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Optimal energy management for a jaw crushing process in deep mines

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ABSTRACT

This paper develops two optimal control models for the energy management of a mining crushing process based on jaw crushers. The performance index for both models is defined as the energy cost to be minimized by accounting for the time-of-use electricity tariff. The first model is referred to as a variable load-based optimal control with the feeder speed and closed-side setting of the jaw crusher as control variables. The second model is the optimal switching control. From the simulation results, it is demonstrated that there is a potential of reducing the energy cost and energy consumption associated with the operation of jaw crushing stations in deep mines while meeting technical and operational constraints. Due to the inefficiency of the jaw crushing machine, whose no-load power consumption is between 40 and 50% of its rated power, the optimal switching control technique is shown to be a better candidate in reducing both energy cost and consumption of the jaw crushing station. The benefit of having an ore pass with a big storage capacity is shown to be of great importance in achieving more energy cost reduction of the primary jaw crushing station while improving the switching frequency profile associated with the switching controller.

1. Introduction

Due to the difficulty of the power utilities in continuously meeting the steadily growing energy demand, DSM (demand-side management) scheme is being implemented in several countries in the world. The aim of DSM is to plan the power grid at the customers' side in such a way to influence their energy consumption behaviour in order to meet the utility's desired load shape [1].

In South Africa for instance, Eskom, the main electricity supplier, introduced the TOU (time-of-use) tariff-based DSM in the 1990s due to the electricity crisis, by trying to motivate customers to shift their loads out of the peak period [2].

Mining sectors account for about 15% of the total electrical energy consumption in South Africa, of which gold mining leads with 47% followed by platinum mining, taking 33% whilst 20% is consumed by the remaining mines.[1] It is further indicated that processing occupies the second place in mining energy consumption within the country with 19% of the total energy, preceded by materials handling which consumes 23%. This shows that mining sectors, especially gold mines have an important role to play in reducing South Africa's peak load, which will also reduce the cost associated with their energy consumption.

For materials handling in mining sectors, some research works have been carried out to investigate the potential of reducing the energy cost based on TOU tariff. In Ref. [3] for instance, the DSM technique is studied for an optimal hoist scheduling of a deep level mine twin rock winder system. Optimal energy control strategies for coal mining belt conveyors are investigated in Refs. [4–7]. All of these studies demonstrate a great potential in reducing the energy cost associated with the operation of mining materials handling based on TOU tariff.

However, there have been relatively less research works dedicated to the energy cost management of comminution (crushing and grinding) circuits which are the first two stages of mineral processing in mining industries. A recent research paper was published in the area of energy cost optimization of a ROM (run-of-mine) ore grinding/milling circuit [8]. It is shown that a cost reduction of $9.90 per kg of unrefined product can be achieved when the optimal energy cost management is applied to a ROM ore grinding circuit processing platinum. Very few research works have been so far attempted in crushing electricity bill reduction. Other papers such as Refs. [9–13], use the TOU tariff-based DSM for the optimal operation of a water pumping station. An optimal load management for air conditioning loads is studied in Ref. [14], where a case study shows a reduction of 38% in peak demand with an annual cost saving of 5.9%, under TOU tariff. The benefit of the

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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

$p(t)$	time-of-use (TOU) electricity tariff (currency/kWh)
W_i	Bond's work index of ore (kWh/short-ton)
P_{80}	particle size that is larger than 80% by mass, of all particles in a product material sample (m)
F_{80}	particle size that is larger than 80% by mass, of all particles in a feed material sample (m)
Q_{OVS}	mass flow rate of oversize run-of-mine (ROM) ore material (t/h)
Q_{UDS}	mass flow rate of undersize ROM ore material (t/h)
CSS	and T closed-side setting and throw of the jaw crusher (m)
S_F	ore shape
F_{max}	maximum size of the feed ore material (m)
S_C	opening of the screen/distance between grizzly bars (m)
Q_F	mass flow rate of ROM ore material from the feeder to the scalper (t/h)
V	linear speed of the apron feeder (m/s)
ρ	bulk density of the ore material (t/m^3)
B	skirt width of the apron feeder (m)
D	bed depth of material on the apron feeder (m)
η_V	volumetric efficiency of the apron feeder
γ	undersize fraction or ratio of the ore material
$F_{80_{USC}}$	F_{80} for unscalped feed ore material (m)
η_D	overall drive efficiency
P_0	no-load mechanical power of the jaw crusher (kW)
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/kWh)
"min" and "max"	minimum and maximum of the variable
P_{max}	maximum size of the ore product material (m)
P_{max}^{up}	upper bound/limit of P_{max} (m)
M_{ROM}	mass of ROM ore available in the storage system (t)
Q_{ROM}	mass flow rate of ROM ore material into the ore pass storage system (t/h)
$M_{ROM_{(0)}}$	initial value of M_{ROM} (t)
Q_{PR}	mass flow rate of ROM ore from the jaw crusher (t/h)
N	rotational speed of the jaw crusher (rpm)
w and G	width and gap of the jaw crusher (m)
D_V	vertical depth between jaws (m)
F_{av}	average feed size (m)
M_{TPR}	total mass production of the crushed ROM ore (t)
p_o, p_s, p_p	off-peak, standard and peak TOU electricity prices (currency/kWh)

optimal load shifting based on TOU tariff, with application to manufacturing systems is also shown in Ref. [15]. In Refs. [16,17], a dynamic or more flexible TOU tariff-based DSM, referred to as real time pricing-based DSM is applied to the optimal scheduling of electrical energy supply systems.

Compressive crushers such as jaw, gyratory and cone crushers are known to be inefficient machines with the no-load power ranging from 30 to 50% of their rated power [18,19]. Hence, one way to improve the efficiency of these machines is through their operation efficiency by reducing their energy consumption and cost during their operation.

Jaw crushers, specially, form the core heavy-duty machines used since decades for crushing of coarse and hard ROM ores such as gold, copper, cobalt, zinc ores, etc., in primary stations of mining industries [20–22]. These are also used for the same purpose for ROQ (run-of-quarry) rocks in aggregate industries.

In the past, the common objectives in mining comminution process consisted of achieving a large production capacity (throughput maximization) and amount of fines [8]. Minimizing the energy consumption has been put as the last objective due to the relatively lower electricity price in the past. However, due to the electricity crisis encountered by many countries nowadays, the electricity price is seen to annually increase at a big rate. An annual price increase of 8% will be applied from 01-April 2013 to 31-March 2018 in South Africa for instance.[2] Hence, for a primary crushing circuit, the control objectives can be adapted as follows (adapted from Ref. [8]):

- achieve a product size less than a specified value,
- achieve a specified average production capacity (throughput) over a given period by minimizing the costs associated with the power consumption.

This paper is our first attempt to the optimal control for energy cost minimization in a primary crushing station of deep underground mines. Two techniques which take into account the TOU tariff are developed. One is referred to as the VL (variable load)-based optimal control while the other one is the optimal switching control. The former takes account of the jaw crushing energy model and optimally coordinates the feeder speed, closed-side setting and the working time of the jaw crusher for energy cost minimization. The optimal switching control optimally coordinates the on/off status and working time of the jaw crushing station to achieve the energy cost reduction; this is referred to as optimal load shifting. Solutions of the two techniques are compared to the current strategy used as a baseline solution in order to validate the effectiveness of the results.

This work is laid out as follows: Section 2 presents the mathematical formulation of the two optimal control techniques and the current control model of the primary jaw crushing station. The simulation results are given and discussed in Section 3 before concluding the work in the last section.

2. Model development

2.1. System description

Fig. 1 shows a typical configuration of a deed underground mine. The coarse ROM/blasted ore is loaded from different production stops (muckpiles) by LHD (Load-Haul-Dump) vehicles, and hauled to the tipping points [23] of the ore pass from where the ore material is transferred by gravity to the lower level of the mine. On the collection level, the ore is reduced to smaller size by primary crushers and stored in a storage buffer such as ore bin or silo. The crushed ore is then transported to the bottom of the shaft station by conveyor belts, dump trucks or trains (in this figure, a conveyor belt is considered), loaded into skips/buckets and hoisted to the surface bins, silos or stockpiles by the rock winder. From here, the ore is transported to the production plant for further processes such as secondary and tertiary crushing, grinding/milling, concentration, etc., for extraction of the valuable mineral.

The primary jaw crushing station is usually installed underground in mines and operates in open circuit as shown in Fig. 2.

[2] Eskom, Revenue Application – Multi Year Price Determination 2013/14 to 2017/18 (MYPD3), http://www.eskom.co.za.