching control strategy optimizes the on/off status of the belt conveyors to minimize the energy cost, and leaves the feed rate and belt speed to be uncontrolled. The TOU tariff is integrated into the objective function of this optimization. The control variable of this optimal control strategy is the on/off status of the belt conveyors of a conveying system. For an individual belt conveyor, its status can be represented by the switching function as follows

$$u_i(t) = \begin{cases} 1, & \text{when switched on}, \\ 0, & \text{when switched off}. \end{cases} \tag{6}$$

$u_i(t)$ is a binary integer and can not be any value in the interval $(0, 1)$. $u_i(t) = 1$ denotes that the ith conveyor is working at time t, while $u_i(t) = 0$ means the ith conveyor is switched off.

In this optimal switching control problem, the power of the ith conveyor, denoted by P_i, is considered constant when this conveyor is switched on. It comes from the assumption that the belt conveyor works with constant feed rate and fixed belt speed. Incorporated with the discrete form of the switching function, the power of the ith conveyor at jth sample time is $P_i^j = P_i u_i^j$. Hence, (5) is rewritten as

$$J = \sum_{i=1}^{n} \sum_{j=1}^{N} P_i u_i^j p^j T_s. \tag{7}$$

This cost function can be taken as the objective function of the optimal switching control problem which is to minimize the energy cost subject to relevant constraints. The typical constraints of this optimal problem originate from the storage capacities and the total productions. All the constraints can be expressed as the following general form

$$g(u^j, jT_s) \leqslant 0. \tag{8}$$

In the following case study, the detailed description of the constraints for this problem will be analyzed and formulated.

Eventually, the optimal switching control problem is formulated as

$$\min \quad J(u_i^j : 1 \leqslant i \leqslant n, 1 \leqslant j \leqslant N) = \sum_{i=1}^{n} \sum_{j=1}^{N} P_i u_i^j p^j T_s,$$
$$\text{subject to} \quad g(u^j, jT_s) \leqslant 0. \tag{9}$$

The solution to this problem, denoted by

$$\bar{u} = (\bar{u}_1^1, \bar{u}_2^1, \ldots, \bar{u}_n^1,\ \bar{u}_1^2, \bar{u}_2^2, \ldots, \bar{u}_n^2, \ldots,\ \bar{u}_1^N, \bar{u}_2^N, \ldots, \bar{u}_n^N)$$

is the optimal operational instructions for the belt conveyors. Each element of the operational instruction, $\bar{u}_i^j$, is either 0 or 1. So the optimization problem in this case is a binary optimization problem.

3.2. VSD based optimal control problem

Nowadays, many belt conveyors are equipped with VSDs, where the VSD based optimal control strategy can be applied. For a belt conveyor with VSD, its power at the jth sample time can be expressed as $P_i^j = f_P(V_i^j, T_i^j)$ according to (3). Combining P_i^j with (5), we obtain the total electricity cost as follows

$$J = \sum_{i=1}^{n} \sum_{j=1}^{N} f_P(V_i^j, T_i^j) p^j T_s. \tag{10}$$

This cost function can be taken as the objective function of the VSD based optimal control problem.

In practice, large ramp rates of belt speed do harm to certain equipment or components of the belt conveyor. One way to reduce the ramp rate of belt speed is to integrate it into the objective function for minimization. Thus, an additional part, $\sum_{i=1}^{n} \sum_{j=1}^{N-1} (V_i^{j+1} - V_i^j)^2$, is added to the objective function (10). The modified objective function is expressed as follows

$$J = \sum_{i=1}^{n} \sum_{j=1}^{N} f_P(V_i^j, T_i^j) p^j T_s + \varpi \sum_{i=1}^{n} \sum_{j=1}^{N-1} (V_i^{j+1} - V_i^j)^2, \tag{11}$$

where ϖ is a weight, which is employed to balance the economic performance and the technical specification. A second way to consider the ramp rate constraints is to directly impose lower and upper bounds for $V_i^{j+1} - V_i^j$. A third way is to further model the dynamics of the drive systems, so, dynamical constraints of V_i^{j+1} and V_i^j can be established. In this paper, the first way of dealing with ramp rate constraints is employed for simplicity purpose. Another reason for us to build a technical constraint into the objective function is to show that a performance efficiency indicator can represent a balance between an economic indicator and a technical indicator. We will show how operation efficiency can be driven by optimizing a performance efficiency indicator.

There are other constraints. The typical ones come from the storage capacities, the total productions, the belt speeds, the feed rates and the unit mass of the material on the belt. All these constraints can be expressed as the following general form

$$g(V^j, T^j, jT_s) \leqslant 0. \tag{12}$$

In the following case study again, a detailed description of the constraints will be given.

Now, the VSD based optimal control problem is formulated as

$$\min \quad J(V_i^j, T_i^j : 1 \leqslant i \leqslant n, 1 \leqslant j \leqslant N) = \sum_{i=1}^{n} \sum_{j=1}^{N} f_P(V_i^j, T_i^j) p^j T_s + \varpi \sum_{i=1}^{n} \sum_{j=1}^{N-1} (V_i^{j+1} - V_i^j)^2,$$
$$\text{subject to} \quad g(V^j, T^j, jT_s) \leqslant 0. \tag{13}$$

The solution to this problem, $[\overline{V}_i^j, \overline{T}_i^j$:1 ⩽i ⩽n, 1 ⩽j ⩽N], is the operational instructions for the belt conveyors, where

$$\overline{V}_i^j = (\overline{V}_1^1, \overline{V}_2^1, \ldots, \overline{V}_n^1, \overline{V}_1^2, \overline{V}_2^2, \ldots, \overline{V}_n^2, \ldots, \overline{V}_1^N, \overline{V}_2^N, \ldots, \overline{V}_n^N)$$

and

$$\overline{T}_i^j = (\overline{T}_1^1, \overline{T}_2^1, \ldots, \overline{T}_n^1, \overline{T}_1^2, \overline{T}_2^2, \ldots, \overline{T}_n^2, \ldots, \overline{T}_1^N, \overline{T}_2^N, \ldots, \overline{T}_n^N).$$

In this case, the problem at hand is a real-value optimization problem.

The optimal switching control and the VSD based optimal control are now cast into the ordinary optimal control problems where various control system techniques can be applied. In the following section, the two optimal control strategies are to be applied to the coal conveying system in a coal-fired power plant.

4. A case study of the coal conveying system in a coal-fired power plant

4.1. Overview of the system

The coal conveying system in a coal-fired power plant at an anonymous location is shown as Fig. 1. At present, this power plant has two 600 MW units. Two 1000 MW units will be set up in the future. The coal conveying system is designed for four units. The raw coal is delivered to this power plant by a vessel. Two continuous ship unloaders along with three belt conveyors, C1, C2, and C3, transfer the raw coal from the vessel to the coal storage yard. Then, the coal is fed to boilers through C4, C5, C6, C7, and C8 belt

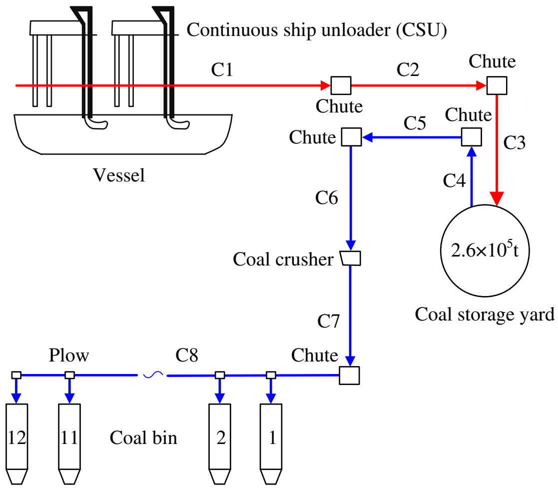

Fig. 1. Process flow diagram of the coal conveying system.

conveyors to meet the demand of the two units. Between C6 and C7, there is a coal crusher. Each boiler has six coal bins. The total capacity of the 12 bins is sufficient to sustain the two units for 11.8 h under rated loads.

Actually, each belt conveyor has its backup standby; the two belt conveyors make one pair. For example, C1 consists of two belt conveyors, C1A and C1B. Under the conventional operational mode, only one belt conveyor of the pair runs and another one is on standby. Hence, it is reasonable to take one belt conveyor of each pair for investigation.

The feeding process from coal storage yard to the coal bins is suitable for energy optimization because it can be isolated to be controlled independently and has rather big buffers (coal bins) for optimal scheduling. The coal crusher will not be included in the following investigation because it follows its own optimal control strategy. The design parameters of C4, C5, C6, C7, and C8 are shown in Table 1. According to the methods in [26], we can obtain the coefficients of the energy calculation models of C4–C8 using the basic parameters in Table 1 and the other detailed design parameters from the specification. The bulk density of the coal along C7 is greater than that of the coal along C6 because the crusher decreases the particle size of the coal. It results in $Q_{G\_MAX6} \leqslant Q_{G\_MAX7}$, even though C6 and C7 have the same belt parameters.

The TOU tariff is an important input of the proposed optimal control strategies. In the case study, the regional power grid has its own TOU tariff. It can be described by

$$p(t) = \begin{cases} p_o, & \text{if } t \in [0, 8), \\ p_s, & \text{if } t \in [8, 9) \cup [12, 19) \cup [22, 24), \\ p_p, & \text{if } t \in [9, 12) \cup [19, 22), \end{cases} \tag{14}$$

where t is the time of any day in hours (from 1 to 24); p_o, p_s, and p_p are the off-peak, standard and peak TOU energy tariff in an anonymous monetary unit, A/kW h. At present, $p_o = 0.5p_s$, $p_p = 1.58p_s$, and $p_s = 0.7$ A/kW h.

4.2. Forecast of the coal consumption

The load of an unit is usually determined by economic dispatch [27]. Thus, the coal consumption of the unit can be forecasted through its load assignment and inherent characteristics. It can be represented as a quadratic function as follows [28,29]

$$F(P_d) = aP_d^2 + bP_d + c, \tag{15}$$

where P_d is the load assignment of the unit (MW), $F(P_d)$ is the coal consumption rate (t/h) and the three coefficients, a, b, and c are determined by inherent characteristics of the unit. In this case study, the two units are the same model and from the same manufacturer. They are supposed to have the same function of coal consumption with $a = -4.045 \times 10^{-5}$, $b = 0.3994$, and $c = 12.02$. These coefficients are derived from the specification of the unit.

The economic dispatch is usually implemented repeatedly and periodically. In the rest of the paper, 24 h are taken as the time interval of the optimal control problems. In view of system analysis, it is reasonable to treat the 12 coal bins as an unity. The total capacity of the bins can be calculated by TCB = 2 × 11.8 × $F(600)$ = 5595.5 t. For the sake of the feasibility and reliability of the coal conveying system, an upper limit (HL) and a lower limit (LL) are employed for the remaining coal in the bins. HL is generally set to be 85% of TCB and LL is set to be 35% of TCB. At any time, the remaining coal in the bins (RCB) should be within the range between HL and LL.

4.3. Assumptions for the system

The following assumptions are made in order to model the coal conveying system as simplified optimal control problems.

1. At any time, the coal storage yard always has enough coal to supply the feeding process.
2. Under the current control strategy and optimal switching control strategy, the belt conveyor operates either with its rated belt speed and upper limit of feed (when switched on) or with the feed rate of 0 (t/h) and power of 0 (kW) (when switched off). The upper limit of feed rate of ith belt conveyor, donated by T_{pi}, is determined by the its feeder or the feed rate of its upstream conveyors. A belt conveyor's T_p is always less than or equal to its rated feed rate. Furthermore, under certain conditions, T_p may be far less than the rated feed rate due to the mismatched feeder or material blockage.
3. The time delay associated with the coal from the coal storage yard to coal bins is ignored.

Table 1
The parameters of the belt conveyors under investigation.

Conveyors	C4	C5	C6	C7	C8
Width of the belt (mm)	1400	1400	1400	1400	1400
Feed rate [rated/maximum] (t/h)	1500/1800	1500/1800	1500/1800	1500/1800	1500/1800
Belt speed (m/s)	2.5	2.5	2.5	2.5	2.5
Center-to-center distance (m)	129.5	309.5	200.9	287.86	171.25
The net change in elevation (m)	16	8	12	12	0
θ_1	2.3733×10^{-4}	2.3733×10^{-4}	2.3733×10^{-4}	2.1359×10^{-4}	2.1359×10^{-4}
θ_2	3.5519×10^{3}	8.5097×10^{3}	6.9623×10^{3}	8.1479×10^{3}	6.4065×10^{3}
θ_3	0.0031	0.0031	0.0031	0.0028	0.0028
θ_4	47.4471	46.8719	93.4937	143.3385	13.3984

4. The dynamic energy consumption associated with start-up and stop of the belt conveyor is not taken into account.
5. Because this study is concentrated on the optimal control of belt conveyor system, the coal crusher is not taken into account. It is controlled by an independent control system.
6. At the beginning and the end of the control interval, the remaining coal in the bins, denoted by ICB, takes a constant and fixed value, which is necessary for the repeatedly implementation of the optimal control. In the following investigation, ICB is set to be 50% of TCB.
7. Twenty four hours and twenty minutes are taken as the optimal control interval and sample time, respectively. Thus, $N = \frac{t_f - t_0}{T_s} = 72$.

4.4. Current control strategy

A sequential control system (SCS), implemented by programmable controller (PC), is employed for this coal conveying system. It focuses mainly on the feasibility and reliability. The current control strategy for the feeding process is elaborated as follows. The SCS calculates the amount of the remaining coal periodically through the coal levels in the bins. If the remaining coal in the bins goes down less than LL, the SCS runs C4–C8 belt conveyors to feed coal to the bins. On the other hand, if the remaining coal goes up greater than HL, the SCS stops the feeding process.

4.5. Formulation of the optimal switching control strategy

In the feeding process, C4–C8 are serially interlinked and there are not buffers between them, hence, they should be switched on or switched off synchronously. They share the same switching function, u^j, and the same feed rate. In this case study, the objective function has the following specific form

$$J(u^j : 1 \leqslant j \leqslant N) = \sum_{i=4}^{8} \sum_{j=1}^{N} P_{i\_MAX} u^j p^j T_s, \tag{16}$$

where P_{i_MAX} $(4 \leqslant i \leqslant 8)$ is the power of the ith conveyor running with the rated speed and the upper limit of the feed rate, T_p. Because $\sum_{i=4}^{8} P_{i\_MAX}$ and T_s are constant, they can be removed from (16) to obtain the simpler form of the objective function as follows

$$\min J(u^j : 1 \leqslant j \leqslant N) = \sum_{j=1}^{N} u^j p^j. \tag{17}$$

The constraints for this optimal control problem are listed as follows:

1. At any time, the amount of the remaining coal in the bins, RCB, is within the range between HL and LL:

$$\mathrm{LL} \leqslant \mathrm{RCB}^j \leqslant \mathrm{HL}, \quad (1 \leqslant j \leqslant N). \tag{18}$$

2. The total amount of coal fed to the boilers is greater than or equal to the total consumption of the two units:

$$\sum_{j=1}^{N} T_p u^j T_s \geqslant \sum_{j=1}^{N} \mathrm{CC}^j T_s, \tag{19}$$

where CC^j is the coal consumption rate of the two units at the jth sample time.

The constraint (19) also guarantees that at the beginning and the end of each control interval the amount of the remaining coal in the bins keeps the approximate value.

This optimal switching control of belt conveyors is a binary integer programming problem. We use the *bintprog* function of the MATLAB Optimization Toolbox to solve this problem. *bintprog* has the following form

$$\begin{aligned} \min \quad & f^T x, \\ \text{subject to} \quad & A \cdot x \leqslant b, \\ & Aeq \cdot x = beq, \end{aligned} \tag{20}$$

where x is a binary integer vector. For this case study, x is the on/off status of the belt conveyors. It can be formulated as

$$x = [u^1, u^2, \ldots, u^N]^T, \tag{21}$$

and f is defined as

$$f = [p^1, p^2, \ldots, p^N]^T. \tag{22}$$

The constraints for this problem, (18) and (19), should be formulated as the form of (20). The remaining coal in the bins at the jth sample time, RCB^j, is expressed as

$$\mathrm{RCB}^j = \mathrm{ICB} + T_s \sum_{k=1}^{j} T_p u^k - T_s \sum_{k=1}^{j} \mathrm{CC}^k. \tag{23}$$

Combined with (23), the constraint (18) is changed to

$$-\sum_{k=1}^{j} u^k \leqslant \frac{-\mathrm{LL} + \mathrm{ICB} - T_s \sum_{k=1}^{j} \mathrm{CC}^k}{T_p T_s}, \tag{24}$$

and

$$\sum_{k=1}^{j} u^k \leqslant \frac{\mathrm{HH} - \mathrm{ICB} + T_s \sum_{k=1}^{j} \mathrm{CC}^k}{T_p T_s}. \tag{25}$$

The constraint (19) can also be changed to

$$-\sum_{j=1}^{N} u^j \leqslant -\sum_{j=1}^{N} \mathrm{CC}^j. \tag{26}$$

Then (24)–(26) are formulated as the inequality constraint of (20). When j ranges from 1 to N, (24) and (25) generate N inequalities, respectively. Constraint (26) is for the total amount and it contains one inequality. Hence, the formulated matrix A has the dimensions of $(2N + 1) \times N$ and b is a vector with dimension N.

4.6. Formulation of the VSD based optimal control strategy

Under the control of the VSD based optimal control strategy, the objective function of the feeding process has the following specific form

$$\min\ J(V_i^j, T_i^j) = \sum_{i=4}^{8} \sum_{j=1}^{N} f_P(V_i^j, T_i^j) p^j T_s + \varpi \sum_{i=4}^{8} \sum_{j=1}^{N-1} (V_i^{j+1} - V_i^j)^2. \tag{27}$$

The constraints for this optimal control problem are listed as follows.

1. Because C4–C8 are serially interlinked and there are not buffers between them, the feed rates of C4–C8 should be the same at any time:

$$T_4^j = T_5^j = T_6^j = T_7^j = T_8^j, \quad (1 \leqslant j \leqslant N). \tag{28}$$

2. At any time, the remaining coal is within the range between HL and LL:

$$\mathrm{LL} \leqslant \mathrm{RCB}^j \leqslant \mathrm{HL}, \quad (1 \leqslant j \leqslant N). \tag{29}$$

The remaining coal at the jth sample time is calculated by

$$\mathrm{RCB}^j = \mathrm{ICB} + T_s \sum_{k=1}^{j} T_4^k - T_s \sum_{k=1}^{j} \mathrm{CC}^k, \tag{30}$$

Table 2
The load assignment of the two units.

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12
Load (MW)	1136	1140	1148	1156	1160	1168	1172	1176	1184	1192	1196	1200
Coal consumption rate (t/h)	451.66	453.07	455.89	458.72	460.13	462.95	464.36	465.77	468.58	471.39	472.79	474.19
Time (h)	13	14	15	16	17	18	19	20	21	22	23	24
Load (MW)	1192	1184	1176	1164	1160	1168	1176	1192	1184	1168	1152	1144
Coal consumption rate (t/h)	471.39	468.58	465.76	461.54	460.13	462.95	465.77	471.39	468.58	462.95	457.31	454.48

where T_4^k can be substituted by the feed rates of the other belt conveyors because C4–C8 share the same feed rate all the time.

3. The total amount of coal fed to the boilers is greater than or equal to the total consumption of the two units:

$$\sum_{j=1}^{N} T_4^j T_s \geqslant \sum_{j=1}^{N} CC^j T_s. \tag{31}$$

4. At any time, the belt speeds of C4–C8 are within the feasible domain:

$$V_{i\_MIN} \leqslant V_i^j \leqslant V_{i\_MAX}, \quad (4 \leqslant i \leqslant 8, 1 \leqslant j \leqslant N). \tag{32}$$

5. At any time, the feed rates of C4–C8 are within the feasible domain:

$$T_{i\_MIN} \leqslant T_i^j \leqslant T_{pi}, \quad (4 \leqslant i \leqslant 8, 1 \leqslant j \leqslant N), \tag{33}$$

where T_{pi} is the upper limit of the feed rate of the ith belt conveyor.

6. For each belt conveyor under investigation, the unit mass of the material on the belt, Q_G, should be less than its maximum value:

$$Q_{G4}^j = \frac{T_4^j}{3.6V_4^j} \leqslant Q_{G4\_MAX}, \quad (1 \leqslant j \leqslant N),$$

$$\vdots$$

$$Q_{G8}^j = \frac{T_8^j}{3.6V_8^j} \leqslant Q_{G8\_MAX}, \quad (1 \leqslant j \leqslant N). \tag{34}$$

The *fmincon* function of MATLAB Optimization Toolbox is used to solve this VSD based optimal control problem. It has the following general form

$$\begin{aligned} &\min\ f(x),\\ &subject\ to\\ &c(x) \leqslant 0,\\ &Ceq(x) = 0,\\ &A \cdot x \leqslant b,\\ &Aeq \cdot x = beq,\\ &lb \leqslant x \leqslant ub. \end{aligned} \tag{35}$$

For this case study, the control variable, x is a vector containing the feed rates and belt speeds of C4–C8. Consequently, the dimension of x is 10 N. Constraints (32) and (33) are formulated as lb and ub of (35). Constraint (28) is formulated as the equality function, $Ceq(x)$. The left constraints, (29), (31) and (34) are integrated into the inequality function, $c(x)$. When this optimal control problem is solved, the optimal operational instructions of C4–C8 are given by

$$\bar{x} = [\overline{V}_4^1, \overline{V}_4^2, \ldots, \overline{V}_4^N,\ \overline{T}_4^1, \overline{T}_4^2, \ldots, \overline{T}_4^N, \ldots,\ \overline{V}_8^1, \overline{V}_8^2, \ldots, \overline{V}_8^N,\ \overline{T}_8^1, \overline{T}_8^2, \ldots, \overline{T}_8^N].$$

5. Simulation results

In this section, the current control strategy, the optimal switching control strategy and the VSD based optimal control strategy are simulated. A 24-h load assignments along with the corresponding

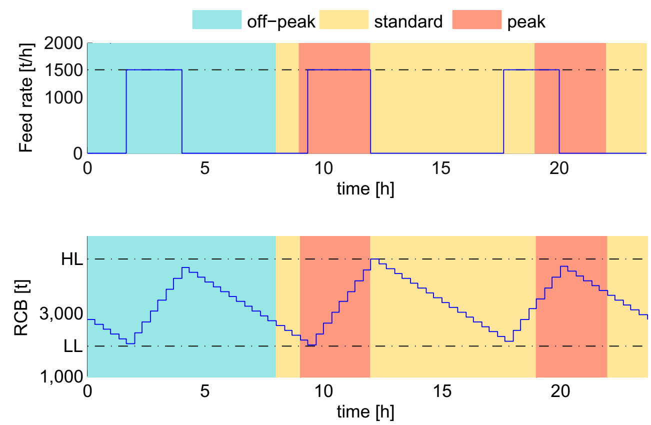

Fig. 2. Current control strategy with T_p = 1500 t/h.

coal consumption rates, as shown in Table 2, are used for the following simulations. The two units are supposed to have the same load assignment. This assumption comes from the fact that the two units have the same characteristics. For all the following simulations, ICB and ϖ in (27) are set to 50% × TCB and 500, respectively; moreover, the efficiency of the drives and motors, η_d and η_m, are set to 0.9408 and 0.945, respectively according to the specifications of the power plant.

In practice, many belt conveyors operate below their rated feed rates, even with empty belts. The loading limits of the feeders and the improper operation procedures are the main reasons for that. In order to analyze the influence resulting from the limited feed rates, two conditions (the upper limits of the feed rate T_p = 1500 t/h and T_p = 750 t/h) are used for investigation, respectively.

5.1. T_p = 1500 t/h

One thousand and five hundred tons per hour is the rated feed rates of the belt conveyors. Firstly, the current control strategy without optimization is applied to the conveying system. The result is shown as Fig. 2. Its legends are also valid for Figs. 3, 4, 7–9. Secondly, the optimal switching control strategy is simulated with the result as shown in Fig. 3. Thirdly, the VSD based optimal control strategy is simulated to get the result as shown in Fig. 4. Under the condition of the current control strategy or optimal switching control strategy, the belt conveyors run with V = 2.5 m/s and T = 1500 t/h (when switched on) or with V = 0 m/s and T = 0 t/h (when switched off) according to the assumptions. The feasibility of the current control strategy is proved by Fig. 2. However, it runs the belt conveyors during peak time without consideration of the TOU tariff, which results in more energy cost consequently. In Fig. 3, the operation status of the belt conveyors is optimally controlled with consideration of the relevant constraints. These operation instructions shift the working time of the belt conveyors away from the peak time to minimize the energy cost. The VSD based optimal control strategy stops the belt conveyors during peak-time to save energy cost, as shown in

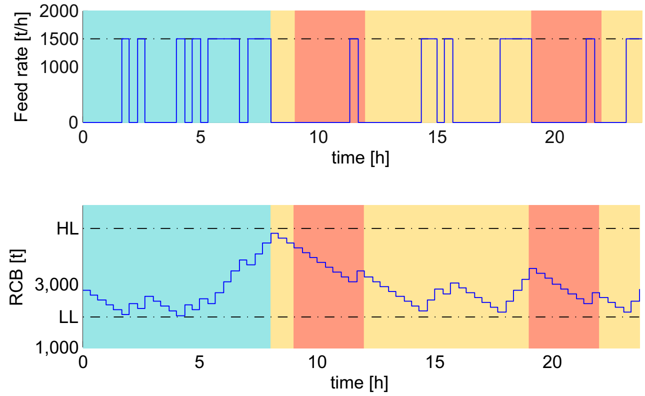

Fig. 3. Optimal switching control strategy with $T_p = 1500$ t/h.

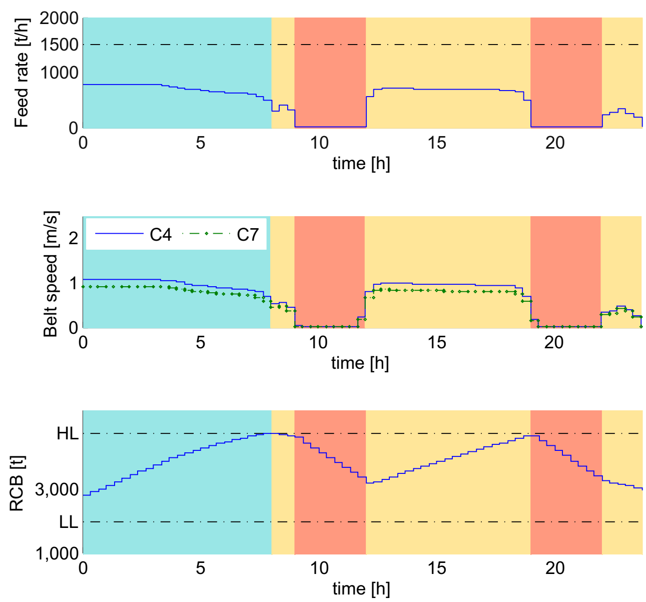

Fig. 4. VSD based optimal control strategy with $T_p = 1500$ t/h.

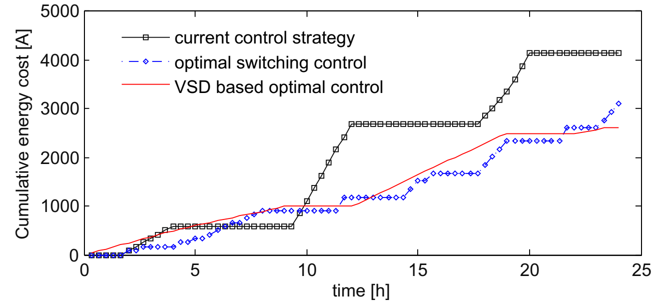

Fig. 5. Cumulative cost with $T_p = 1500$ t/h.

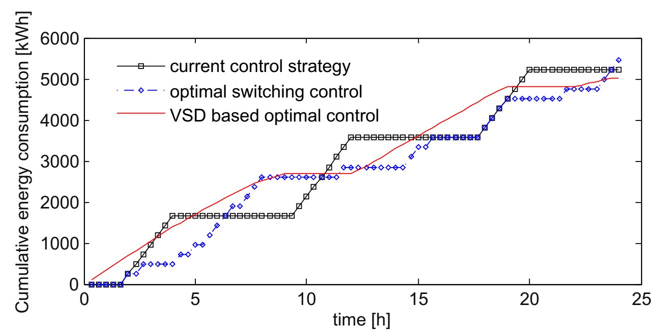

Fig. 6. Cumulative energy consumption with $T_p = 1500$ t/h.

Fig. 4. During off-peak and standard time, the feed rates and belt speeds are optimally coordinated to obtain high operation efficiency. In Fig. 4, the speed of C7 is always lower than that of C4. It results from the increase of bulk density of the coal after the crusher.

The cumulative energy cost and the cumulative energy consumption of the three strategies are show in Figs. 5 and 6, respectively. We take the current control strategy as the baseline. It is shown in Table 3 that the optimal switching control strategy reduces the energy cost dramatically by up to 28.26%, however, it can hardly save energy because it only optimizes when the energy is consumed instead of how the energy is consumed. In Fig. 6, the optimal switching control strategy consumes more cumulative energy than the current control strategy, because the former transferred more coal as shown in Table 3. On the other hand, 5.38% of the energy saving and 37.38% of the cost reduction from the VSD based optimal control strategy are realized as seen from Table 3. Most of its cost reduction comes from the coordination of the TOU tariff and the working time of the belt conveyors; and the other part is from its energy saving. The energy saving is achieved by controlling the feed rate and belt speed of each belt conveyor to keep its Q_G near the maximum value, Q_{G_MAX}. The rated feed rates of C4–C8 do not coordinate their rated belt speeds optimally, which is where the energy saving of the VSD based optimal control comes from.

5.2. $T_p = 750$ t/h

$T_p = 750$ t/h is used to demonstrate the operation condition of the belt conveyor with decreased feed rate. According to the assumptions, the belt conveyors, under the condition of the current control strategy or optimal switching control strategy, run either with $V = 2.5$ m/s and $T = 750$ t/h (when switched on) or with $V = 0$ m/s and $T = 0$ t/h (when switched off). The simulation results of the current control strategy, the optimal switching control strategy and the VSD based optimal control strategy are shown as Figs. 7–9, respectively. With the limited feed rate ($T = 750$ t/h) and rated belt speed, the current control strategy and the optimal switching control strategy require longer working time to fulfil the same task. The simulation result of the VSD based optimal control strategy is similar to that with $T_p = 1500$ t/h as shown in Fig. 4. However, the values of feed rate and belt speed in Fig. 9 are smaller than those in Fig. 4.

The cumulative energy cost and the cumulative energy consumption with $T_p = 750$ t/h are shown in Figs. 10 and 11, respectively. It is clearly shown in Fig. 10 that the optimal switching control and the VSD based optimal control achieve great reductions (21.37% and 35.42%, respectively) of energy cost, comparing with the current control strategy. At the same time, 15.35% of the energy saving is achieved by the VSD based optimal control strategy. This condition, with feed rate of $T = 750$ t/h, is farther away from the optimal operation condition of the belt conveyor system than that with rated feed rate ($T = 1500$ t/h). It is why the energy saving of the VSD based optimal control strategy from this condition (15.35%) is much larger than that from the condition with rated feed rate (5.38%). Anyway, the considerable energy sav-

Table 3
Performance of the optimal control strategies.

Strategies	Total amount of the coal (t)	Energy consumption (kW h)	Energy cost (A)	Unit energy consumption (kW h/t)	Unit energy cost (A/t)	Energy saving (%)	Cost saving (%)
T_p = 1500 t/h							
Current control strategy	11,000	5226.3	4137.3	0.475	0.376	/	/
Optimal switching control strategy	11,500	5463.8	3103.0	0.475	0.270	0.00	28.26
VSD based optimal control strategy	11,130	5003.4	2621.5	0.449	0.235	5.38	37.38
T_p = 750 t/h							
Current control strategy	11,000	5837.0	4011.6	0.530	0.365	/	/
Optimal switching control strategy	11,250	5969.6	3211.1	0.530	0.285	0.00	21.73
VSD based optimal control strategy	11,130	4999.5	2621.3	0.449	0.236	15.35	35.42

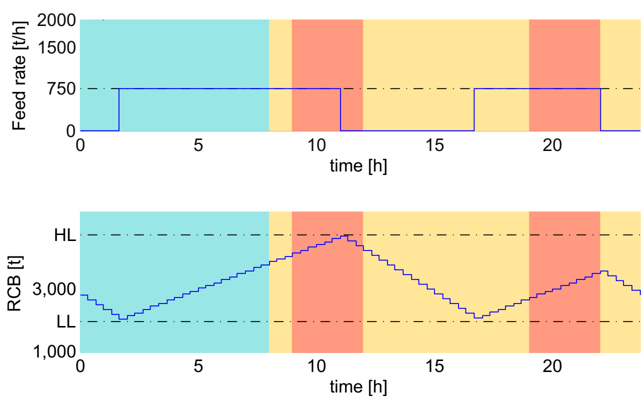

Fig. 7. Current control strategy with T_p = 750 t/h.

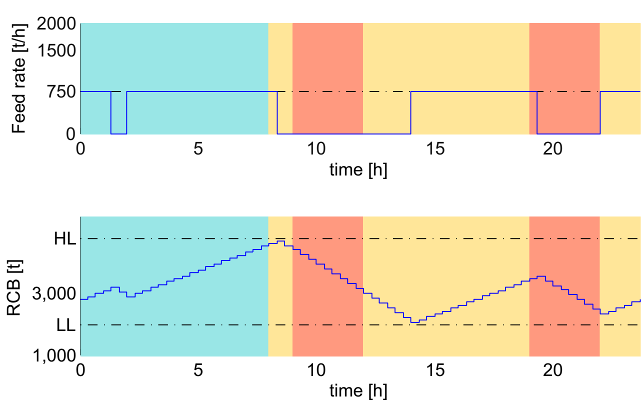

Fig. 8. Optimal switching control strategy with T_p = 750 t/h.

ing, resulting from the VSD based optimal control strategy, is proved by the simulation results, with an economic indicator, energy cost, instead of a direct indicator of energy consumption being employed as the optimization objective function. In fact, the belt conveyors are driven by the performance indicator to operate in their optimal efficiency, consequently, the energy saving is achieved.

In practice, if the belt conveyor systems are already equipped with VSDs, then the VSD based optimal control strategy can be applied easily. On the other hand, for those systems without VSDs, extra capital cost is required. In this case study for example, 10 VSDs are needed by C4, C5, C6, C7, and C8 to implement the VSD based optimal control strategy; and each VSD costs about 63,000 A. Under the same working condition and electricity price as used in the simulation, the payback period of the VSDs is roughly 1.15–1.26 years.

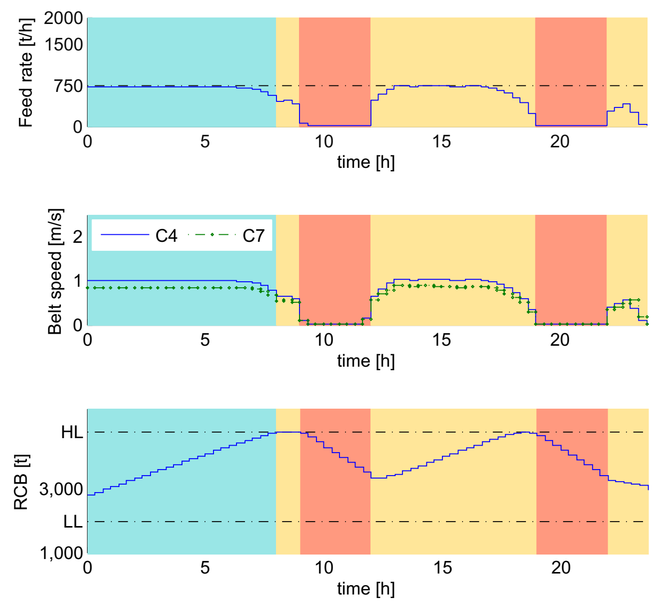

Fig. 9. VSD based optimal control strategy with T_p = 750 t/h.

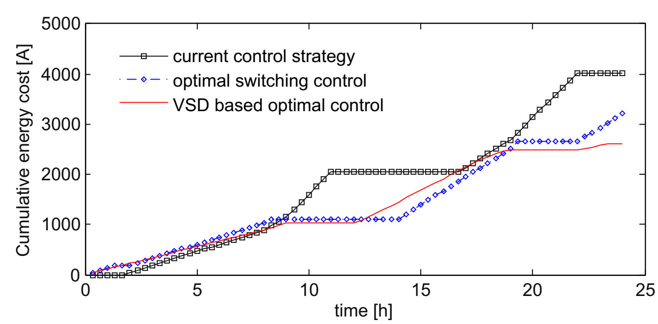

Fig. 10. Cumulative energy cost with T_p = 750 t/h.

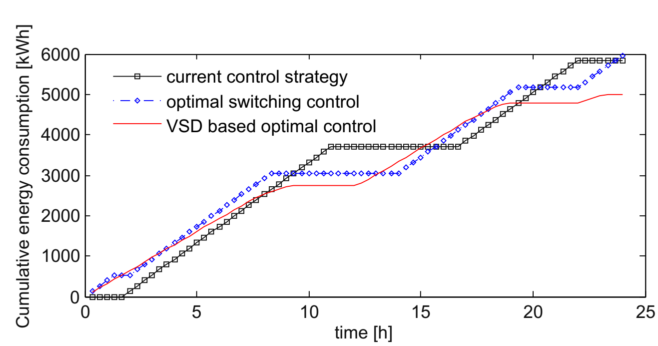

Fig. 11. Cumulative energy consumption with T_p = 750 t/h.

6. Conclusion

Generally, the improvement of energy efficiency of a belt conveyor system can be achieved through any one of its four components (performance, operation, equipment, and technology). This paper focuses on the most practical part, operation efficiency. An optimal switching control strategy and a VSD based optimal control strategy are proposed to improve the operation efficiency of the belt conveyor system, respectively. The former integrates the operation status and the TOU tariff into an objective function and takes other system and external constraints into consideration. Under this control strategy, the operation efficiency of belt conveyors is improved by optimally coordinating the on/off status of the belt conveyors and time. The VSD based optimal control strategy involves the energy model of belt conveyors, the TOU tariff and ramp rates of belt speed into its objective function. With this strategy, the improvement of the operation efficiency of belt conveyors is achieved by optimally controlled operational instructions concerning its working time, belt speeds and feed rates. Operation efficiency can indeed be reflected by the coordination of two or more physical sub-systems, by scheduling the time when energy is used or by the human skill that is operating the system. Operation efficiency of the belt conveyor system is achieved by optimizing a performance indicator, in other words, the performance indicator drives the operation in its optimal efficiency. A coal conveying system in coal-fired power plant is used for a case study. The optimal switching control strategy achieves large reductions of energy cost, however, it can hardly save energy. On the other hand, the VSD based optimal control strategy reduces the energy cost greatly, meanwhile, it saves the energy consumption considerably as well. An energy consumption reduction, while making financial sense, makes the VSD based optimal control strategy a sustainable scheme for energy management. Furthermore, a conclusion can be drawn that the belt conveyors with higher belt speeds or further decreased feed rates have the larger potential for improvement of operation efficiency.

The simulation also reveals that the computation of the two optimal control strategies is not very complex, hence they can be integrated with the existing SCS or implemented by an individual industrial personal computer (IPC). The two optimal control strategies can be implemented as open loop control or closed-loop control. The open loop implementation guides the operators to achieve the optimal operation of the belt conveyor system without interference with the existing control system. On the other hand, the closed-loop implementation drives the belt conveyors directly with its optimal operational instructions. It operates the belt conveyor systems in their optimal operation efficiency automatically, at the same time, it relieves the operators as well. The two optimal control strategies for belt conveyor systems are formulated as the general optimal control problems, hence, they can be easily applied to other conveying systems or similar industrial application areas.

References

[1] Hager M, Hintz A. The energy-saving design of belts for long conveyor systems. Bulk Solids Handl 1993;13(4):749–58.
[2] Marais J, Mathews E, Pelzer R. Analysing DSM opportunities on mine conveyor systems. In: Industrial and commercial use of energy conference; Cape Town, South Africa; 28–30 May 2008.
[3] Alspaugh MA. Latest developments in belt conveyor technology. MINExpo 2004; Las Vegas, NV, USA; 27–30 September 2004.
[4] Reicks AV. Belt conveyor idler roll behaviours. In: Alspaugh MA, editor. Bulk material handling by conveyor belt, vol. 7. Colorado: SME; 2008. p. 35–40.
[5] Staniak K, França Jr J. Energy saving in long distance conveyors – novel idler technology. In: Hennies WT, Ayres da Silva LA, Chaves AP, editors. Mine planning and equipment selection. Rotterdam, Netherlands: Balkema; 1996. p. 479–86.
[6] Tapp AG. Energy saving troughing idler technology. Bulk Solids Handl 2000;20(4):437–49.
[7] Jansen M. The development of energy-optimized conveyor belts – a joint project of the conveyor belt group of ContiTech AG and RWE power AG. World Min 2008;60(2):83–7.
[8] De Almeida AT, Fonseca P, Bertoldi P. Energy-efficient motor systems in the industrial and in the services sectors in the European Union: characterisation, potentials, barriers and policies. Energy 2003;28:673–90.
[9] Blaabjerg F, Pedersen JK, Rise S, Hansen H, Trzynadlowski AM. Can soft-starters help save energy? IEEE Indus Appl Mag 1997(September/October):56–66.
[10] Middelberg A, Zhang J, Xia X. An optimal control model for load shifting – with application in the energy management of a colliery. Appl Energy 2009;86:1266–73.
[11] Marx DJL, Calmeyer JE. An integrated conveyor energy model methodology. Trans South African Inst Elec Eng 2004;95:256–64.
[12] Marx DJL, Calmeyer JE.A case study of an integrated conveyor belt model for mining industry. IEEE AFRICON 2004; Gaborone, Botswana; 15–17 September 2004.
[13] Lauhoff H. Speed control on belt conveyors – dose is really save engery? Bulk Solids Handl 2005;25(6):368–77.
[14] Van Den Heuvel B. Investigations dealing with variable-speed drives of belt conveyor systems. World Min 2006;58(2):105–13.
[15] Daus W, Köerber S, Becher N. Raw coal loading and belt conveyor system at Nochten opencast mine – a new conveying and loading system based on drives controlled and adjusted by frequency converter. Braunkohle Surf Min 1998;50(2):117–30.
[16] Köhler U, Sykulla M, Wuschek V. Variable-speed belt conveyors gaining in importance. Braunkohle Surf Min 2001;53(1):65–72.
[17] Koopmann K, Weber D, Keller C, Daus W, Köber S. Conveying device for opencast mines. US Patent 6 209 711 B1, April 3; 2001.
[18] Kusumaningtyas I, Lodewijks G. Toward intelligent power consumption optimization in long high-speed passenger conveyors. In: Proceedings of the 2007 IEEE Intelligent Transportation Systems Conference; Seattle, WA, USA; 30 September–3 October 2007.
[19] Steven RB. Belting the worlds' longest single flight conventional overland belt conveyor. Bulk Solids Handl 2008;28(3):172–81.
[20] Gerard B. Optimisation of overland conveyor performance. Aust Bulk Handl Rev 2009(January/February):26–36.
[21] ISO. Continuous mechanical handling equipment – belt conveyors with carrying idlers – calculation of operating power and tensile forces. 2nd ed. ISO 5048; 1989.
[22] DIN. Continuous conveyors-Belt conveyors for loose bulk materials – basis for calculation and dimensioning, DIN 22101; 2002.
[23] JIS. Rubber belt conveyors with carrying idlers – calculation of operating power and tensile forces, JIS B 8805; 1992.
[24] Hager M, Simonsen H. Calculation and design of belt conveyors for bulk material. Braunkohle Surf Min 2000;52(3):245–60.
[25] GoodYear. Handbook of conveyor and elevator belting. Akron, Ohio: The Goodyear Tire & Rubber Company; 1975.
[26] Zhang S, Xia X. A new energy calculation model of belt conveyor. IEEE AFRICON 2009; Nairobi, Kenya; 23–25 September 2009.
[27] Xia X, Zhang J, Elaiw A. A model predictive control approach to dynamic economic dispatch problem. In: 2009 IEEE Bucharest Power Tech Conference; Bucharest, Romania; 28 June–2 July 2009.
[28] Wood AJ, Wollenberg BF. Power generation, operation, and control. 2nd ed. NewYork: Wiley; 1996.
[29] Park JB, Lee KS, Shin JR, Lee KY. A particle swarm optimization for economic dispatch with nonsmooth cost functions. IEEE Trans Power Syst 2005;20(1):34–42.