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Improving energy efficiency of cyclone circuits in coal beneficiation plants by pump-storage systems

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HIGHLIGHTS

- A pump-storage system (PSS) is introduced in a coal washing plant to reduce energy consumption and cost.
- Optimal operation of the PSS under TOU tariff is formulated and solved. Life cycle cost analysis of the design is done.
- Simulation results show the effectiveness of energy efficiency improvement and load shifting effect of the proposed approach.
- An annual 38% reduction of overall cost of the coal washing plant with 2.86 years payback period is achieved.
- Capacity improvement of power plants contracted to the coal mine is expected as less electricity is required to get fuel.

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ABSTRACT

A pump storage system (PSS) is introduced to the coal preparation dense medium cyclone (DMC) plants to improve their energy efficiency while maintaining the required medium supply. The DMC processes are very energy intensive and inefficient because the medium supply pumps are constantly over-pumping. The PSS presented is to reduce energy consumption and cost by introducing an addition medium circulation loop. The corresponding pump operation optimization problem in the PSS scheme under time-based electricity tariff is formulated and solved, based on which the financial benefits of the design is investigated using life cycle cost analysis. A case study based on the operation status of a South African coal mine is carried out to verify the effectiveness of the proposed approach. It is demonstrated that the energy cost can be reduced by more than 50% in the studied case by introducing a 160 m^3 storage tank. According to life cycle analysis, the PSS Option 1 yields an annual 38% reduction of the overall cost for the beneficiation plant with a payback period of 2.68 years.

1. Introduction

Due to the fast increasing electricity demand, many countries are facing the threats of electricity blackouts, which results in enormous economic losses [1]. To avoid such blackouts, studies are done in the field of rolling blackouts [2], and demand response programs [3]. An energy efficiency improvement approach is proposed for the coal mining industry to address the energy shortage problem. Specifically, the coal cleaning dense medium cyclone (DMC) plants are studied.

It is a common practice that power stations are built right next to coal mines to save fuel transport cost. The coal mine is contracted to supply the power station while the power station provides electricity for the mine. Under such circumstances, improving energy efficiency of the coal mine leads to not only energy cost savings for the mine but also fuel cost reduction and improved supply capacity for the power station.

According to Eskom, the South African electricity public utility, mining industry takes about 15% of Eskom's annual output.[1] Moreover, electricity contributes 56% to mining industry's energy usage from 2002 to 2009 in South Africa according to available statistics.[2] This implies that reducing electricity consumed by the coal mines contracted to power stations can offer a great opportunity for alleviating grid pressure. Yet, many coal washing plants in South Africa are built many years ago when electricity demand is low. The overall design is about limiting capital expenditure and operational downtime, rather than focusing on energy efficiency.

The pumping systems are operating at very low energy efficiency in coal mines. For instance, over-sizing of pumps are very common and the operation of those pumps only considers

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[1] Eskom 2011, Towards an energy efficient mining sector.
[2] Statistics of South Africa 2012, D0405.1.1-Energy accounts for South Africa, 2002–2009 (Discussion document).

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operation safety. In the dense medium cyclone (DMC) coal beneficiation process, only 25% of the pumped medium are used by the DMC while the other 75% simply flows back the corrected medium tank without being used.

Therefore, there is a great opportunity for reducing energy consumption of the DMC coal processing plant by energy-efficient pumping systems. This corresponds to one of the most important areas in mining industry in terms of energy efficiency improvement—pumping systems—which were assessed to be able to save 14% of electricity cost if proper energy efficiency solutions are applied.[3]

Although many studies have been done on the power generating plants concerning generation dispatching [4–6], maintenance scheduling [7–9] and renewable energy integration [10], little attention has been paid to the power plants' contracted coal mines [11]. The focus of this study is to improve energy efficiency of the power station contracted coal mines so that the mine itself and the power station can benefit from such improvement.

In view of this, a pump storage system (PSS) is introduced to the DMC circuit. The PSS is used for two purposes. Firstly, it is used to add an additional medium circulation loop to the existing system to reduce the differential head of the pumps such that energy consumption can be reduced. Secondly, it is utilized to store the medium and consequently store energy when the grid demand is low in order to reduce energy cost and relief grid pressure.

Two options of PSS are presented in this study considering practical needs. The dynamics of the DMC process with the PSS options are modeled and the corresponding optimal operation problem of the proposed system is formulated under the time-based electricity tariff afterwards. The optimal operation problems considers the operation of multi-pumps under the time-based tariff. Though switching control of a single pump is not technically expensive, the operation of multi-pumps is complex and under investigation by many researchers [12,13]. Current practice for controlling such system resorts to rule-based methods [14,15]. In recent years, mathematical techniques are introduced to solve this problem, such as the optimization of pumping stations and air conditioning systems done in 2012 and 2013 [16,17,12,18,13].

In pump station studies, [17] presented an improved dynamic programming method for single-pump operation in a pumping station in order to reduce energy cost. [12] extended the results of [17] to multi-pump operation with pump switching cost considered. The focus of [17,12] is to reduce the computation time incurred with the pump operation scheduling problem. In [18], multi-pump control of a pump station with the objective of minimizing pump switching frequency is presented. It gives a two stage control strategy which firstly determines the number of pumps that should be running and then decides which pump specifically to turn on (off). The pump operation only has ten states and thus the algorithm is a kind of switching control between different states.

Similarly, a decision-making procedure is proposed in [16] and the pump operation scheduling of a water distribution system is investigated in [13] to reduce energy consumption.

The operation problem is essentially a switching control problem which is mainly solved either by dynamic programming method [17,12] or heuristic decision making methods [16,18] in those studies. The introduction of time-based electricity tariffs that aims to reduce peak load and relief grid pressure further imposes difficulties for the optimal operation of such multi-pump systems. In this study, mathematical formulation of the system dynamics and the corresponding optimal operation problem are presented. The optimal operation problem is treated as a binary integer programming problem and solved by the CPLEX optimization tool.[4] Optimization results show the advantages of the proposed system in terms of energy consumption and cost savings.

Take advantage of the operating cost of the system derived from the solution of the optimal operation problem, the financial feasibility and benefits of the proposed system is further evaluated. Life cycle cost analysis method is employed for this purpose, and it is shown that the proposed system results in preferable results in terms of both cost reduction and grid pressure alleviation.

It is also noted that the proposed approach does not affect the product quality of the cyclone separation process because it does not change the flow rate of medium supply to the DMC. Instead, it changes the medium supply circuit in configuration and operation to save energy.

The problem is further elaborated in Section 2 followed by two different configurations of the PSS in Section 3. After that, the system dynamics of the DMC plant with PSS is modeled in Section 4. Section 5 presents the formulation of the operation optimization problem. Life cycle analysis of the proposed design is done in Section 6. Case studies based on real-plant data are carried out in Section 7 to affirm the proposed system's financial viability and effectiveness in improving energy efficiency. Then conclusion is drawn in Section 8.

2. Problem statement

Coal preparation plant consists of several coal cleaning processes to wash the run-of-mine coal so that it can be transported to market [19]. This study focuses on improving energy efficiency of the dense medium cyclone separation processes such that the energy cost of the mine can be reduced and consequently reduce the fuel cost of its contracted power stations.

The schematic diagram of the cyclone separation process is shown in Fig. 1 [20]. It can be seen that raw coal and dense medium pumped from the corrected medium tank, which normally situated in the basement of the plant, are blended in the mixing box before entering the cyclone for separation.

In the cyclone process, the feed, mixture of raw coal and dense medium, enters tangentially near the top of the cylindrical section of the cyclone, thus forming a strong swirling flow. Centrifugal forces cause the rejects or high ash particles with high specific gravity to move towards the wall and to discharge in the underflow through the spigot. The lighter particles are caught in an upward stream and pass out as clean coal through the cyclone overflow outlet via the vortex finder.

The dense medium supplied to the cyclone is essential for the separation efficiency and product quality [21,22]. For each coal washing module, there is a corrected medium pump used to supply medium to the cyclone. The medium is pumped from the corrected medium tank to the distributor where it is split into two streams, one to the mixing box and the other flows back down to the corrected medium tank. The resulting clean coal and rejects are subject to drain and rinse screens to recover the medium and to yield clean coal.

One thing worth noting is that the part of medium that flows back down to the bottom of the plant is used in practice for operation safety reasons. Insufficient medium at the cyclone will result in drops of production rate and quality of the plant. Therefore, under-pumping is undesired and must be avoid at all cost. Therefore, plant operators always try to avoid under-pumping to maintain the quality of fine coal.

Current practice to maintain the coal quality is realized by pumping more medium than it is required by the cyclone separa-

[3] US Department of Energy 2007, Mining Industry Energy Bandwidth Study.

[4] ILOG 2008, CPLEX 11.0 User's Manual.