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Optimal energy control of a crushing process based on vertical shaft impactor ☆

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HIGHLIGHTS

- Energy optimal control strategy of a VSI crushing process is modeled.
- Potential of a daily energy cost saving of about 49.7% is shown.
- Potential of a daily energy saving of about 15.3% is shown.
- Most of energy cost saving is due to the optimal load shifting under time-of-use tariff.
- Energy saving is due to the operation of the process at the boundary of the admissible region.

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ABSTRACT

This paper presents an optimal control model to improve the operation energy efficiency of a vertical shaft impact (VSI) crushing process. The optimal control model takes the energy cost as the performance index to be minimized by accounting for the time-of-use tariff and process constraints such as storage capacity of the VSI crusher hopper, capacity of the main storage system, flow rate limits, cascade ratio setting, production requirement and product quality requirement. The control variables in the developed model are the belt conveyor feed rate, the material feed rate into the VSI crusher rotor, the bi-flow or cascade feed rate and the rotor tip speed of the crusher. These four control variables are optimally coordinated in order to improve the operation energy efficiency of the VSI crushing process. Simulation results based on a crushing process in a coal-fired power plant demonstrate a potential of a daily energy cost saving of about 49.7% and energy saving of about 15.3% in a high-demand season weekday.

1. Introduction

Vertical shaft impact (VSI) crushers are processing machines which are usually used in tertiary crushing stations of both aggregate and mining industries for crushing of hard rock material or ores when a product material with cubical shape and large amount of fines is required [1,2]. When compared to other tertiary crushers such as cone crushers, VSI crushers are becoming nowadays attractive due to their higher energy efficiency [1,3].

Processing machines form one of the biggest energy conversion systems in mining industries. In South Africa, for instance, 19% of the total electricity consumed by mining industries is used to run processing machines.[1] This therefore gives rise to a new research potential towards the possibility of improving the energy efficiency of processing machines such as VSI crushers, in order to further reduce their energy consumption or energy cost.

The energy efficiency of most energy conversion systems can be generally categorized in four components: technology efficiency, equipment efficiency, operation efficiency and performance efficiency [4–6]. The higher efficiency of a VSI crusher when compared to other tertiary crushers such as cone crushers, as above discussed, is mainly due to its technology efficiency improvement. The technology of VSI crushers is based on impact breaking action using the rotor kinetic energy while in cone crushers, for instance, the rock is broken by compression action. Another important feature that makes the VSI crusher to be technologically efficient is the cascade flow or bi-flow [1] option. This is defined as a fraction

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[1] Eskom, The Energy Efficiency series: Towards an energy efficient mining sector, <http://www.eskomidm.co.za>.

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Nomenclature

J_C	total energy cost (*currency*)
P_{el}	electrical power function of the drive motor (W)
t_0 and t_f	initial and final time of the control horizon (h)
$p(t)$	time-of-use (TOU) electricity tariff (currency/Wh)
R_1, R_2	inner radius and outer radius of the crusher rotor (m)
u_1, u_2	particle velocity into and exiting the crusher rotor (m/s)
ω	angular speed of the crusher rotor (rad/s)
V_t	rotor tip speed of the crusher (m/s)
ψ	angle between the tangential velocity and relative velocity of the particle (rad)
D_{open}	average diameter of the crusher inlet (m)
P_m	mechanical crushing power (W)
η	overall drive efficiency (–)
t_s and j	sampling period (h) and jth sampling interval
n_s	total number of sampling intervals
p_j	electricity price at jth sampling interval (currency)
T_R	material feed rate into the crusher rotor (t/h)
T_F	belt conveyor feed flow rate into the crusher (t/h)
T_{CSD}	cascade flow rate or bi-flow rate (t/h)
T_1	mass flow rate into the crusher hopper (t/h)
T_2	mass flow rate from the crusher hopper (t/h)
T_3	mass flow rate from the screen (t/h)
T_{RC}	recirculated material mass flow rate (t/h)
T_C	mass flow rate of the material consumption (t/h)
"*min*" and "*max*"	minimum and maximum of the variable
β	recirculated mass flow ratio (–)
α_{CSD}	cascade flow or bi-flow ratio (–)
M_H	material mass available in the crusher hopper (t)
M_{H_0}	initial value of M_H (t)
M_S	material mass available in the storage system (t)
M_{S_0}	initial value of M_S (t)
Klc	fracture toughness (mode 1) of the rock (Pa $m^{0.5}$)
ρ	bulk density of the rock material (kg/m^3)
V_p	propagation velocity of the elastic waves in the rock (m/s)
dF and dP	feed mean size and product mean size (m)
p_o, p_s, p_p	off-peak, standard and peak TOU electricity prices

of the feed rock material which bypasses the crusher rotor and broken through collision action with the bed of rock material projected from the rotor. Since the cascade flow is not crushed by using the rotor kinetic energy, the amount of cascade flow is therefore free of energy consumption, which justifies the improvement in energy efficiency. The rock-to-rock technology of VSI crushers also minimizes the wear rates on machine parts[2] and hence forms part of the category of equipment efficiency improvement due to the fact that the maintenance requirement will be reduced.

The energy efficiency of VSI crushers can also be improved during their operation through the optimal coordination of some varying parameters but also the working time based on time-of-use (TOU) electricity tariff. This therefore forms part of operation efficiency improvement. When the TOU tariff is taken into account for operation efficiency improvement of VSI crushers, the performance efficiency is improved through energy cost minimization, taken as an external indicator.

TOU electricity tariff is one of demand-side management (DSM) schemes, that is being introduced in several countries. It aims at reducing the power utility peak load by motivating customers to reduce or shift their load from peak periods that are penalized at high electricity cost to off-peak and standard periods where the electricity cost is cheaper [7]. By this means, customers can rearrange their daily load profiles to achieve minimal energy costs.

Several research works have been conducted to deal with the operation efficiency control of material handling equipment in mining industries. Research papers such as [8–10] investigate the optimal control strategies of belt conveyor systems for coal mining industries in order to achieve minimal energy cost based on TOU electricity tariff. In [11], an optimal control strategy is studied for the optimal hoist scheduling of a deep level mine twin rock winder system. Other research works such as [12–16] apply TOU tariff-based DSM for minimization of the energy cost associated with the operation of water pumping stations. TOU tariff-based DSM is also investigated to deal with the optimal energy cost management of water heating systems in [17] and refrigeration systems in [18]. A more flexible TOU-based DSM, referred to as real time pricing-based DSM, is applied to the optimal scheduling of a distribution network system in [19] and industrial combined heat and power plants in [20].

In all the aforesaid research works, the potential of reducing the system energy cost based on TOU tariff is proved. However, from the literature, the optimal energy management of crushing processes is very rare to find. Although in our previous work [21], optimal energy control strategies are investigated on a crushing process, only a compressive crushing process based on jaw crusher is studied. Furthermore, only the dynamics of the mass stored in the upstream storage system (ore pass system) is considered, while in practice, the storage capacity of the downstream storage system (silo ore stockpile) may be limited and hence violated.

The focus of this paper is to establish an optimal energy control model that improves the operation energy efficiency of a VSI crushing process by reducing the corresponding energy consumption and cost. The optimal control model takes into account the TOU electricity tariff and other system limitations such as the mass storage dynamics of the upstream storage system (VSI crusher hopper), the mass storage dynamics of the downstream storage system (that feeds the consumption point), cascade ratio setting, production requirement and product quality requirement. Four control variables are optimally tuned in order to minimize the control objective. These are the belt conveyor feed rate, the material feed rate into the VSI crusher rotor, the bi-flow or cascade feed rate and the crusher rotor speed. A case study is given and the performance achieved by the developed control strategy is shown when compared to the current control strategy, which is used as a baseline.

The layout of this paper is given as follows: Sections 2 and 3 present, respectively, the mathematical model of the optimal energy control strategy and current control strategy of a VSI crushing process. A case study of the crushing process in a coal-fired power plant is given in Section 4, where the obtained simulation results are discussed before a conclusion is given in the last section.

2. Optimal control model of a VSI crushing system

2.1. System description

The operating principle of the VIS crusher is given in [1,2,22–24]. The ore/rock material falls vertically into the rotor through

[2] Metso, Barmac VSI crushers, <http://www.metso.com>.

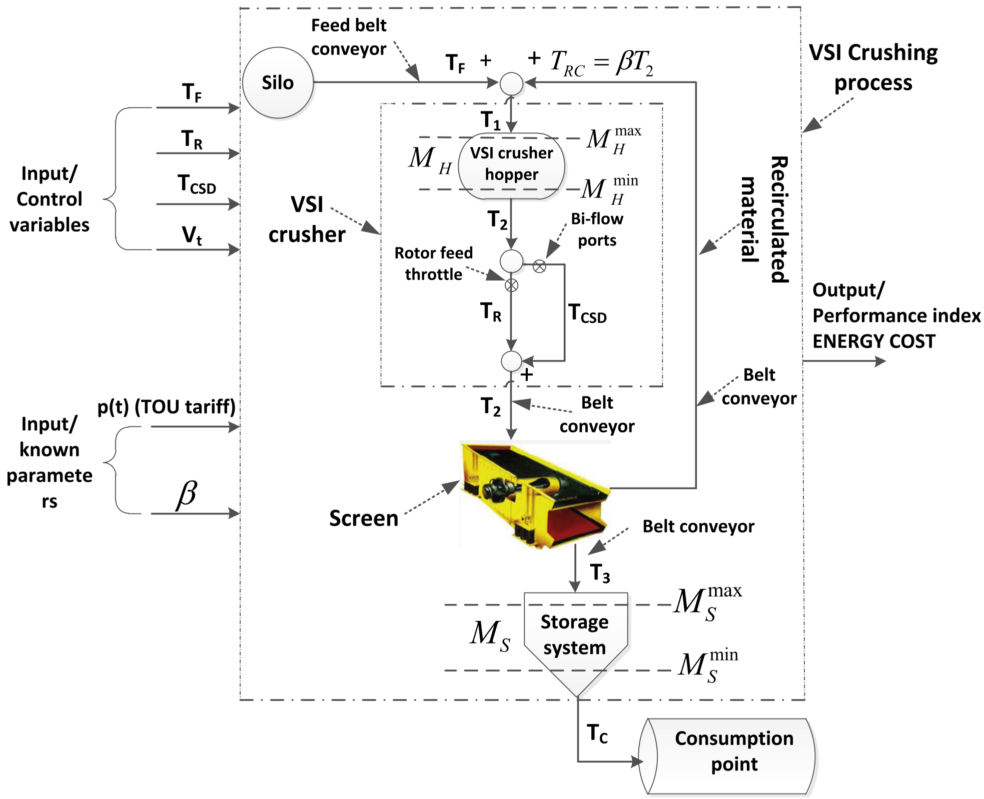

Fig. 1. Schematic of a tertiary mining VSI crushing station (adapted from [1]).

the feed hopper and then accelerated to an edge speed of the high-speed rotor of about 50–85 m/s, before being projected towards the surrounding rock bed formed during operation. However, during operation, a fraction of material does not pass through the rotor, and this is crushed through collision action with the projected rock particles from the rotor. This fraction is commonly referred to as cascade flow or bi-flow. The rock breaking nature in VSI crusher is therefore achieved through rock-to-rock impact; hence the name impact crusher.

A typical VSI crushing station with closed circuit is shown in Fig. 1. In practice, the four control variables considered in this work are plausable choices. The belt conveyor feed rate T_F and the crusher rotor speed V_t are adjusted through variable-speed drive (VSD) systems. The material feed rate into the VSI crusher rotor T_R is adjustable through a throttle [2], also called rotor feed throttle which is controlled by a hydraulic motor. The cascade feed rate T_{CSD} is adjustable through a certain number of adjustable bi-flow ports in the hexagonal hopper.[3]

One should note that the rotor feed throttle and the bi-flow ports are normally located inside the VSI crusher hopper.[4] Hence, the fact that these two adjustment devices are put outside the VSI crusher hopper as shown in Fig. 1, is just for a more clear representation.

In mining or aggregate industries, the tertiary crushing station is usually preceded by coarser crushing stations, namely, the primary and secondary crushing stations. A primary crusher such as jaw or gyratory crusher, reduces the ore/rock material from very large size, say, 0–1000 mm down to 0–250 mm before a secondary crusher such as a cone crusher, can reduce the primary ore product (0–250 mm) down to about less than 100 mm. In tertiary crushing station with closed circuit as shown in Fig. 1, the crushed material from the crusher is screened. The rock material with a size less than the screen aperture size goes to the storage system and the one with higher size is recirculated to the crusher input.

2.2. General assumptions for the system

The following assumptions are made to build the optimal energy model strategy of the VSI crushing process in this work:

1. At any time, the silo feeding the VSI has enough material to supply the feed belt conveyor.
2. The time delay associated with the crushing process, from the silo to the consumption point is not taken into account.
3. Any form of dynamic energy consumption of the crushing process is ignored.

2.3. Objective function

The optimal control model of a VSI crusher system in this work considers the energy cost as the objective function to be minimized by incorporating the TOU electricity tariff as an input to the model. A general function expressing this objective function can be written as:

$$J_C = \int_{t_0}^{t_f} P_{el}(t)p(t)dt. \tag{1}$$

The net mechanical (shaft) power model of the VSI crusher based on Euler turbine equation is expressed in [2] as a function of the tangential component of the particle velocity entering the rotor u_1, tangential component of the particle velocity exiting the rotor u_2, and the rotor angular speed ω. This is given as follows [2]:

$$P_{m_{net}} = T_R(\omega R_1 u_1 - \omega R_2 u_2), \tag{2}$$

[3] Sandvik, Merlin-VSI:Setting the standard in VSI crushing, <http://www.miningandconstruction.sandvik.com>.
[4] Metso, Barmac VSI crushers, <http://www.metso.com>.

with

$$u_1 = \frac{T_R}{\rho \frac{\pi D_{open}^2}{4}} cos\psi + \omega R_1, \tag{3}$$

$$u_2 = V_t cos\psi + \omega R_2, \tag{4}$$

$$V_t = \omega R_2. \tag{5}$$

Combining Eqs. (2)–(5) yields a new Euler turbine equation expressed as a function of the material feed rate into the crusher rotor T_R and rotor tip speed V_t as:

$$P_{m_{net}} = \frac{R_1 cos\psi}{3.24\pi R_2 \rho D_{open}^2} V_t T_R^2 + \frac{1}{3.6}\left(\frac{R_1^2}{R_2^2} - cos\psi - 1\right) T_R V_t^2. \tag{6}$$

Note that in Eq. (2), T_R is expressed in kg/s while in Eq. (6), this is expressed in t/h. Letting $k_1 = \frac{R_1 cos\psi}{3.24\pi R_2 \rho D_{open}^2}$ and $k_2 = \frac{1}{3.6}\left(\frac{R_1^2}{R_2^2} - cos\psi - 1\right)$, the analytical model to predict the net mechanical power of the VSI crusher is obtained as follows:

$$P_{m_{net}} = k_1 V_t T_R^2 + k_2 T_R V_t^2. \tag{7}$$

The total mechanical power is obtained by adding the non-load mechanical power consumption of the VSI crusher to Eq. (7). The non-load mechanical power is the power required to overcome the VSI crusher rotor inertia and the bearing friction. Both of these vary with the VSI crusher speed. However, the power required to overcome the bearing friction is relatively small, hence it can be neglected. A fair estimation is to assume that the non-load mechanical power is directly proportional to the rotor tip speed V_t with a proportional constant k_3. Hence, the analytical model to predict the mechanical power consumption of the VSI crusher is expressed as:

$$P_m = k_1 V_t T_R^2 + k_2 T_R V_t^2 + k_3 V_t. \tag{8}$$

If the angle ψ is assumed to be constant, the coefficients k_1, k_2 and k_3 are constant and mainly depend on the VSI crusher geometry and the characteristic of the material (material density) to be crushed. These three constants can be derived from design parameters or estimated through experiments. However, due a continuous wear of machine parts and variation in the feed characteristic over time, deriving k_1, k_2 and k_3 through experiments would yield accurate results. The least squares (LSQ) parameter estimation algorithm [25] can be used to estimate the coefficients k_1, k_2 and k_3 when experimental data are available.

To validate the power model given by Eq. (8), Figs. 2 and 3 show the comparison between the predicted crushing power and manufacturer's data for Bermac VI-series VSI crushers.[5] The coefficients in the power model have been estimated to be $k_1 = 7.1 \times 10^{-4}$, $k_2 = 2 \times 10^{-1}$ and $k_3 = 0.6256 \times 10^3$. In Fig. 2, the power requirement of the VSI crusher is plotted against the rotor throughput rate for a given rotor tip speed of 50 m/s, while in Fig. 3, the power requirement is plotted against the rotor tip speed for a given rotor throughput rate of 300 t/h. The comparative results show a good agreement between the predicted power consumption of the VSI crusher and the manufacturer's data. However, for a higher accuracy, the parameters in model (8) need to be estimated based on field test data for a particular VSI crusher.

Note that since the model (8) is derived from Euler turbomachinery equations, this can also be used to predict the power consumption of turbopumps and fans.

The electric power consumption function P_{el} of the VSI crusher defined in Eq. (1) can be expressed as:

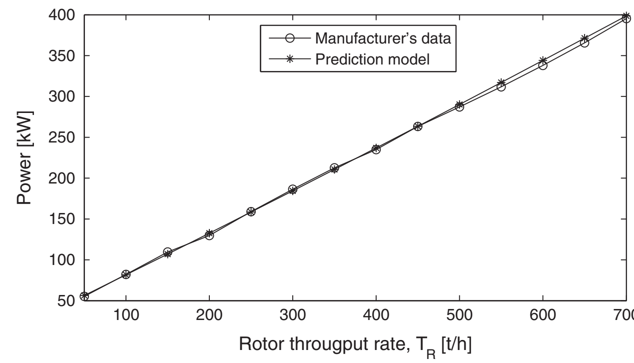

Fig. 2. Power curves for $V_t = 50$ m/s.

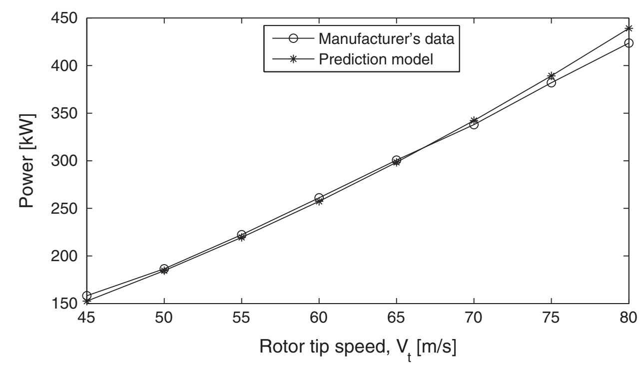

Fig. 3. Power curves for T = 300 t/h.

$$P_{el} = \frac{1}{\eta}\left(k_1 V_t T_R^2 + k_2 T_R V_t^2 + k_3 V_t\right), \tag{9}$$

where the drive efficiency η composed of the electric motor drive and transmission belt drive, is assumed to be constant in this work. However, in practice, the efficiency of the electric motor drive decreases as the load decreases and can be improved by adapting the flux level to the loading level of the motor, especially at very light load [26]. The substitution of Eq. (9) into Eq. (1) yields the explicit form of the objective function as follows:

$$J_C = \frac{1}{\eta}\int_{t_0}^{t_f}\left(k_1 V_t(t) T_R^2(t) + k_2 T_R(t) V_t^2(t) + k_3 V_t(t)\right) p(t) dt. \tag{10}$$

Due to the discrete nature of the TOU electricity tariff, the objective function given by Eq. (10) may be continuous but not differentiable. Hence, a numerical approach is suitable to solve this problem. The objective function expressed in continuous-time domain by Eq. (10) can therefore be discretized as follows:

$$J_C = t_s \frac{1}{\eta}\sum_{j=1}^{n_s}\left(k_1 V_{t_j} T_{R_j}^2 + k_2 T_{R_j} V_{t_j}^2 + k_3 V_{t_j}\right) p_j, \tag{11}$$

where the electricity price p_j is assumed constant at the jth sampling interval.

2.4. Constraints

2.4.1. Limits on control variables

$$\begin{cases} T_F^{min} \leqslant T_{F_j} \leqslant T_F^{max}, & (1 \leqslant j \leqslant n_s), \\ T_R^{min} \leqslant T_{R_j} \leqslant T_R^{max}, & (1 \leqslant j \leqslant n_s), \\ T_{CSD}^{min} \leqslant T_{CSD_j} \leqslant T_{CSD}^{max}, & (1 \leqslant j \leqslant n_s), \\ V_t^{min} \leqslant V_{t_j} \leqslant V_t^{max}, & (1 \leqslant j \leqslant n_s). \end{cases} \tag{12}$$

[5] Metso, Nordberg Barmac VI-Series VSI Crusher, <http://www.metso-bulgaria.com>.

2.4.2. Mass balance in the crushing circuit

The mass balance equations at different nodes of the VSI crushing process as shown in Fig. 1 can be written as:

$$\begin{cases} T_1 = T_F + T_{RC}, \\ T_2 = T_R + T_{CSD}, \\ T_2 = T_3 + T_{RC}. \end{cases} \quad (13)$$

The recirculating mass flow rate T_{RC} can be related to the total mass flow rate into the screen T_2 through a ratio, referred to as recirculating mass flow rate ratio β as follows:

$$T_{RC} = \beta T_2. \quad (14)$$

The mass balance given by Eq. (13) can be combined with Eq. (14) to give a new set of mass balance equations expressing the non-control variables, referred to as dependent variables, in terms of the three control variables as follows:

$$\begin{cases} T_{1_j} = T_{F_j} + \beta_j\left(T_{R_j} + T_{CSD_j}\right), & (1 \leqslant j \leqslant n_s), \\ T_{2_j} = T_{R_j} + T_{CSD_j}, & (1 \leqslant j \leqslant n_s), \\ T_{3_j} = (1-\beta_j)\left(T_{R_j} + T_{CSD_j}\right), & (1 \leqslant j \leqslant n_s), \\ T_{RC_j} = \beta_j\left(T_{R_j} + T_{CSD_j}\right), & (1 \leqslant j \leqslant n_s), \end{cases} \quad (15)$$

where β_j is assumed to be measured or predicted at jth sampling interval.

These dependent variables can therefore be obtained after getting the optimal control solutions (control variable values) of the problem.

2.4.3. Limits on dependent variables

The limitations on the total mass flow rate into the VSI crusher hopper T_1 may be wanted. The flow rate of recirculating material T_{RC} and the ones into and from the screen device, respectively, T_2 and T_3 to be transported may also be restricted by the capacity of the belt conveyors. Based on Eq. (15), these constraints are given as:

$$\begin{cases} T_1^{min} \leqslant T_{F_j} + \beta_j\left(T_{R_j} + T_{CSD_j}\right) \leqslant T_1^{max}, & (1 \leqslant j \leqslant n_s), \\ T_2^{min} \leqslant \left(T_{R_j} + T_{CSD_j}\right) \leqslant T_2^{max}, & (1 \leqslant j \leqslant n_s), \\ T_3^{min} \leqslant (1-\beta_j)\left(T_{R_j} + T_{CSD_j}\right) \leqslant T_3^{max}, & (1 \leqslant j \leqslant n_s), \\ T_{RC}^{min} \leqslant \beta_j\left(T_{R_j} + T_{CSD_j}\right) \leqslant T_{RC}^{max}, & (1 \leqslant j \leqslant n_s). \end{cases} \quad (16)$$

2.4.4. Limits on mass storage states

During the normal operation of the VSI crushing process, the dynamics of the mass stored in the VSI crusher hopper and downstream storage system should be kept within allowable capacity limits of each storage device, so as to avoid the material overflowing.

2.4.4.1. Limits on the mass storage state in the VSI crusher hopper. The material dynamics in the VSI crusher hopper can be expressed by a discrete-time difference equation as follows:

$$M_{H_j} = M_{H_{j-1}} + t_s\left(T_{1_{j-1}} - T_{2_{j-1}}\right), \quad (1 \leqslant j \leqslant n_s). \quad (17)$$

By recurrence manipulation, the mass stored in the crusher hopper at the jth sampling interval can be expressed in terms of the initial mass available, M_{H_0} as:

$$M_{H_j} = M_{H_0} + t_s\sum_{i=1}^{j}\left(T_{1_i} - T_{2_i}\right), \quad (1 \leqslant j \leqslant n_s). \quad (18)$$

Taking into account of the mass balance, given by $T_{1_j} = T_{F_j} + \beta_j\left(T_{R_j} + T_{CSD_j}\right)$ and $T_{2_j} = T_{R_j} + T_{CSD_j}$ in Eq. (15), the limitations on mass storage state in the VSI crusher hopper can be finally written as:

$$M_H^{min} \leqslant M_{H_0} + t_s\sum_{i=1}^{j} T_{F_i} + (\beta_i - 1)\left(T_{R_i} + T_{CSD_i}\right) \leqslant M_H^{max}, \quad (1 \leqslant j \leqslant n_s). \quad (19)$$

2.4.4.2. Limits on the mass storage state in the storage system. Following the same procedure as above, the limitations on mass storage state in the downstream storage system are given as:

$$M_S^{min} \leqslant M_{S_0} + t_s\sum_{i=1}^{j}\left[(1-\beta_i)\left(T_{R_i} + T_{CSD_i}\right) - T_{C_i}\right] \leqslant M_S^{max}, (1 \leqslant j \leqslant n_s), \quad (20)$$

where M_{S_0} is the initial mass available in the storage system.

2.4.5. Production requirement

For reliability purpose, the total amount of crushed material fed to the consumption point (plant) should be greater than or equal to the total consumption of the plant. This is expressed as:

$$\sum_{j=1}^{n_s} T_{3_j} t_s \geqslant \sum_{j=1}^{n_s} T_{C_j} t_s, \quad (21)$$

which can be rewritten as:

$$\sum_{j=1}^{n_s}(1-\beta_j)\left(T_{R_j} + T_{CSD_j}\right)t_s \geqslant \sum_{j=1}^{n_s} T_{C_j} t_s, \quad (22)$$

with $T_{3_j} = (1-\beta_j)\left(T_{R_j} + T_{CSD_j}\right)$ as given in Eq. (15). Note that the material consumption rate T_C is assumed to be predicted for a given control horizon.

2.4.6. Product quality requirement

In both mining and aggregate crushing plants, one of the requirement is that, the mean size of the product material d_P has to be lower than a specified value d_P^{max}, regardless of the variation of the feed mean size d_F. For a given d_F, the relationship between d_P from a VSI crusher and the VSI crusher speed V_t is given as follows [27]:

$$d_P = \left(\frac{4.472 K l_c d_{F_j}}{2\rho V_p V_{t_j}}\right)^{2/3} \leqslant d_P^{max}, \quad (1 \leqslant j \leqslant n_s), \quad (23)$$

where d_F is considered as a predictable parameter at each jth sampling interval. Eq. (23) shows that, the VSI crusher speed can be continuously adjusted in order to meet the product quality requirement.

2.4.7. Limits on bi-flow or cascade ratio

Usually, the cascade or bi-flow ratio is maintained at a constant value depending on the nature of the rock material to be crushed [28]. The bi-flow material increases the rock-to-rock impact action, by improving the efficiency and throughput capacity of the VSI crusher. However, increasing cascading material is similar to slowing the rotor speed, leading to a negative effect on the product size distribution (coarse particle size in the product). Hence, for efficiency purpose, crusher manufacturers recommend operating the VSI crusher with a bi-flow ratio of 10–15% [1]. Up to 10–15% cascade material can be utilised without a significant change in product gradation or quality, meantime 10–15% extra product (throughput capacity) is gained for no extra power use or wear part consumption.[6]

The bi-flow or cascade ratio, noted α_{CSD}, is defined as the ratio between the cascade feed rate T_{CSD} and the material feed rate into the crusher rotor T_R.

At each j^{th} sampling interval, the constraint on the cascade ratio can be expressed as follows:

$$\frac{T_{CSD_j}}{T_{R_j}} = \alpha_{CSD}, \quad (1 \leqslant j \leqslant n_s), \tag{24}$$

which can be rewritten in a linear form as follows:

$$T_{CSD_j} = \alpha_{CSD} T_{R_j}, \quad (1 \leqslant j \leqslant n_s). \tag{25}$$

3. Current control strategy

In practice, the VSI crushing process operates continuously, while the flow rates are adjusted in such a way to meet the system constraints and achieve the total plant production target/requirement. Hence, the current control strategy can be formulated as an optimal control problem with the objective function being the quadratic deviation between the total actual plant production and the total plant target for a given control horizon. The mathematical model of the current control strategy of the VSI crushing process as shown in Fig. 1 is therefore given as:

$$min J_{PR} = \left[\sum_{j=1}^{n_s}(1-\beta_j)\left(T_{R_j} + T_{CSD_j}\right)t_s - \sum_{j=1}^{n_s} T_{C_j} t_s\right]^2, \tag{26}$$

subject to constraints (12)–(25).

4. Case study: crushing process in a coal-fired power plant

The work presented in [8] investigates the optimal control strategies of a coal conveying system in order to minimize the energy cost associated with the belt conveyor systems. The coal crusher present in the aforesaid coal conveying system is not included in the optimal energy control problem since it is stated that the coal crusher system follows its own optimal control strategy. In this work, the coal crusher in [8] is assumed to be a VSI crushing machine and therefore, the same system is used to simulate the optimal energy control strategy of a VSI crushing process developed in this research work. This assumption is reasonable since for pulverized hard coal-fired power plants such as those found in South Africa, for instance, VSI crushers are appropriate to be used in the last stage of the crushing circuit before the crushed coal is sent to the grinding mill circuit for coal pulverization. This is because VSI crushers offer the advantage of producing significantly more fine material as compared to other crushers used for hard rocks. Hence, a relatively large amount of fines smaller than 75 μm (pulverized coal) can be screened and sent directly to the boiler while the coarser coal particles are sent to the grinding mill. Moreover, it is reported in [1] that the higher fine content obtained by VSI crushing is valuable for the subsequent grinding mill since this will reduce the work and hence the power needed by the mill.

4.1. Data presentation

4.1.1. Coal consumption and coal storage system

In view of the above, data such as power plant capacity, coal bin capacity, load assignment and forecast coal consumption are obtained from [8]. In this reference, with a given load assignment profile, the coal consumption is predicted based on a quadratic function. The predicted coal consumption rate T_C is shown in Fig. 4. Based on the given coal-fired power plant with two 600 MW units, the estimated total bin capacity (TBC) is 5595.5 t.

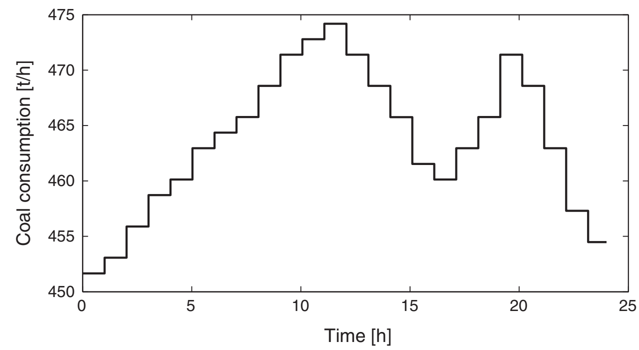

Fig. 4. Foretasted coal consumption rate.

In this work, the upper limit M_S^{max} and lower limit M_S^{min} of the downstream storage system (coal bin) are set, respectively, to 90% and 20% of TBC. The initial mass stored $M_{S,0}$ in the storage system is assumed to be 50% of TBC.

4.1.2. Coal characteristics

The bulk density ρ of the anthracite coal is 1506 kg/m^3, the propagation velocity of its longitudinal elastic waves V_p is 1890 m/s and its fracture toughness Klc is 0.19325 Mpa m$^{0.5}$.

4.1.3. VSI crusher

A 400 kW (600 hp) Barmac VI-series VSI crusher[7] is used for simulation purpose in this work. In order to allow the cascade feed material for such a soft material to be crushed, the maximum operation tip speed V_t is set (45 m/s. The cascade ratio α_{CSD} is considered to be 10%. The rotor outer radius R_2 is 0.525 m. The maximum rotor feed rate T_R^{max} is set to 700 t/h. With the cascade ratio of 10%, the maximum feed rate T_1^{max} is obtained to be 770 t/h. The power model coefficients are $k_1 = 7.1 \times 10^{-4}$, $k_2 = 2 \times 10^{-1}$ and $k_3 = 0.6256 \times 10^3$ as derived in Sub-Section 2.3. The overall drive efficiency η is assumed to be 95%.

4.1.4. Time-of-use electricity tariff

The recent Eskom Megaflex Active Energy-TOU electricity tariff is used for simulation purpose. To be more specific, the crushing station is supposed to operate under the non-local authority rate. The control horizon in this work is assumed to be within the high-demand season (from June to August) weekday. This is given as[8]:

$$p(t) = \begin{cases} p_o = 0.3656 \text{ R/kWh if } t\epsilon[0,6] \cup [22,24], \\ p_s = 0.6733 \text{ R/kWh if } t\epsilon[6,7] \cup [10,18] \cup [20,22], \\ p_p = 2.2225 \text{ R/kWh if } t\epsilon[7,10] \cup [18,20], \end{cases} \tag{27}$$

where R is the South African currency Rand and t is the time of any weekday in hours (from 0 to 24).

4.2. Simulation results and discussion

The control horizon $[t_0, t_f]$ and sampling time t_s of, respectively, 24 h and 15 min are used for both current control and optimal control strategies. For all simulations, the recirculated material is not

[6] Metso, Barmac VSI crushers, <http://www.metso.com>.

[7] Metso, Nordberg Barmac VI-Series VSI Crusher, <http://www.metso-bulgaria.com>.

[8] Eskom, Tariffs & Charges Booklet 2013/2014, <http://www.eskom.co.za>.

considered, that is, $\beta = 0$. The upper limit on the flow rates of all belt conveyors is set to 770 t/h which corresponds to the higher limit of the total throughput rate of the crusher (including the cascade feed rate). To account for the product quality requirement, the maximum product mean size d_p^{max} is set to 3 mm.

The *fmincon* function of MATLAB Optimization Toolbox is used to solve all the problems in this work.

The comparative simulation results between the current control and optimal control strategies are shown in Figs. 5–8 and Tables 1–3. In these figures, the dotted lines denote the upper and lower bounds of the corresponding variable. Note that the legend of Fig. 5 also applies to Fig. 6. The feasibility of both current control and optimal control strategies are demonstrated from these figures where it can be seen that the crushing process operates under the specified constraints.

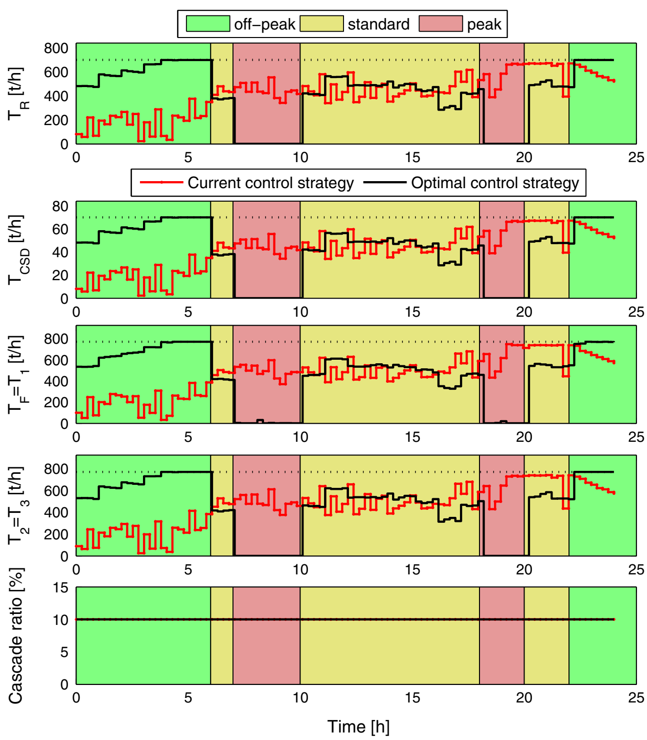

Fig. 5. Coal flow rates and cascade ratio.

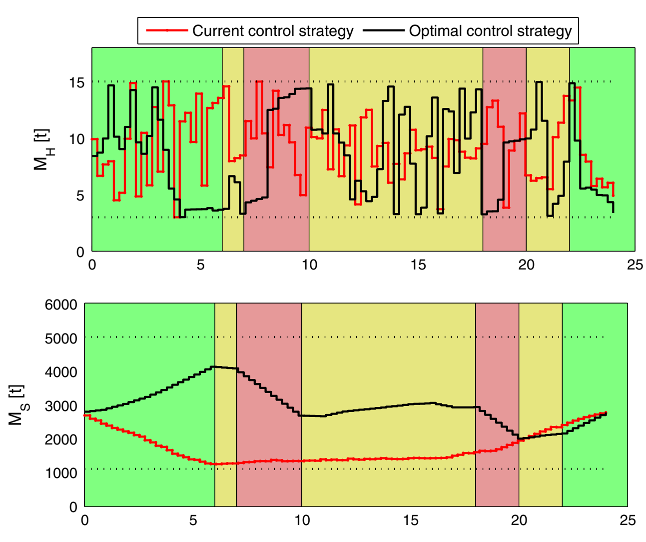

Fig. 6. Coal level in the storage systems.

4.2.1. Cost saving discussion

Although the feasibility of both control strategies are technically proved through simulation results, it can be seen from Fig. 5, that the current control strategy runs the VSI crushing process without consideration of the TOU electricity tariff. With this, the load (coal flow rates) is almost evenly distributed across the 24 h-control horizon without shifting the load out of peak time. The reason is that the current control strategy does not have any information on the TOU tariff during the process control. As result of this, a higher energy cost is incurred. Simulation results obtained by the current control strategy in this work reflect the practical operation of most crushing processes. In practice, most crushing processes run continuously with almost a constant feeding (material feed rate) for a given operation period while achieving the total production requirement (total plant throughput) and meeting

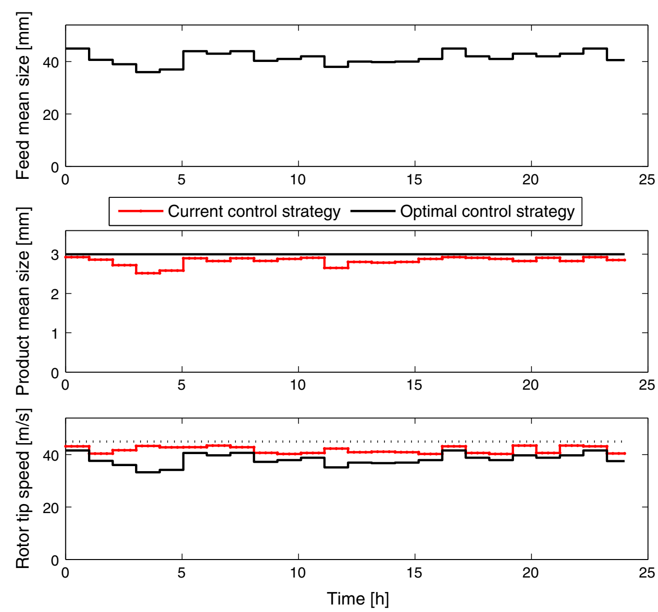

Fig. 7. Coal mean sizes and VSI crusher speed.

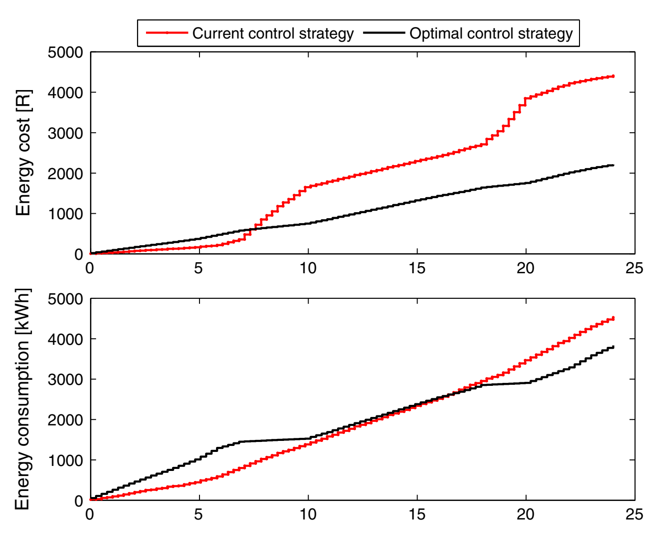

Fig. 8. Cumulative energy cost and consumption.

Table 1
Total production and corresponding energy cost and consumption.

Strategy	Total production (t)	Energy cost (R)	Energy consumption (kWh)
Current control strategy	11,130	4407.64	4527.92
Optimal control strategy	11,130	2213.37	3833.22

Table 2
Cost savings of the optimal control strategies.

Strategy	Unit energy cost (R/t)	Cost saving (%)
Current control strategy	0.3960	/
Optimal control strategy	0.1989	49.77

Table 3
Energy savings of the optimal control strategies.

Strategy	Unit energy consumption (kWh/t)	Energy saving (%)
Current control strategy	0.4068	/
Optimal control strategy	0.3444	15.34

other constraints associated with the operation. The material feed rate T_F is usually controlled/regulated at a certain constant value by feeding equipments such as vibrating feeders, apron feeders or belt conveyors. However, for the case of tertiary or last crushing stage such as VSI crushing process, the belt conveyors or vibrating feeders equipped with VSD systems are mostly employed for feeding control. Apron feeders, which are heavy-duty feeding machines are commonly used in primary crushing processes where the feeding is usually characterized by coarse rock/ore material. However, the crushing station may be shut down in presence of disturbances. These disturbances are for instance, the introduction in the crusher of oversize material which would result in imbalance of the VSI crusher but also the overload of the machine impeller.

Since the hopper of the VSI crusher is usually of negligible capacity (a maximum of 15 t in this work), its dynamics M_H as shown in the first graph of Fig. 6, does not have a considerable effect on the crusher output flow rate T_2, whenever the feed rate of the VSI crusher $T_1 = T_F$ changes. This justifies the fact that the crusher feed rate $T_1 = T_F$ almost equals its output flow rate T_2 as shown in the third and fourth graphs of Fig. 5.

On the other hand, from the same figure (Fig. 5), it is seen that the optimal control strategy runs the VSI crushing process by optimally shifting the load from peak time to off-peak and standard time in order to minimize the associated energy cost. It can be seen that during peak time, the coal feed rate into the VSI crusher rotor T_R is zero in order to save the energy cost, while during off-peak time, this is maximized in order to meet the production target at a cheaper energy cost. The second graph of Fig. 5 shows that the cascade flow rate T_{CSD} varies proportionally with the rotor feed rate T_R in order to constantly maintain the cascade ratio to its reference value of 10% as demonstrated through the last graph of the same figure. The effectiveness of the optimal energy control strategy can also be seen with reference to the coal levels in the storage systems. Fig. 6 shows that unlike the current control strategy, during peak time, the coal amount in the upstream storage system (VSI crusher hopper), M_H, increases while during off-peak time, this decreases. The reason is that, with the optimal control, the coal material is stored instead of being fed to the crusher during peak time, while during off-peak time, the coal material is drawn from the hopper and processed by the crusher at a cheaper energy cost. In the downstream storage system, it is seen that the coal amount M_S decreases during peak time while during off-peak time, this increases. This is due to the fact that the coal material which was processed during off-peak and standard time when the cost of energy is cheap, is now fed to the coal grinding station (if available) or consumption point (boiler) during peak time, when the crusher is not allowed to process the coal material due to the higher energy cost.

The cumulative energy cost and energy consumption of the current control and optimal control strategies are shown in Fig. 8 while Tables 1–3 summarize the performance of the optimal control strategy. The analysis of Fig. 8 clearly shows that, at the end of the control horizon (24 h), the optimal control strategy dramatically reduces the energy cost with comparison to the current control strategy taken as baseline. The actual energy cost saving obtained is evaluated to about 49.7% as shown in Table 2.

4.2.2. Energy saving discussion

The simulation results through the second graph of Fig. 8 demonstrates that the energy consumption is also reduced, although the energy cost is considered as performance index. The reason for the energy consumption reduction is that, the optimal control strategy runs the VSI crusher at a slightly reduced speed when compared to the current strategy, as can be seen in the third graph of Fig. 7, by operating the system at the boundary of the admissible operating region limited by the product quality constraint as shown in the second graph of Fig. 7. It can therefore observed that, in order to minimize the economical performance such as the energy consumption, the operating point of the VSI crushing process has to be obtained by pre-setting the product quality index at its most worse but feasible value (limits). This is due to the conflict nature between the economical performance objectives (energy consumption, energy cost, etc.) and the technical performance objectives (product size reduction ratio, maximum product size, etc.) which makes the crushing process to be a multi-objective optimization problem in reality. For this case study where the product quality index is considered to be the product mean size, its maximum value has been set to 3 mm, as can be seen in the second graph of Fig. 7.

The energy saving of about 15.3% is achieved. This means that, not all 49.7% energy cost saving is achieved through load shifting. Some amount of energy cost saving is due to the 15.3% energy reduction. However, most of this cost reduction comes from the optimal load shifting. Note that the rotor speed cannot be further reduced for more energy reduction due to the product quality constraint.

Practically, most VSI crushing stations are equipped with real-time monitoring and control systems which include VSD systems. This means that no systems upgrade or extra capital cost is normally needed in order to achieve the energy consumption based on the optimal coordination of the VSI crusher speed or the energy cost reduction based on optimal load shifting.

Although simulation results in this work show a great potential in reducing both energy consumption and cost of a VSI crushing process, some challenges related to the implementation of the optimal energy control strategy need to be addressed in practice. Firstly, all the input parameters to the model such as TOU electricity tariff, recirculated mass flow ratio, material consumption rate, and particle size distribution of the feed material need to be accurately and continuously predicted. Secondly, if an open-loop optimal control strategy (optimal setting values are manually entered by the operators in the supervisory control and data acquisition system) is to be used, the success of the optimal energy control strategy will depend on the skills of the process operators. Thirdly, since the energy saving is achieved through matching the VSI crusher speed with the change in particle size distribution of the feed material, the sensor used for the continuous measurement of the feed particle size distribution has to be of high accuracy level.

5. Conclusion

Vertical shaft impact (VSI) crusher is one of the most used crushing machine in the last stage (tertiary or quaternary) of crushing processes in both mining and aggregate industries. This due to its high technology efficiency, ability of yielding large amount of fines (valuable for mining industries) and product with cubical shape (valuable for aggregate industries). However, the possibility of improving the efficiency operation of the VSI crushing process during its operation is not covered in the literature.

In this paper, a practical model to improve the operation efficiency of a VSI crushing process is firstly developed. The performance objective considered for the operation efficiency is the minimization of the energy cost with integration of the TOU tariff. Secondly, in order to evaluate the feasibility of the model, a case study of a crushing process in a fire-coal power plant is solved. The simulation results performed through MATLAB Optimization Toolbox demonstrate the feasibility of the model. Although the energy cost is taken as performance objective, it is proved that the optimal energy control strategy developed in this work can potentially achieve both energy saving and cost saving on a VSI crushing process, while meeting the specified physical and operation constraints of the system. About 15.3% energy saving and 49.7% energy cost saving are achieved. It is observed that most of the energy cost saving comes from the optimal shifting of the load while the energy saving is due to the optimal coordination of the VSI crusher speed.

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