Applied Energy 146 (2015) 65–73

Contents lists available at ScienceDirect

Applied Energy

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

# Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff

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## HIGHLIGHTS

- DSM techniques are applied to an underground mine ventilation network.
- A minimization model is solved to find the optimal speeds of the main mine fan.
- Ventilation on demand (VOD) leads to a saving of USD 213160.
- The optimal mining schedule, together with VOD, leads to a saving of USD 277035.
- According to a case study, a maximum of 2 540 035 kW h can be saved per year.

## ARTICLE INFO

*Article history:*
Received 4 August 2014
Received in revised form 10 January 2015
Accepted 30 January 2015

*Keywords:*
Energy efficiency
Load management
Mine ventilation
Optimization
Time of use tariff
Ventilation on demand (VOD)

## ABSTRACT

In the current situation of the energy crisis, the mining industry has been identified as a promising area for application of demand side management (DSM) techniques. This paper investigates the potential for energy-cost savings and actual energy savings, by implementation of variable speed drives to ventilation fans in underground mines. In particular, ventilation on demand is considered in the study, i.e., air volume is adjusted according to the demand at varying times. Two DSM strategies, energy efficiency (EE) and load management (LM), are formulated and analysed. By modelling the network with the aid of Kirchhoff's laws and Tellegen's theorem, a nonlinear constrained minimization model is developed, with the objective of achieving EE. The model is also made to adhere to the fan laws, such that the fan power at its operating points is found to achieve realistic results. LM is achieved by finding the optimal starting time of the mining schedule, according to the time of use (TOU) tariff. A case study is shown to demonstrate the effects of the optimization model. The study suggests that by combining load shifting and energy efficiency techniques, an annual energy saving of 2 540 035 kW h is possible, leading to an annual cost saving of USD 277035.

## 1. Introduction

With growing concerns about the environment and energy security across the globe, these areas of research also become popular. Carbon emissions trading has been a common area of interest with regard to environmental studies [1,2]; and demand side management (DSM) programmes are introduced around the world as an effective and quick solution to the increasing energy concerns. DSM programmes seek to reduce the gap between power supply and demand broadly by energy efficiency improvement, energy conservation interventions, fuel switching, load expansion and self-generation, among which energy efficiency (EE) and load management (LM) are the most popularly used methods in the industrial sector [3]. The LM approach aims to reduce electricity demand at peak periods by giving monetary incentive to shift load to off-peak periods, e.g., in the form of the time of use (TOU) tariff or demand response [4,5]. The EE approach aims to reduce overall electricity consumption by installing energy efficient equipment and/or optimizing industrial processes, e.g., by making use of variable speed drives (VSDs).

DSM techniques are applied in various industries as can be found in literature. Some applications consider load shifting by finding the optimal switching times of equipment or processes according to the TOU tariff, e.g., controlling conveyor belts [6,7], pumps [8,9], geysers [10] and equipment that form part of a batch process [11]. These examples show significant cost saving compared to the baseline case, but actual energy saving is very little because the objective is focused on load shifting from peak periods. Considerable attention has also been drawn to EE improvement of

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http://dx.doi.org/10.1016/j.apenergy.2015.01.134
0306-2619/

industrial processes by the application of VSDs. In particular, the application of VSDs to fans and pumps have been studied [12–14], reasons being that VSDs offer more energy saving than a simple switching strategy [7,12] and a small reduction in the speed can result in large energy savings [15–17]. However, these examples do not consider LM under the TOU tariff in order to shift load from peak time. Thus very few cases consider obtaining energy saving and peak load shifting with application of DSM techniques, simultaneously [18]. In particular, little evidence is found of application of VSDs to achieve both LM and EE in mining ventilation networks.

It is known that the industrial sector consumes about 37% of the world's total delivered energy, and out of this, the mining industry contributes about 9% [19]. Mine ventilation is crucial for safety reasons, because it is responsible for clearing out noxious and flammable gasses; and also provides a comfortable working environment underground. The rating of the fans that provide ventilation, depending on its use, can range from 100 kW [20] to about 3000 kW [21]. Thus, contribution by the ventilation fans towards the total power consumption is quite significant. Research suggests that, depending on the type of mine, up to 40% [22] of the total electricity used, and up to 60% [23] of mining operating cost can be attributed to ventilation underground.

Existing studies on mine ventilation networks vary in objectives. Some consider making use of computer programmes in conjunction with survey data to model the changes in the structures of the ventilation network to achieve safe and economic solutions [24,25]. These cases do not consider LM or EE in any way. Other studies are performed with the objective of running the ventilation system more efficiently to reduce costs, e.g., in [26] a review is done at the beginning of every week to determine which levels will be inactive for the next week, such that the auxiliary fans in those levels can be switched off. This study considers EE but not by application of VSDs. Optimization techniques are sometimes employed, e.g., [27,28] discuss the use of nonlinear programming methods to find the optimal flow rates in the branches such that the rating of the fan, required to supply the network, is minimized; [29] shows the use of genetic algorithms (GA) to decide on the optimum number, location, and size of booster fans/regulators in the network; [21] makes use of mixed integer programming (MIP) to find the optimal angles of the auxiliary fan blades, in order to match the varying flow rates throughout the different stages in a mine. These studies are all performed with the objective of minimizing energy consumption and/or related costs, but there is no consideration for the TOU or the application of VSDs.

Literature suggests that it is common practice around the world, especially in older mines, to run ventilation fans continuously, regardless of production needs. Also, they are sized to meet the maximum volume requirements over their operating period. Examples of this can be found in Slovenia [30], Canada [31] and South Africa [32]. As such, the concept of ventilation on demand (VOD) is explored [33,34]. The idea is to allow variable air flow by adjusting the speed of the fan over time (based on the demand), as opposed to running them at full capacity at all times. These studies make use of VSDs to perform EE measures, but there is no consideration for shifting load from peak times according to the TOU tariff. Another limitation is that only auxiliary fans are selected to be part of the VOD programmes, as opposed to the main mine fan. This is done because changing the speed of the main fan will affect the entire network and is more complicated to control than the auxiliary fans.

The novelty of this paper is that it focuses on applying both DSM strategies together (load shifting and energy efficiency) to the main fan in an underground mine ventilation network. Also, no study has been found that performs optimization which incorporates the fan laws together with the ventilation network. Thus, energy efficiency is achieved by determining an optimal speed profile for the main fan according to VOD. In addition, LM is introduced, by optimizing the mine schedule according the TOU tariff, such that further energy cost reduction can be achieved.

The ventilation network is first mathematically modelled by extending the work shown in [27,28], whose main feature is modelling the network using Kirchhoff's current and voltage law. Then, the optimal schedule of a set of given mining processes is found by solving an optimization problem formulated. Thereafter, the fan speed optimization problem is solved to determine the optimal fan speed profile throughout the mining processes that matches the VOD and reduces energy consumption. For the fan speed optimization problem, the fan's operating point is correctly determined by incorporating the fan laws and the network's system curve to get a realistic figure of the savings [18,35]. A case study is presented to demonstrate and verify the effectiveness of the optimization model built. The results show that by combining load shifting and energy efficiency techniques, an annual energy saving of 2 540 035 kW h is possible, leading to an annual cost saving of USD 277035.

The rest of the paper is organized as follows. Section 2 presents the formulation of the ventilation problem. A case study is given in Section 5. Section 6 concludes this study.

## 2. Problem formulation

The problem is divided in two parts, EE and LM. For the EE case, the fan speed is adjusted according to the varying demand of air flow rate throughout the day. In the case of the LM, the optimal starting time of the mining schedule is found (according to the TOU tariff) that leads to minimum cost; and then the fan speed is adjusted accordingly.

For either case, the ventilation network needs to be modelled. To help understand the model better, an example of a simple network is presented. A path in a network can be defined as a directed chain from the inlet node to the outlet node. In addition, an assumption is made to simplify the model that says, the airflows in all branches contained in the path must have the same direction. The total number of paths in a network $n_p$ is given by $n_p = n - m + 1$, where $n$ is the number of branches and $m$ is the number of nodes. In Fig. 1, there is 1 fan, 13 branches, 9 nodes, and thus, 5 paths.

Tellegen's theorem states that "the power provided to the system and the power consumed in the network must be equal" [36]. From a ventilation network point of view, it can be concluded that the sum of air power supplied by the fans must be equal to the sum of power losses incurred in the branches of the network.

The analogy of circuit theory is often used in modelling flow distribution networks by comparing the flow rate to current, and the voltages to the pressure [27,28]. Thus Tellegen's theorem, along with Kirchhoff's laws form the basis to modelling an airflow distribution network.

The adaptation of Kirchhoff's current law is given by

$$\sum_{j=1}^{n} B_{ij} Q_j = 0, \ \text{for } i = 1, \ldots, m, \tag{1}$$

where $j$ is the branch number, $n$ is the total number of branches, $Q_j$ is the flow rate of branch $j$, $i$ is the node number, $m$ is the total number of nodes, $B_{ij}$ is the element of an $m \times n$ incidence matrix $B = [B_{ij}]$ that describes the node-to-branch incidence

$$B_{ij} = \begin{cases} 1, \text{if flow in branch } j \text{ enters node } i; \\ -1, \text{if flow in branch } j \text{ leaves node } i; \\ 1, \text{if branch } j \text{ is not incident with node } i. \end{cases}$$