Implementation of Variable Frequency Drive on Underground Main Fans for Energy Savings—Case Study

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ABSTRACT :*Energy is a fundamental need for industries in every part of the world. The cost of electricity has increased significantly in the recent years and this trend is expected to continue in the coming years as well. Ventilation is a key component in the design and execution of all underground mine operations. Energy-efficient ventilation design is crucial for maintaining safe working conditions in underground coal or metal mines. Ventilation demand in metal mines may vary throughout the year, and a careful redesign of the ventilation system can optimize energy costs to a good extent. This paper investigates the potential for energy savings in underground metal mines by installing variable frequency drives (VFDs) on the main ventilation fans to provide variable control of airflow. VFDs are cost-effective, easy to control and require little maintenance. It has been found that significant amounts of electrical energy can be saved by installing VFDs on the main ventilation fans.*

KEYWORDS -*Mine ventilation, Ventilation on demand, Variable frequency drive, Energy saving*

I. INTRODUCTION

Developing efficient patterns energy usage in industry is becoming a growing concern for both environmental and economic reasons. It was reported that industries consume about 37% of the world's total distributed energy and the share of the mining industry is approximately 9% [1]. This is true for most countries where industries form the largest sector of energy consumers. In Turkey, industry accounted for 47% of the total electricity consumption in 2015 [2]. The demand for energy demand grows in direct proportion to the economic growth of a country. It is predicted that over the next 25 years, energy consumption by the industrial sector worldwide will increase by an average of 1.2% per year and that by 2040, energy consumption by industries will account for 50% of the world's total delivered energy 2040 [3].

In mining, the ore can be mined by surface (open pit) and underground methods depending on the features of the deposit. According to previously published literature, in 2014, there were 2500 mines in operation, with 52% performing surface mining, 43% performing underground mining, and 5% making use of other methods around the world [4]. It is reported that, depending on the type of mine, approximately 40% of the total electricity used [5], and up to 60% of the operating cost [6] is related to providing underground ventilation.

In underground metal mines, main fans supply fresh air depending on the requirement and are operated for 24 h a day at maximum capacity. The total airflow requirement depends on the number of production and development levels and the nature and intensity of activities in each of these locations. As a rule, in all mines, ventilation systems are designed for the 'worst-case-scenario' regarding the demand for ventilation. Moreover, this scenario usually occurs during the last quarter of the mines' operating life [7]. Once the ventilation pattern for a mine has been designed, the system usually operates at this peak level throughout the operating life of the mine. As a result, during the early stages of mine operation when the mining depths as well as the production rates are relatively low, the total intake air volume could be much higher than the mine's actual ventilation needs at that point in time. It must be evaluated whether operation at this 100% volumetric capacity is required or not. This redundancy increases the mine's total energy consumption. Ventilation redundancy can be defined as the difference between the total intake airflow delivered by the primary fans minus the sum of the activity-based air volumes required to be delivered to the production areas.

In a typical metalliferous underground mine, the production cycle comprises drilling, explosive charging, blasting the ore, mucking, cleaning and rock support operations. The ventilation requirement for each differs depending on the quantity of diesel equipment used for the operation. The energy consumption can thus be potentially reduced by optimizing the ventilation system so that only the necessary amount of air is supplied when and where the need arises. The increasing energy costs associated with mining have become an issue that needs to be addressed for future sustainable production. Energy management, proper ventilation planning and control strategies in mine ventilation-on-demand and cooling-on-demand strategies are getting more significant [8]. There are several modelling packages such as Ventsim, VnetPC and Vuma available for ventilation design but the integration of ventilation modelling into the life cycle plan of mines have not been studied much.

VFDs are already in use for adjusting pump and fan speeds in the heating, ventilation and air conditioning of buildings. In these applications, the flow of water or air is controlled by speed adjustment, which is an energy-efficient method of flow control [9]. VFDs supply soft-start, which decreases the electrical stresses associated with full-voltage motor start-ups and also reduce tear and wear [10]. With advancements in technology, the use of VFD for industrial control systems is becoming a standard practice. In paper [11], researchers discussed energy saving techniques for ventilation fans in underground coal mines and application of VFDs to coal mines. The aim of this study is to evaluate the applicability and energy-saving performance of VFDs in main ventilation fans for three metalliferous underground mines in Turkey.

II. MATERIALS AND METHODS

2.1 Underground Mine Ventilation

The main purpose of an underground ventilation system is to supply fresh air in the required amount to whole mine where personnel may work or travel [12]. Fresh air enters the mine from the surface through a ventilation shaft or adit and is then distributed all through the mine by a network of internal ventilation rises and ramps. Air flows are controlled by regulators and auxiliary ventilation systems. Fresh air is distributed to the working areas through temporarily mounted ventilation fans and spiral ducting (Fig. 1).

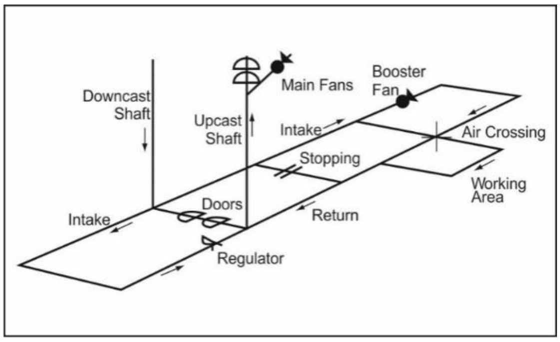

Figure 1. Components of mine ventilation system

Main fans produce and control the mine's ventilation airflow and are usually located at or near the surface [13]. Fans impart hydraulic energy to the air and cause airflow. This is done by converting rotational mechanical energy into hydraulic energy. The two most commonly applied types of fans used for mine ventilation are centrifugal fans and axial fans, although in some situations mixed-flow fans are also used.

Main fans can be located underground when fan noise is considered a problem or if shafts need to be completely free of airlocks. The choice of surface main fan location is illustrated in Figure 2. In Fig. 2A, exhaust ventilation connects the main fan to the upcast shafts. In Fig. 2B, forcing ventilation connects the main fans to the downcast shaft. Moreover, in Fig. 2C, push–pull ventilation connects main fans to both the upcast and downcast shafts.

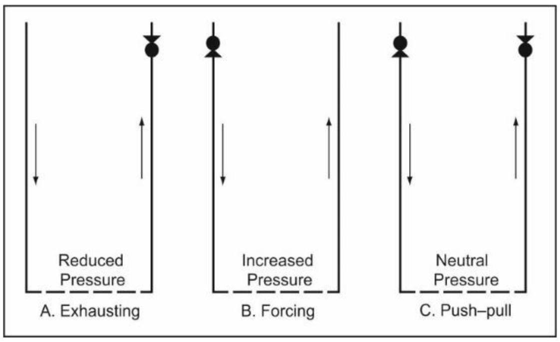

Figure 2. Possible surface main fan locations

2.2. Variable Frequency Drive

Typically, electric motors are designed to run at a steady speed and sized to provide the maximum required power output. VFDs work by controlling the waveform of the current and voltage supplied to the motor [14]. A VFD is a type of adjustable speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying the input frequency and voltage

[15]. An example of controlling the speed of a motor is represented schematically in Fig. 3 [16]. A VFD is installed between the power supply system and the electric motor that it drives. A VFD essentially comprises a rectifier, a control and protection regulator and an inverter.

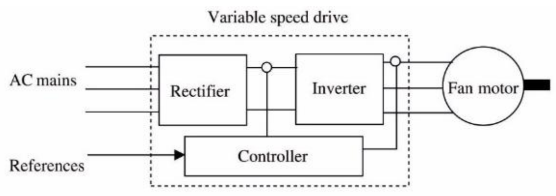

Figure 3. Block diagram of a VFD system

VFDs are already in use in pumps and for the optimization of building ventilation. Several studies have shown that using variable speed motors is the most efficient method for realizing energy savings when operating under a given load [17, 18, 19]. A VFD installation reduces energy consumption, increases energy efficiency, improves power factor and process precision and reduces the mechanical stress on the fan and motor.

Energy consumption in fans follows the affinity laws. These laws relate the quantities such as flow rate, head and shaft speed, which determine the fan performance, with the power or speed. The commonly used fan laws are represented by Equations 1, 2 and 3 that represent the relation among the basic fan parameters [20].

$$\frac{Q_a}{Q_b} = \frac{(N_a)}{(N_b)} \quad (1)$$

$$\frac{p_a}{P_b} = \frac{(N_a)^2}{(N_b)^2} \quad (2)$$

$$\frac{HP_a}{HP_b} = \frac{(N_a)^3}{(N_b)^3} \quad (3)$$

where: Q = flow
N = speed
p = pressure
HP = power

It is clear that, a fan's flow is directly proportional to its speed. To produce 50% of the maximum flow rate, the fan must run at 50% of the maximum speed. Since the power requirement is proportional to the third power of the speed, the fan would require only 12.5% of the rated power (0.5 × 0.5 × 0.5 = 0.125% or 12.5%) at this point of operation [21]. Therefore, a 50% reduction in flow results in an 87.5% reduction in the energy input.

2.3. Case Study

Usually, main fans in mines are controlled using across-the-line starters that are simple in operation and have a low capital cost. Normally, main ventilation fans are controlled manually and operated 24 h a day at maximum capacity. As a result, large amount of current is being drawn at each start-up of motor and during full-time motor operation phase. In fully mechanized metal mines, diesel equipment is used extensively. Here the ventilation requirements depend on the power capacity of the diesel equipment fleet. The basic rule is that there should be sufficient ventilation to dilute the exhaust gases and particulates to quantities below their threshold or limiting values. For design, many ventilation engineers assume a requirement of 0.06 to 0.08 m^3/s of airflow for each kW of diesel power, with all equipment being cumulative in any one air split [13].

Metal mines in Turkey, just like their counterparts in other countries, are now seeing increased levels of equipment automation and diesel equipment usage. Therefore, the demand for extensive ventilation is also increasing. In this study, the ventilation requirements of three highly mechanized, metalliferous, underground mines in Turkey have been analyzed and projected airflow demand schedules for event-based ventilation were determined. To ensure confidentiality, in this study, each mine is identified by a number and real names of the mines are not given here. The names Mine A, Mine B and Mine C are used to present the results of this study. Table 1 lists the production capacities, total airflow quantities, total power of diesel equipment, airflow per tonne mined and airflow per diesel power of these underground mines.

The method used in this survey is based upon the mine's future production planning data to determine the long term airflow requirement of the mines. Firstly, the existing primary and auxiliary ventilation systems in the mines have been modelled, solved and balanced using Ventsim. Ventsim™ is a ventilation simulation software designed for underground mines [22]. Then, the total planned air-volume requirements of the development and production workings of each mine has been calculated for the next five years.

Table 1. Summary of ventilation data collected from three mines

Mine	Production (tonnes/day)	Total airflow (m^3/s)	Total diesel power (kW)	Quantity	
				(m^3/s/tonne)	(m^3/s/kW)
Mine A	1300	250	4060	0.192	0.062
Mine B	4500	185	4350	0.041	0.043
Mine C	3750	260	7520	0.069	0.035

Table 2 shows the potential energy savings arising from the speed reduction achieved by the use of VFDs on industrial motors [23]. This data has been used to estimate the energy savings in main fan motors when VFDs are used. As mentioned previously, the airflow is directly proportional to the speed of the fan.

Table 2. Potential savings due to VFD through speed reduction

Average speed reduction (%)	Potential energy savings (%)
10	22
20	44
30	61
40	73
50	83
60	89

By running Ventsim software, the ventilation requirements of each mine for the next five years have been calculated. The fan speeds required to achieve these ventilation rates and the annual power savings have been determined and is summarized in Tables 3, 4 and 5.

In Mine A, the primary ventilation system takes in 250 m^3/s of fresh air using two adits. The return air is exhausted by a series of axial-type main fans running at 1500 rpm with a total installed power of 540 kW. Simulation results show that, for the next five years, the air flow requirement will increase from 215 to 240 m^3/s in a steady, ramp-up fashion. The results indicate that it is possible to save a significant amount of energy, especially over the next three years, by the installation of VFD on the main fans.

Table 3. Estimated ventilation requirements of Mine A

Years	Ventilation requirement (m^3/s)	Main fan speed (rpm)	Fan speed reduction (%)	Energy savings through VFD	
				(%)	(kW)
1	215	1290	14.00	31.28	1,479,527
2	220	1320	12.00	26.93	1,273,859
3	225	1350	10.00	22.43	1,060,887
4	235	1410	6.00	12.96	613,031
5	240	1440	4.00	7.99	378,148
				Sum	**4,805,453**

Mine B has a high production capacity and more production stopes and developments when compared to other mines. The total installed power of the axial-type main fans that run at 1200 rpm is 1100 kW. Currently, 185 m^3/s fresh air enters the mine via the decline. Ventsim model simulations indicate that the true fresh air requirement of the mine is 160 m^3/s for the next year. Using a VFD unit to adjust the fan speed results in a reduction in the airflow rate and a 30.23% reduction in the energy consumption of the fan.

Table 4. Estimated ventilation requirements of Mine B

Years	Ventilation requirement (m^3/s)	Main fan speed (rpm)	Fan speed reduction (%)	Energy savings through VFD	
				(%)	(kW)
1	160	1038	13.51	30.23	2,913,313
2	165	1070	10.81	24.27	2,338,737
3	170	1103	8.11	18.03	1,736,991
4	175	1135	5.41	11.50	1,108,075
5	180	1168	2.70	4.69	451,990
				Sum	**8,549,106**

Mine C shows significant energy-saving potential through the installation of a VFD on the main fan. A total of 260 m^3/s fresh air enters the mine through an adit and the decline. The return air passes through a series of ventilation rises and is exhausted by a pair of 385-kW axial-type main fans running at 1200 rpm. Calculations indicate that, over a period of five years, a total energy saving of 10,906,378 kW can be realized using this new scheme.

Table 5. Estimated ventilation requirements of Mine C

Years	Ventilation requirement (m^3/s)	Main fan speed (rpm)	Fan speed reduction (%)	Energy savings through VFD	
				(%)	(kW)
1	210	969	19.23	41.92	2,827,466
2	215	992	17.31	38.13	2,571,861
3	220	1015	15.38	34.20	2,306,627
4	230	1062	11.54	25.90	1,747,272
5	235	1085	9.62	21.54	1,453,152
				Sum	**10,906,378**

It is well known that the per-kW implementation cost of VFD decreases with increasing power rating. As per published data, the cost of low-voltage VFD units were approximately US$ 200/kW for 75-kW motor and US$ 117 /kW for 275-kW motor in South Africa during 2013 [24]. The total cost includes the cost of the VSD unit itself as along with the costs associated with consultation, cabling, installation and commissioning. Currently, VFDs have relatively low demand in Turkey and their prices are higher as compared to other European countries due to the import costs involved. Therefore, the unit cost of VFD implementation was assumed to be US$ 250 /kW. Table 6 presents the estimated cost savings over five years, payback period and environmental effects of VFD implementation. An energy cost of $0.10/kWh is chose for the calculations. Results from this survey showed that simple payback can be achieved within 10.6 to 16.8 months from the mines. The implementation of VFD technology to main fans benefits the environment through the reduction in energy consumption, which, in turn, helps to reduce the environmental impact of greenhouse gas emissions. It has been reported that the rate of CO_2 emission for electricity generation in Turkey is 0.48 kg /kWh [25].

Table 6. Summary of survey results

Mine	Estimated power savings in 5 years ($)	İmplementation cost of VFD ($)	Payback period (months)	CO_2 emission reduction in 5 years (tonnes)
Mine A	480,545	135,000	16.8	2306.62
Mine B	854,911	275,000	19.3	4103.57
Mine C	1,090,638	192,500	10.6	5235.06

III. CONCLUSION

In this paper, the potential for energy savings in three underground metal mines by installing VFDs on the main ventilation fans was investigated. Main fans are the primary means of setting up and controlling the ventilation airflow within mines. They supply fresh air into the mine depending on the requirement and are usually operated 24 h a day at maximum capacity. Main fans are designed to operate so as to accommodate the maximum ventilation demand which occurs mostly in the last quarter of mine life. By installing a VFD control it is possible to save a significant amount of energy during the early stages of mine life cycle, when the ventilation demand is low due to shallower mining depths, lower production rates and less leakage. The energy savings arise from the decreased power requirement for the operation of the motor at reduced speeds. These savings can be increased further since maintenance issues to combat wear and tear are reduced due to lower fan speeds. The financial viability of installing a VFD depends on the cost of electricity, fan size, running time and the desired reduction in the airflow rate. Our study predicts that it is possible to save more than one million dollars in Mine C over the next five years. Payback period on a VSD is found to be less than two years for all the three mines. Additionally, CO_2 emissions can also be reduced by up to 5235.06 tonnes in five years.

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