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RESEARCH ARTICLE

# Energy Savings Through VOD (Ventilation-on-Demand) Analysis in Indian Underground Coal Mine

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**ABSTRACT** The mining sector's sustainability is contingent upon operational efficiency improvements. This has resulted in significant improvements in industrial energy efficiency, resulting in reduced emissions and resource waste. Indian mine ventilation fans were discovered to be energy guzzlers, paving the way for more efficient driving techniques. A thorough investigation of cost savings, energy savings, and pollution reductions associated with different airflow scenarios utilizing Tandsi underground coal mine ventilation networks were conducted. Two applications of ventilation-on-demand were investigated: dynamic and steady-speed reduction. Economic feasibility suggests that variable speed drives operating at medium voltage (3.3 kV) may be utilized in ventilation-on-demand systems. With the adoption of ventilation-on-demand solutions, a total yearly electrical energy savings of 1070618 kWh might be accomplished. The estimated cost savings are 119588 US $, with a payback period of seven months on average. Emissions of greenhouse gases have been reduced by around 37% annually. A variable speed drive operating at medium voltage (3.3 kV) may be placed on the Tandsi mine ventilation fan to improve efficiency and decrease emissions. These audits identify underutilized resources that may be used to increase mining sustainability and profitability.

**INDEX TERMS** Energy efficiency, VOD, ventilation network, energy savings, VSD, ventilation fan.

## I. INTRODUCTION

Growing economies consume more materials and energy [1], [2]. Global industrial energy consumption will rise by 1.4% per year [3]. Environmental and energy security issues require intelligent energy solutions [4], [5]. Increasing operational effectiveness is a 21st-century norm [6]. The economy's strength depends on companies' biggest clients taking proactive energy efficiency measures [7]. India and South Africa's prosperity comes from natural mining resources and the long-term effects of mining [8]. According to research, the mining industry uses outdated methods that disregard sustainability [9], [10]. The global mining sector is using more efficient equipment like low voltage variable speed drives on pumping systems, ventilation fans, and cooling systems [11]. Experiments reduced the cost of low voltage VSDs [12]. VSDs save money in complex industrial systems [14]. The best-case study results come from cyclical systems with part-load scenarios [14]. Variable speed drives can save 25 to 50% of mining's energy [15]. Mine ventilation networks ensure a safe, productive work environment [16]. Subterranean work areas must have enough airflow to exhaust and dilute harmful particles [17].

Bulk air cooler and booster fan ventilation networks use surface or subterranean suction fans and transport air underground. Bulk air coolers cool mine ventilation air [13]. Before reaching the operating areas, air passes through the main and auxiliary booster fans [18]. Surface or subsurface refrigeration systems cool bulk air coolers. Variable speed drives in refrigeration and chiller facilities are successful, according to research [9]. Intake guide vanes, variable speed drives, and better-designed fan blades improve mine ventilation [19].

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Mines regulate fan airflow volume with intake guide vanes (IGVs) and consistent speed [20]. IGVs offer energy benefits but increase frictional resistance and decrease pressure [21]. Overusing centrifugal fans or impellers causes cracked blades [22]. Construction has successfully installed VSDs with tiny fans [13]. Built-in HVAC systems meet peak loads [23]. Idle and half-load save energy.

Redesigning fan blades saved energy [17]. Blade replacement is impractical due to initial and payback costs [18]. Medium voltage variable speed drives were not used in any of these methods via dynamic ventilation-on-demand (VOD) that ensures smooth airflow for underground mining operations [26], [27], [28]. Simulation, modeling, and dynamic control enable ventilation-on-demand (VOD) [29]. South African mines run at maximum airflow regardless of output needs [30]. All ventilation fans run full-time [31]. Return airways lose 28% of subterranean airflow [32]. 74% of intake air is lost through ducting and ventilation doorways in deep-level gold mines [33]. Considering the above, it is prudent to estimate a leakage rate of 28% oversupplied and underutilized mine ventilation in the working zones [33], [34]. Modulation and leak repair can reduce airflow leaks and improve airflow use. Dynamic and static ventilation on-demand increases airflow. Dynamic VOD applications control airflow.

Using the cyclical nature of mining airflow needs to change shifts [30]. Static VOD applications reduce mine ventilation network flow [20]. Establishing actual airflow needs and meeting them after leaks are fixed can achieve this [35]. This is the first-time leak repair has allowed a decrease in airflow, resulting in energy savings and lower emissions. MV VSDs can regulate primary mine ventilation fans for adequate airflow underground [35]. Both dynamic and static control may be needed to manage ventilation [36]. Using MV VSD to control fan speed improves airflow management [29]. Pilot-scale VSD experiments in Canada showed variable airflow's benefits in gold mines [37]. However, these technologies have not been deployed in South African mine ventilation networks or MV VSDs [38]. Previous research focused on small capacity motors, such as chiller, compressor, pump, and fan motors [9].

According to VOD and TOU, a theoretical model was developed and solved to determine the optimal fan speeds for a South African mine. VOD is successful in this minimization model when energy efficiency and load management are used. Taking TOU energy prices into account regulates ventilation fan speed, resulting in a dynamic fan power profile [30]. The load-shifting control saves energy during peak loads and other times. The optimizer reduces energy costs while ignoring ventilation and GHG emissions [1]. Using and regulating VSDs, which reduce airflow volume, can increase energy efficiency in building services [23]. Changeable circumstances usually increased savings. Cost-saving measures for Indian mine ventilation networks should include static and dynamic applications.

It is normal practice to operate main ventilation fans with constant speed and airflow rate in Indian underground coal mines, irrespective of the need for the production process. They are also built to handle the greatest possible airflow requirements for the period of their operational stage. Instead of continuing to run fans at full speed all the time, the idea is to gradually adjust their speeds (according to demand) to enable variable airflow. Therefore, this study is important to implement the idea of ventilation on demand (VOD) by using VSD to implement energy efficiency initiatives.

This study focused on a 3.3 kV, 250 kW motor for Tandsi Mine's primary ventilation fan. Fans with 1000 kW or more were not evaluated. South Africa's political, socioeconomic, and physical characteristics make VOD on mine ventilation networks underappreciated [39], [40]. Directorate General of Mines Safety, Govt. of India prohibits demand ventilation in Indian underground coal mines.

This study evaluates two VSD implementations in the Indian Tandsi underground coal mine. Energy consumption and cost savings are estimated to assess the main mine ventilation fan's energy consumption, GHG emissions, and financial viability.

The following sections make up the remainder of this article. Section II describes the fundamental theory regrading primary ventilation fan performance, characteristics of medium voltage 3.3 kV variable speed drive, and its financial feasibility towards installation with 3.3kV, 250 kW electric motor to drive primary ventilation fan of Tandsi Mine. A VOD potential analysis in Indian underground coal mine can be found in Section III. In Section V, the study is concluded.

## II. FUNDAMENTAL THEORY

### A. FAN PERFORMANCE CHARACTERISTIC

With a fixed blade angle centrifugal fan at a constant speed, it's important to understand how changing speed affects ventilation fans [37]. Primary mine ventilation fans are centrifugal [41], [42]. Each primary ventilation fan's performance is described by the OEM's performance curve [31] in terms of the static pressure needed to provide a given airflow volume [43]. Variable intake guide vane angles or speeds affect fan efficiency, system resistance, and other performance [44]. Figure 1 shows the characteristic curve of a Mine Ventilation Fan Model No. APG-2500 installed at India's Tandsi Mine. M/s Suburban Industrial Works, Kolkata, India (Original Equipment Manufacturer), made this curve. Decreased fan speed under a given system resistance reduces air pressure and power [45]. Pressure and airflow rate explain underlying principles. Equation (1) shows main ventilation fan efficiency. Static efficiency is defined as the ration of air power to shaft power [31]. Static air power is the product of static pressure and fan speed [41]. Equation (1) links pressure and airflow volume. VOD requires the fan to meet demand [30], [31]. Modeling VOD requires calculating airflow volume and power. Static efficiency is calculated as follows:

$$\eta_s = \frac{P_a}{P_{sh}} = \frac{m(H_1 - H_2)}{\rho P_{sh}} = \frac{Q(H_1 - H_2)}{P_{sh}} \tag{1}$$

where $\eta_s$ is the static efficiency (%); $P_a$ is the air power (kW); $P_{sh}$ is the shaft power (kW); $m$ is the airflow mass flow rate (kg/s); $(H_1 - H_2)$ is the pressure difference from initial to output conditions in (kPa); $\rho$ is the air density in (kg/m$^3$); $Q$ is the airflow volume in (m$^3$/s).

Airflow volume and power are linked by fan affinity laws [37]. The laws link fan speed, shaft power, and fan pressure. The affinity laws are:

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{2}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{3}$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{4}$$

where $P$ denotes the power (kW), $N$ denotes the speed of the fan (rpm), $H$ denotes the pressure (kPa), and $Q$ denotes the airflow volume (m$^3$/s). Subscripts 1 and 2 are initial and output conditions respectfully.

Equation (4) shows that airflow volume ratio is proportional to fan speed ratio. A small reduction in fan speed causes significant power loss [10].

Variable speed drives control fan motors and change airflow volume [30]. This affects the cubic power-airflow relationship [11], [12]. Regulating fan speed to provide a predefined airflow volume calculates shaft power.

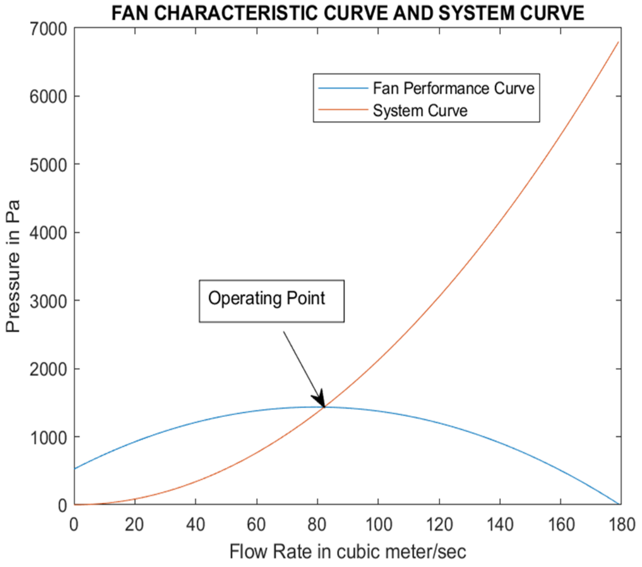

**FIGURE 1.** Fan characteristic curve of main ventilation fan installed at Tandsi UG mine.

## B. CHARACTERISTICS OF VARIABLE SPEED DRIVE

Variable speed drives use PWM to vary electric motor current, voltage, and frequency. These outputs can regulate motor torque, speed, and power [46]. Variable duty point modulation provides the most efficient variable load management [47]. Conventional IGV controls eliminate friction and pressure drop by opening IGVs to 100% and regulating flow with VSDs [10]. Motor current load losses of 2% to 3% result in 97% to 98% VSD efficiency [37]. VSDs reduce GHG emissions and life-cycle costs [10]. VSDs help industries reduce energy costs [6]. Many successful case studies have been conducted on boilers, conveyor systems, refrigeration systems, and pumping systems [48], [49]. The relationship is established between motor power and rated speed in terms of their respective proportions [12].

## C. FINANCIAL FEASIBILITY

Before deployment, the financial viability of installing VSDs should be carefully assessed [6]. Payback period (PBP) and ROI are used to evaluate energy projects [50]. Efficiency experts Nehler and Rasmussen found that the PBP contributes most to project feasibility [51]. This also applied to South Africa's multinational mining companies [10]. In this research, the PBP was used to determine a project's viability. Equation (5) determines a project's PBP [12].

$$PBP = \frac{C_{TE}}{C_{TS}} \tag{5}$$

where $PBP$ is the annual payback period, $C_{TE}$ is the annual project expenditure (US\$) (including the capital, installation, and commissioning costs), and $C_{TS}$ is the annual cost savings (US\$).

In South Africa, overall cost savings are calculated using energy savings and electricity tariffs due to TOU power pricing [52]. Energy projects with PBPs less than one-third of an electric motor's life expectancy are feasible. Electrical motors in mine ventilation fans have a 25-year lifespan [53]. Energy projects using fan motors with a PBP of less than eight years will be financially viable. International case studies show that VSD utilization initiatives have PBPs of less than two years [48]. This meets South Africa's mining sector's feasibility criterion [10]. Technological advances and increased use of VSD have reduced costs in the past five years [12]. Low voltage VSD applications have benefited the industry [6]. Although 3.3 kV VSDs have become less expensive (US\$/kW), their deployment has been limited [48]. Table 2 shows the prices of 3.3 kV VSDs for Indian mine ventilation fans.

VSD projects on high-capacity motors become more practical. Due to limited demand, MV VSDs are more expensive in South Africa [10]. This shows the importance of evaluating VOD in South African mining. Due to low demand, 3.3kV VSD is expensive in India. The Indian Mining Sector's VOD potential must be evaluated.

MV or LV VSDs are chosen based on the controlled equipment's supply voltage and rating [12]. For optimal control in medium voltage mining systems, only MV VSDs may be installed [24]. LV VSDs cannot be installed on mine ventilation fans [6]. When comparing LV and MV VSD installations, the payback time should be used as the deciding factor [51]. Modern MV VSD manufacturers have solved significant technical issues [12]. Technical issues are unnecessary if the MV VSD drive is installed and commissioned properly [10].

Manufacturers offer extended maintenance plans and guarantees to keep MV VSDs running for at least five years [54]. Manufacturers surveyed offer mine workers free training and quick help for five years. Before capital-intensive ventures, low-hanging fruit initiatives should be implemented [51].

## III. VOD POTENTIAL

The ventilation networks of the Tandsi mine were examined as part of the evaluation of VOD potential. The Tandsi Mine ventilation networks' service delivery and energy usage were assessed. The ventilation networks were of varying sizes to allow for a complete evaluation of VSD use in a nationwide setting. Tandsi UG coal mines with different degrees of complexity and production rates were included in the study.

### A. TANDSI MINE VENTILATION NETWORKS

When planning ventilation, three coal mining shifts must be considered. Each change requires airflow, but for different reasons [55]. Each shift drills, charges, blasts, and loads. During shifts, main ventilation fans and underground booster fans ventilate subterranean working areas. This ensures that temperature and particle matter requirements are met [56]. Hazardous particles (toxic blasting gases and dust) are neutralized and expelled between shifts for 2 hours [30]. Miners leave the production face and move to the main shaft haulage area until the clearing period is over or they leave the mine [21]. Many writers have examined ways to improve mine ventilation networks [41]. Du Plessis *et al.* used IGV control to reduce costs in South African mines [24]. Chatterjee *et al.* created a theoretical VOD optimizer based on TOU power prices to account for actual airflow needs [31]. No research has been done on the viability of MV VSDs in South African and Indian mines [21]. Many writers stressed the need for such research to determine cost savings and emission reductions associated with primary mine ventilation fans [37].

### B. TANDSI MINE ENERGY AUDIT

Energy audits are the first step in assessing energy projects. [57]. An energy audit is a thorough method for evaluating and analyzing systems to identify potential energy savings [58].

Energy consumed by different equipment used in Tandsi UG coal mine was audited to evaluate their annual percentage share of energy consumption [59].

In table 1, the mine ventilation fan represents 17.33% of the total energy consumed in the Tandsi Mine. Installing VSDs on mine ventilation networks can reduce costs by 25 to 50% [15]. South African mines typically operate under constant airflow conditions that provide maximum volume [30]. Indian mine ventilation fans run 24/7 at full capacity [31]. Primary ventilation was audited to assess and characterize an Indian mine's (Tandsi UG coal mine) ventilation network.

Historical data on the ventilation network of the Tandsi underground coal mine were combined with fan performance curves and other system parameters to analyze and characterize present operations [14], [54]. Fan load and energy use should indicate flow modification [14]. Equation (6) can be used to calculate a primary ventilation fan's energy consumption [60].

$$E_{Fan} = (T_o)(L_F)(W_F) \tag{6}$$

where $E_{Fan}$ is fan motor energy consumption (kWh), $T_o$ denotes working hours (h), $L_F$ indicates load factor (percentage), and $W_F$ denotes maximum rated power of fan motor (kW). Load factor is defined as the ratio of measured capacity to motor-rated capacity [58].

**TABLE 1. Annul percentage share of energy consumption [59].**

| Equipment/Load Centre | Energy Consumption (kWh)/Year | % Share |
|---|---|---|
| Mine Ventilation Fan | 13,26,513 | 17.33 |
| Face Equipment | 4,93,711 | 6.45 |
| Coal Transport | 12,18,586 | 15.92 |
| Underground Man & Material Transport | 1,13,286 | 1.48 |
| Underground Pumping | 20,15,412 | 26.33 |
| Coal Handling Plant | 1,64,570 | 2.16 |
| Unit Workshop, Unit Store, Mine administrative office and Illumination (Surface & UG) | 2,94,211 | 3.84 |
| Township | 17,29,620 | 22.59 |
| System losses | 2,98,523 | 3.90 |
| Total | 76,54,432 | 100.00 |

Equation (6) determined the mine's load factor. Table 2 shows the load factor's key finding. The fan motor's static efficiency is 85% at 250 kW. The assessed fan accounted for 22% of the mine's annual energy consumption. The mine's primary fan is a centrifugal, backward-inclined fan with a 3.3 kV supply voltage. The primary ventilation fan has IGV (Inlet Guide Vane) control. Several vanes were stuck in many IGVs. High vibrations damaged these vanes' IGV control mechanism. The primary ventilation fan wasn't variable speed. In India, the potential for VOD via VSD on the primary mine ventilation fan has neither been studied nor implemented. Lack of knowledge about VSD implementation and evaluation may account for its absence in VOD [15]. South Africa's cheap power prices meant mine workers didn't prioritize energy efficiency [52]. As a result, energy conservation measures were overlooked, as is the case now [21]. Most employees were willing to install VSDs as part of VOD efforts if the financial benefits were shown in a PBP. In India, electricity costs are higher for coal mines, so management is exploring installing 3.3 kV VSD on the main ventilation fan. Using VSD technology, the Tandsi mine's VOD potential can be assessed. Table 2 's power load factors indicate inefficient operations that can be mitigated by VSD airflow volume modulation. Tandsi Mine's load factor is below 80%. Inefficient IGV control of the mine ventilation fan led to a low power load factor. Low factor means variable airflow control can improve operational efficiency. Thus, VSDs are in high demand. VSDs must be financially viable.

**TABLE 2.** **Electrical characterization of tandsi mine ventilation network.**

| Electrical Characteristics | |
|---|---|
| Load Factor | 78% |
| Qty. of Installed Fan | 02 Nos. |
| Qty. of Operating Fan | 01 No. |
| Individual Fan rated power | 250 kW |
| Total Fan rated power | 500 kW |
| Total average power demand | 195 kW |
| Total Annual Energy Consumption | 17,08,200 kWh/Year |

### C. SAVING CALCULATIONS

Estimates of savings should be as precise and cautious as possible [61]. Numerous techniques exist for calculating VSD savings on pump and fan motors [58]. This research used a simplified technique to calculate energy savings [12]. This method is ideal for evaluating complex systems like mine ventilation networks [12]. Equation (7) can be used to calculate energy savings from installing MV VSDs on mine ventilation fans [24].

$$ES_{Fan} = (T_o)(SP_F)(W_F) \tag{7}$$

where $ES_{Fan}$ is the energy saved (kWh); $T_o$ is the running hours (h), $SP_F$ is the energy savings percentage (%) for an anticipated decrease in airflow, and $W_F$ is the fan motor's maximum rated capacity (kW).

Energy conservation reduces coal-fired power plant GHG emissions [62]. More than 65% of India's energy comes from coal. South Africa's GHG emissions grew by 20% between 2000 and 2009, so energy savings may contribute to a paradigm shift toward sustainable growth [63]. Equation (8) can be used to estimate GHG emission reductions from energy savings [6].

$$ER_{GHG} = ES_{Fan} \sum (F_{\%} \times E_F) \tag{8}$$

where $ER_{GHG}$ denotes annual reductions in $CO_2$, $SO_2$, and $NO_x$ GHG emissions (kg), $ES_{Fan}$ denotes electrical energy savings (kWh), $F_{\%}$ denotes the percentage of fuel used to generate electricity (%), and $E_F$ denotes coal-fired electricity generation emission factors (kg/kWh). $CO_2$, $SO_2$, and $NO_x$ have 0.990, 0.00825, and 0.00411 (kg/kWh) emission factors [70]. When evaluating Indian underground coal mines' VOD potential, consider emission reductions.

## IV. RESULTS

The next part evaluates VOD in Indian coal mines via 3.3 kV VSDs, using all study data. VSD adoption can save energy, reduce costs, and reduce GHG emissions. Equations (6) - (8) were used to evaluate the effects of varying airflow volume. Finally, financial indicators were computed for each airflow volume scenario to determine its feasibility.

### A. VOD POTENTIAL IN INDIAN UNDERGROUND COAL MINE

VOD potential can be assessed in dynamic and static control applications [10], [48]. VOD meets the varying airflow requirements of various mining operations throughout a typical mining day [31]. VOD creates a dynamic daily airflow profile and fan speed/energy profile. In some cases, underground airflow is oversupplied or inefficiently used, requiring constant speed reductions [41], [32]. Inadequate underground seals, deteriorated ducting, improper circuit design, and unforeseeable mining changes cause low airflow utilization [41], [27]. 28 percent of ventilation fan airflow is lost to return airways in South African mines [32]. Installing ventilation seals that direct airflow to underground work areas increases airflow efficiency. After that, South African mines can reduce supplied airflow by 28% while maintaining service [16], [21]. Any change to the underground ventilation network's configuration affects system resistance and energy consumption [41]. To illustrate the theoretical maximum potential of VOD applications calculated using affinity law equations, the system resistance was assumed to remain constant. Changes in the underground ventilation network configuration will reduce energy savings. In a dynamic, expansive environment, it's impossible to eliminate all leaks [16]. This must be considered, along with pilot case study results versus theoretical energy savings and emission reductions. Constant speed applications must be examined before assessing VOD's potential in Indian mines.

Table 4 shows the fan's energy consumption at Tandsi UG. Under different airflow conditions, the fan's energy consumption was estimated. As mentioned, the drop in airflow may be due to an overstock or subterranean ventilation sealing improving airflow use (28 percent leakages). Construction of subterranean seals at mines should reduce airflow as planned.

**TABLE 3.** **Typical 3.3 kV MV VSD costs (US$) in India.**

| Motor Capacity | 250 kW |
|---|---|
| Supplier 1 | 32930 |
| Supplier 2 | 39516 |
| Supplier 3 | 38200 |
| Average 3.3 kV VSD | 36882 |
| Installation@15% | 5532 |
| Commissioning@5% | 1844 |
| 3.3 kV VSD intensity (US$/kW) | 148 |
| Installation intensity (US$/kW) | 22 |
| Commissioning intensity (US$/kW) | 7 |
| Total 3.3 kV VSD intensity (US$/kW) | 177 |
| Additional Optional Costs | |
| 5 Years Warranty | 7376 |
| 5 Years Maintenance | 11065 |
| Critical Spares | 9221 |
| Warranty intensity (US$/kW) | 30 |
| Maintenance intensity (US$/kW) | 44 |
| Critical spares intensity (US$//kW) | 37 |
| Total cost intensity (US$/kW) | 288 |

Table 3 shows that the overall cost of the MV VSDs includes installation, commissioning, bypass panels, five-year maintenance, and warranty, and building new substations to house the MV VSDs. The only cost is running the mine's fan. The standby fan was omitted; it will be added and operated by MV VSDs to provide ventilation redundancy. Subterranean airflow seal costs were not included. Each mine's ventilation network determines how many airflow seals are needed. Airflow seal prices and requirements vary greatly. Tandsi UG mine cost savings should be weighed against MV VSD and airflow seal expenses [10]. As technology improves, MV VSD costs have dropped [64].

**TABLE 4.** **VSD installation cost for Tandsi UG coal mine.**

| $E_{Fan}$ | Energy consumption with 3.3 kV VSD under constant reduction of airflow ($E_{VSD}$) | | | | $C_{TE}$ |
|---|---|---|---|---|---|
| Without 3.3 kV VSD ($E_{NO\_VSD}$) | 10% Airflow | 15% Airflow | 20% Airflow | 28% Airflow | All costs included |
| kWh/year | kWh/year | kWh/year | kWh/year | kWh/year | US$ |
| 1708200 | 1596510 | 1344934 | 1121280 | 817413 | 71920 |

Certain countries, like the EU, have implemented minimum energy performance requirements to encourage MV VSD installation [64]. Adoption of MV VSDs in South Africa will depend on project finances [10] [65]. The solution incorporates redundancy and flexibility in case of MV VSD failure or maintenance. Most mines examined have standby fans as a backup in case a VSD fails. Most primary ventilation fans use direct online (DOL) or liquid resistance starters [24]. After installing MV VSDs, these starters are connected to bypass panels as a backup. Bypass panels make switching beginning techniques easy [12]. MV VSDs provide gentle starting and stopping, enough torque, and cooling [10].

This research chose a 10%-28% decrease in airflow to determine the greatest possible savings from sealing and repairing subterranean airflow leaks [32]. Under different airflow conditions, the savings and payback times of installing MV VSD on the mine's major ventilation fan were evaluated. Table 5 summarizes adding 3.3 kV VSDs and reducing supply airflow. Tandsi UG coal mine can save 1070618 kWh/year by reducing airflow by 28%. 1060 tonnes of $CO_2$ will be avoided annually. Similar reductions in sulfur dioxide and nitrogen oxide emissions will be made. Constant speed applications at Tandsi mine could save $1,19588 annually, with a seven-month payback. Each airflow reduction scenario had a shorter payback time than the benchmarked 24 months, indicating they were feasible.

The findings suggest that medium voltage 3.3 kV VSDs could be installed on main ventilation fan motors in Indian underground coal mines for constant speed applications. Table 5 shows that MV VSD savings and financial feasibility increase when airflow and fan speed are reduced. This research assumed a maximum airflow decrease of 28%, but the literature shows subterranean airflow utilisation can be improved by 50% [30], [66]. Kocsis researched Canadian mines and found best practises. A 20% leakage rate is reasonable, highlighting the potential in South Africa and internationally [67]. By fully opening the IGVs, the pressure drop associated with IGV control is reduced. These savings are hard to measure, so they weren't included [68]. Assessing VOD potential in South African mines should include dynamic applications. During underground mining operations, these applications need a dynamic airflow profile [31], [41].

**TABLE 5.** **Evaluation of VOD potential for constant speed applications.**

| Feasibility indicators | | Reduction of Airflow wit VSD | | | |
|---|---|---|---|---|---|
| | Unit | 10% | 15% | 20% | 28% |
| Energy Savings | | | | | |
| $E_{fan}$ ($E_{NO\_VSD}$) | kWh/ year | 1708200 | 1708200 | 1708200 | 1708200 |
| $E_{VSD}$ | kWh/ year | 1245278 | 1049048 | 874598 | 637582 |
| $ES_{fan}$ | kWh/ year | 462922 | 659152 | 833602 | 1070618 |
| $ES_{fan}$% | % | 27.10 | 38.59 | 48.80 | 62.68 |
| GHG Emission Reductions ($ER_{GHG}$) | | | | | |
| $ER_{CO2}$ | kg/ year | 458293 | 652560 | 825266 | 105991 |
| $ER_{SO2}$ | Kg/ year | 3820 | 5438 | 6877 | 8833 |
| $ER_{NOX}$ | Kg/ year | 1903 | 2709 | 3392 | 4400 |
| Payback Period (PBP) | | | | | |
| $C_{TE}$ | US$ | 71920 | 71920 | 71920 | 71920 |
| $C_{TS}$ | US$ | 51709 | 73627 | 93114 | 119588 |
| PBP | Months | 17 | 12 | 9 | 7 |

Normal volumetric airflow in South African deep-level mines is 3 to 6 $m^3$/s per kt of rock mined monthly, or 0.12 m3/s per tonne mined daily [55]. Per mine and shift, mining requirements vary. Each mine has a unique setting, scale, depth, mining strategy, and complexity [35]. Dynamic VOD applications should define airflow needs to demonstrate feasibility [31]. For this large-scale assessment, it was assumed that VOD airflow requirements meet the necessary air-cooling power, heat load rejection capability, and dilution factors for safe and productive mining [31], [55].

This research needs 5.25 m3/s per kt/month of airflow. [69] gives the average airflow requirements for a 200 kt/month mining operation. If the airflow requirements for dynamic VOD are met, energy savings of 30 percent over constant speed applications are possible (Table 5 ). Foreign manufacturers promise savings like the suggested profile [70]. Manufacturers say dynamic VOD can save 40% on electricity [70]. This potential is affected by fan characteristics, ventilation network system resistance, and network complexity [23], [71].

Ventilation controls at production faces are needed to ensure adequate airflow underground [72]. Dynamic VOD applications can be controlled using predefined fan speed profiles or real-time subsurface airflow measurements [30]. Real-time control was omitted because it's capital intensive. Table 5 estimates savings from applying VOD dynamically to mine ventilation fans. This excludes the energy savings from constant-speed applications. Due to lower airflow reduction, constant speed applications have a lower average airflow reduction potential.

By implementing the dynamic VOD application, an estimated energy savings of 544110 kWh/year may be realized on the Tandsi underground coal mine with a 12% decrease in airflow, resulting in an estimated carbon dioxide emission reduction of 539 tonnes per year. Dynamic VOD can save up to \$60777 annually, with a 14-month payback. Dynamic VOD applications are impractical when airflow decreases are less than 12%. These applications surpassed the 24-month industry standard. With the declining cost of MV VSDs and technological advances, these projects may become feasible soon [10]. Dynamic VOD is possible with airflow reductions of more than 12% or when combined with static VOD. When MV VSDs are installed in Indian coal mine ventilation networks, dynamic VOD applications are possible.

### B. POTENTIAL DISCUSSION

A mining ventilation network can use both constant speed and dynamic VOD. This must be done scientifically and realistically to show implementation capabilities and limitations. A conservative mix of these applications was chosen for this research, resulting in a 22% decrease in total airflow. The best practice airflow leakage percentage for Canadian mines is 20% [67]. South African mines don't have an optimal airflow leakage percent yet. South African mines may lose 28% of their airflow [32]. Subterranean airflow leaks may reduce airflow by 10%. The dynamic VOD application with a 12% airflow reduction was also included in the combined analysis. A constant speed application to a mine would reduce airflow by 10% after leaks were sealed; a dynamic VOD application to the Tandsi mine would reduce airflow by an additional 12% and possible energy savings of 31.85%.

The combined sites would save 544110 kWh/year and 539 tons/year of $CO_2$. Similar reductions in $SO_2$ and $NO_x$ emissions will be 5 and 2 tons/year. Constant speed and dynamic applications can save 60777\$ annually, with a 14-months payback. As part of the VOD potential, Tandsi Mine could install MV (3.3 kV) VSDs. If VSDs aren't planned and built with redundancy in mind, they introduce restrictions [12].

In the event of a VSD failure, the system should have enough redundancy to keep running for the duration of the outage. For optimal performance, the MV VSD should also be protected from natural factors [73]. With careful planning and design, these limitations can be overcome. Due to the need for redundancy, this effort will have a minimal impact on mining operations. While the MV VSD is being used to install the backup fan, one fan may continue to run. This criterion for mine ventilation redundancy is specified by the South African Department of Mineral Resources [18]. By installing MV VSDs on primary mine ventilation fans, it is possible to overcome most of the limitations currently associated with this installation method.

**TABLE 6. Evaluation of VOD potential for dynamic applications.**

| Feasibility indicators | | Reduction of airflow with VSD | | | |
|---|---|---|---|---|---|
| | Unit | 3% | 6% | 9% | 12% |
| Energy Savings | | | | | |
| $E_{fan}$ ($E_{NO\_VSD}$) | kWh/ year | 1708200 | 1708200 | 1708200 | 1708200 |
| $E_{VSD}$ | kWh/ year | 1559028 | 1418804 | 1287250 | 1164090 |
| $ES_{fan}$ | kWh/ year | 149172 | 289396 | 420950 | 544110 |
| $ES_{fan}$% | % | 8.73 | 16.94 | 24.64 | 31.85 |
| GHG Emission Reductions ($ER_{GHG}$) | | | | | |
| $ER_{CO2}$ | Kg/ year | 147680 | 286502 | 416741 | 538668 |
| $ER_{SO2}$ | Kg/ year | 1231 | 2388 | 3473 | 4489 |
| $ER_{NOX}$ | Kg/ year | 613 | 1189 | 1713 | 2214 |
| Payback Period (PBP) | | | | | |
| $C_{TE}$ | US\$ | 71920 | 71920 | 71920 | 71920 |
| $C_{TS}$ | US\$ | 16663 | 32326 | 47020 | 60777 |
| PBP | Months | 52 | 27 | 18 | 14 |

## V. CONCLUSION

When medium voltage VSD was used in conjunction with VOD methods, it was discovered that main ventilation fan of the Tandsi mine had significant efficiency potential. The primary mine ventilation fan had significant static and dynamic application potential, according to a comprehensive energy assessment of the Tandsi mine ventilation network. Both applications had payback periods of less than two years, which was a positive financial metric. When both applications are used in a methodical manner, researchers found that the best results can be achieved. A total of 1070618 kWh of electricity could be saved each year by installing MV VSD on the Tandsi mine ventilation fan motor. After that, it's estimated that the total cost savings will be recovered in seven months. GHG emissions, including carbon dioxide, Sulphur dioxide, and nitrogen oxide, would be reduced by an average of 37% compared to current operations. There are some limitations imposed by installing MV VSDs, but their practicality and benefits outweigh them. With the installation of MV VSDs on mine ventilation fans, Indian mines have a distinct VOD potential for both applications. Promoters of energy conservation should take a close look at these and other efforts to improve operational efficiency. This would have a positive impact on the global economy, as well as on the environment. Ventilation network installation and analysis will be an important future area of research for MV VSD applications in the Indian mining industry. In the future, MV VSDs will also be installed on mine winders, compressors, and hoisting systems for increased efficiency. It is possible that new control methods could be developed to improve operational efficiency for combined IGVs and MV VSD technology.

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