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The use of variable speed drives for cost-effective energy savings in South African mine cooling systems

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HIGHLIGHTS

- Energy analysis of 20 South African mine cooling systems.
- Energy savings and feasibility calculated for large-scale variable speed drive implementation.
- An annual electricity saving of 144,721 MW h (32.2%) and CO_2 emission reduction of 132 Mton can be realised.
- Pump and fan application found more viable than chiller application.
- Pilot implementation study shows pump electricity savings of 29.9%.

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ABSTRACT

An industrial energy efficiency improvement through the introduction of modern technology is an important demand-side management initiative. Cooling systems on South African mines have been identified as large electricity consumers. There is significant potential for energy efficiency improvement by the widespread introduction of variable speed drive (VSD) technology. An energy audit was conducted on 20 large mine cooling systems and potential savings and feasibility indicators were calculated. A pilot implementation study was also done on one mine to experimentally validate the estimated savings. In this paper, the results of the audit, the potential savings and the pilot study results are presented. It is shown that large-scale implementation of VSDs on mine cooling system pumps and fans is economically viable. A total annual electrical energy saving of 144,721 MW h, or 32.2%, can be achieved. An annual cost saving of US\$6,938,148 and CO_2 emissions reduction of 132 Mton is possible. The implementation of VSDs on mine chiller compressors will also result in large energy savings, but is not economically feasible at present. Results of the pilot study indicate an electricity savings of 29.9%. The results are important to decision makers and indicate the significant impact that widespread VSD usage on mine cooling systems can have on South African mine sustainability.

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1. Introduction

Improving the energy efficiency of industrial energy users is of global importance. Industry, including the mining sector, uses 37% of the world's total produced energy [1]. Worldwide industrial energy consumption is expected to grow at an average of 1.4% per year over the next 25 years [2].

In South Africa, the rapid increase in economic growth, industrial output and power distribution to previously disadvantaged communities has led to a large increase in electricity consumption since 1993 [3]. The country presently generates 43% of Africa's total electricity [4]. The majority of this electricity is generated by burning coal, making South Africa the 7th largest emitter of greenhouse gas (GHG) emissions per capita in the world [5].

The South African government has pledged a GHG emission reduction of 34% by 2020 [6]. One of the key national plans to achieve this, while avoiding reduced economic growth, is to improve industrial energy efficiency [7,8]. Studies have shown that there is still significant scope for widespread energy efficiency improvements, specifically by focussing more closely on high-demand sectors [3].

Energy efficiency improvement through new technology is an important and usually significant demand-side management (DSM) initiative in industrial systems [1,9]. More specifically, the installation of variable speed drives (VSDs) on chillers, pumps and fans has indicated significant cost-saving potential [10–12]. It has been shown that it is viable to extend the use of VSDs in

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Nomenclature

BAC	bulk air cooler
C_{VSD}	total VSD implementation cost (US$/year)
CCE	cost of conserved energy (US$/MW h)
COP	coefficient of performance
CS_{VSD}	total annual cost savings after VSD implementation (US$/year)
DSM	demand-side management
$EC_{chiller}$	chiller electrical energy consumption before VSD implementation (MW h)
$EC_{chiller,VSD}$	chiller electrical energy consumption after VSD implementation (MW h)
$EC_{pump,fan}$	pump or fan electrical energy consumption (MW h)
EF_{CO_2,SO_2,NO_x}	GHG emissions factor for specific fuel used (kg/MW h)
$ES_{chiller}$	annual chiller electrical energy savings after VSD implementation (MW h/year)
$ES_{pump,fan}$	annual pump or fan electrical energy savings after VSD implementation (MW h/year)
ES_{VSD}	annual electrical energy savings after VSD implementation (MW h/year)
ESP	energy saving percentage associated with speed reduction (%)
ET	electricity tariff (US$/MW h)
ER_{CO_2,SO_2,NO_x}	annual GHG emission reduction (kg/year)
%F	percentage of specific fuel used for electricity generation (%)
GHG	greenhouse gas
IGBT	insulated gate bipolar transistor
LF_c	cooling loading factor
LF_p	pump or fan power loading factor
OH	operating hours (h)
PWM	pulse width modulation
PBP	payback period (years)
$\dot{Q}_c$	chiller rated cooling capacity (MW)
VSD	variable speed drive
$\dot{W}_{rated}$	pump or fan power rating (MW)

chillers and their subsystems, especially in large-scale applications [10,13].

The mining industry is a major role-player in the South African economy. This sector is extremely energy intensive, accounting for 14% of the national electricity supply [14]. Cooling systems are responsible for up to a quarter of the electrical energy consumed at a typical deep level mine [15]. These cooling systems continuously supply chilled water and cold ventilation air to the mine to ensure acceptable underground operational and working conditions for employees and equipment.

Various studies have been conducted regarding energy and cost reductions on mine cooling systems [15–18]. Integrated energy management software for large cooling systems has been developed that can be applied to mine cooling [19]. The effects that variable water flow have on mine cooling service delivery were also shown for a specific case study [20]. However, it has been found that modern energy efficient technologies, more specifically VSDs, are not widely used in South African mine cooling systems. Although there is significant potential to introduce VSDs on many if not all of these systems, a large-scale investigation has not previously been done to evaluate and quantify the potential energy, environmental and cost benefits that might be realised.

This paper therefore investigates the large-scale potential for VSDs on South African mine cooling systems. Energy consumption of chillers, pumps and fans are evaluated and potential energy, cost and GHG emission savings are estimated. Feasibility indicators such as payback period and cost of conserved energy are also calculated. A large-scale energy evaluation of 20 mine cooling systems is supported by validating pilot implementation results. The main objective is to investigate the potential large-scale impact of installing VSDs on mine cooling systems and its contribution to improving South African industrial energy efficiency and sustainability. The results reported by this study can be used as a guideline to energy managers, especially in the South African mine industry, to improve cooling system energy efficiency through the use of VSDs and to increase industrial awareness of VSDs and their widespread applications.

2. Variable speed drive considerations

It is appropriate to review the state-of-the-art in VSD technology, its potential benefits, and considerations when evaluating its feasibility. This is important in context of the effective investigation of its potential on mine cooling systems.

2.1. Energy saving potential

Electric motors have high efficiencies when operating at rated loads. However, it has been shown that almost half of all industrial motors are loaded below 40% rated capacity, resulting in reduced operating efficiency [21]. Variable duty requirements of systems such as pumps, fans and chillers have traditionally been controlled by inefficient methods such as bypass and recirculation pipelines, throttle valves and flow dampers, using constant-speed electric motors [13].

Various studies have shown that using variable speed electric motors is the most efficient and promising method of operating a given load and realise energy savings [22,23]. For example, the increased frictional resistance and pressure drop as a result of valve control can be eliminated or reduced significantly when opening the valve fully and modulating the flow by VSD control instead. It has been shown that for pump systems that operate for more than 2000 h/year, using VSDs to control flow instead of valves will almost always lead to significant life-cycle cost savings and environmental benefits [24].

A VSD is connected between the driven electric motor and the power supply system. It essentially consists of a multi-phase diode rectifier, a control and protection regulator and an inverter with insulated gate bipolar transistor (IGBT) components. Pulse width modulation (PWM) is used to create variable voltage, current and frequency as output to the motor and thereby allows the regulation of speed, torque and power [25].

As a result of significant advances in semiconductor technology, design improvement and intelligent control features, the use of VSDs has become increasingly popular in recent years [26–28]. Successful implementation and optimisation in various sectors have been vindicated, as shown by studies on a refinery [29], cement plant [30], boiler house [31], petroleum plant [32] and conveyor systems [33,34].

Using VSDs in variable torque applications such as pumps, fans and chiller compressors is of particular significance. Large energy savings can be obtained for relatively small variations in motor speed and fluid flow, as explained by the theoretical cubic power-flow affinity law [25]. This concept is illustrated in Fig. 1,

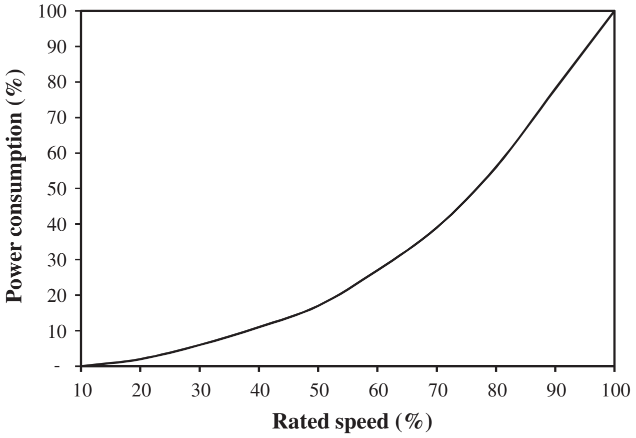

Fig. 1. Electric motor power consumption as a function of speed [35].

Table 1
Typical chiller compressor VSD costs (in US$) in South Africa.

	Voltage (V)	800 kW	1000 kW	1500 kW	Average
Company A	6600	155,125	182,859	240,699	
Company B	6600	164,470	195,019	250,351	
US$/kW		200	189	164	184
Company A	11,000	222,642	250,373	335,815	
Company B	11,000	224,423	265,315	333,756	
US$/kW		279	258	223	253
Installation		9650	9650	9650	
US$/kW		12	10	6	9
US$/kW (6600 V total)		212	199	170	194
US$/kW (11,000 V total)		292	268	230	263

which shows typical real electric motor power consumption as a function of rated speed [35].

VSDs can therefore be an important energy efficiency measure on cooling systems which usually consist of variable torque subsystems. Various studies have been done in this regard. A variable speed pumping scheme was investigated for an academic building chiller system by Tirmizi et al., realising energy savings of up to 13% [36]. Crowther and Furlong showed how variable speed cooling tower fans can also save energy [37]. Qureshi and Tassou confirmed that capacity modulation by applying VSDs to chiller compressors can lead to 12–24% energy savings [12]. Energy savings of 19.7% were presented by Yu and Chan for all-variable speed chiller systems [11]. Common set point requirements used to control VSDs include chiller compressor lift, chilled and cooling water supply pressure, water temperature and water tank levels, depending on the system requirements.

In addition to energy savings, VSDs also present other potential benefits. These include process control improvement [38], system performance and reliability improvement [25], soft starting and stopping, reduced maintenance [39], electric motor and system life extension [40] and power factor correction [41].

2.2. Economic factors

It is important to consider economic factors when evaluating the feasibility of energy efficient technology acquisition. These include the initial capital requirements, the return on investment and the cost per energy saving realised.

The rise in VSD popularity has led to a significant cost reduction in recent years. Low-voltage pump and fan VSD costs of about US$96/kW for a 37 kW unit and US$84/kW for a 745 kW unit were reported in the United States of America during 2011 [42]. Consultation, cabling, installation and commissioning costs were shown to be about US$133/kW in Turkey during 2004 [31]. However, this cost was applicable to the installation of only one 30 kW VSD and is therefore relatively conservative. Similar labour costs will be involved for larger drives and typical costs per kW can be expected to be proportionally lower.

Table 1 shows typical costs associated with medium-voltage VSDs applicable to mine chiller compressors in South Africa. These are costs of VSDs with standard panel protection and essential harmonic filtering equipment. Some chiller compressors have impeller blades that are designed for a very wide range of cooling loads. Other blade designs, especially older ones, accommodate only small load ranges. In these cases it is necessary to suitably alter or replace the impeller and possibly also replace the expansion valve to prevent compressor surges and allow efficient refrigerant flow modulation over the range planned for with the VSD. The average costs of these typical modifications were included in the VSD costs in Table 1 because most mine chillers are older than 15 years. Shown installation costs include typical cabling, programming control adjustments and commissioning requirements.

Table 2 shows typical costs of low-voltage drives applicable to most pumps and fans in South Africa.

Tables 1 and 2 show that VSD cost per kW decreases with increasing power rating. It can also be seen that medium-voltage drives are significantly more expensive than low-voltage drives. Therefore, the benefits of chiller VSDs should be carefully considered before purchase. VSD costs in South Africa are higher in comparison to prices abroad. This can be attributed to the importing costs and the relatively low demand for VSDs in South Africa. However, installation costs are generally relatively low in South Africa.

Cost-effectiveness is commonly indicated by the payback period (*PBP*) as calculated by Eq. (1) [25] and Eq. (2) [1].

$$PBP = \frac{C_{VSD}}{CS_{VSD}} \tag{1}$$

where

$$CS_{VSD} = (ES_{VSD})(ET) \tag{2}$$

It is important that the total incremental cost of implementation (C_{VSD}) includes VSD costs as well as costs associated with necessary system changes, implementation and commissioning. Also,

Table 2
Typical pump and fan VSD costs (in US$) in South Africa.

	Voltage (V)	75 kW	132 kW	160 kW	200 kW	275 kW	Average
Company A	525	17,442	23,231	26,445	31,499	45,003	
Company B	525	10,191	13,740	15,798	17,572	22,104	
Company C	525	8446	13,045	14,920	19,060	23,008	
Company D	525	10,486	14,086	15,058	18,260	25,044	
US$/kW		155	121	113	108	105	120
Installation		3355	3355	3355	3355	3355	
US$/kW		45	25	21	17	12	24
US$/kW (total)		200	147	134	125	117	144

hourly energy savings and tariffs must be taken into account when calculating cost savings (CS_{VSD}). This is because electricity tariffs (ET) are based on time-of-use in South Africa.

It has been shown that a *PBP* of less than one third of the expected electric motor life should be considered viable [1]. Typical feasible *PBP*s for VSDs have been reported as less than 2 years [28,31].

A further measure of cost-effectiveness is the annual cost of conserved energy (CCE) as calculated by Eq. (3) [42].

$$CCE = \frac{C_{VSD}}{ES_{VSD}} \tag{3}$$

A CCE value of US$43/MW h has been reported for VSD installations, indicating that it is one of the most feasible energy efficient measures available [42].

2.3. Potential barriers

Factors that have been found to impede the widespread usage of VSDs include technical, economic and awareness barriers. It is important to be aware of these possible pitfalls and their suggested mitigation measures when evaluating new VSD applications.

The operation of VSDs imposes non-linear loads on power distribution systems. This may lead to problems such as the generation of harmonic voltage and current distortion into the mains supply and radio frequency interference with susceptible equipment. Harmonic distortion not only results in wasted power but also leads to overheating of equipment, decreased motor efficiencies, circuit breaker tripping, premature failure of old motors and communication network errors [13].

Modern VSD features have been developed to mitigate potential technical problems. Typical measures to reduce harmonic distortion include line reactors, input and motor chokes, multi-pulsed systems and active and passive filters [25]. Connector cables should also be shielded and as short as possible while proper grounding must be applied throughout [10]. Technical concerns are mostly unjustified if a VSD is correctly specified and installed for the specific application.

Economic considerations can also lead to VSD project proposals being rejected. Even though VSD costs have decreased, it is still relatively expensive technology. Budgets do not always cater for such costs, especially in organisations where there are split budgets between departments. This may lead to payback periods in excess of 3 years. These issues can be addressed by financial incentives such as rebate structures [25] and organisational financial rewards for savings realised. Although such structures can be very effective, it is important that rebates and savings be appropriately quantified for energy saving applications [10].

There is generally a high level of industrial awareness of VSDs. However, technical personnel are often sceptical about the actual achievable energy savings and concerned about the risks involved. Existing promotional and supporting publications often do not match the user requirements well. It has been suggested that to improve awareness, incentives should be aimed at the needs of sector-specific motor users. These may include independent seminars, calculation software and simple printed or electronic educational tools. It is also important to report successful case studies and results of investigations that accentuate the mitigation of problems and the true benefits of VSDs [10].

Motor users and plant personnel are often also concerned about the after-sales implications that VSDs have such as maintenance requirements, staff training and breakdown support. Maintenance requirements of VSDs are negligible, with the only typical annual replacements necessary being air intake filters. If the drive is specified and installed correctly, there should be no regular maintenance requirements. All surveyed manufacturers also include a 12-month warranty, full breakdown support and training of all relevant plant staff in the VSD costs shown in Tables 1 and 2. These manufacturers also indicated that they offer annual VSD inspections and repairs if necessary at about US$10/kW. It is thus apparent that after-sales concerns are generally unwarranted, given that the drives are suitably implemented.

3. Investigation

South African mine cooling systems were investigated to evaluate typical operation, available technology, energy consumption and potential savings that can be realised from VSD installations. The focus was on estimated VSD potential in the larger context, rather than on site-specific flow control strategies and effects, as reported elsewhere [20].

3.1. Mine cooling systems

Chilled water is needed in deep mines for various purposes. These include bulk cooling of ventilation air, cooling of rock drills and other machinery, rock sweeping operations, dust suppression and underground cooling cars or spot coolers [43]. The combined cooling capacity required is typically 30 MW or more [44]. Large and uniquely designed, integrated cooling systems are required. These systems are installed both on the surface and underground as integral parts of typical semi-closed loop mine water reticulation systems [45]. Fig. 2 schematically shows a typical surface cooling system.

Hot water from end-users and underground drainage water enters storage dams at 30–35 °C from where the water is pumped through pre-cooling towers. These are usually forced draught direct heat exchangers that cool the water down to just above ambient temperature [46]. The pre-cooled water is then pumped through large water-cooled chillers where the temperature is reduced to approximately 2 °C. The arrangement and size of the chillers depends on the requirements of each specific mine. Chiller cooling water is pumped through a set of condenser cooling towers where heat is transferred to ambient. In mine cooling systems electrical energy is therefore consumed mostly by variable torque turbo machinery, as shown in Fig. 2.

Chilled water is either sent directly to the working face and various underground end-users or pumped through bulk air coolers (BACs) [47]. A BAC is a direct contact heat exchanger that uses chilled water to cool ambient air before it is sent down the shaft for ventilation purposes. A typical BAC outlet air wet-bulb temperature of about 8 °C usually ensures that the legally required wet-bulb temperature of 27.5 °C or less is maintained on deep underground production levels [48].

Demand for chilled water underground is sporadic as a result of the complex network of end-users and underground working shifts. Chilled water storage dams ensure that the varying demands of the mine can be met [49]. The network of storage dams is usually interconnected to allow the bypass and/or recirculation of water as required by variations in operating conditions.

Improving the energy and cost-efficiency of mine cooling systems have been investigated by various studies. Pelzer et al. [16] developed a strategy that reduces and controls the inlet water temperature of chillers to improve the chiller coefficient of performance (COP). Swart [17] and Van der Bijl [18] considered the optimisation of electricity costs by developing load shifting strategies. These studies are all based on improved control and scheduling of existing infrastructure. There is still therefore the potential for further energy efficiency improvements through new technology such as VSDs.

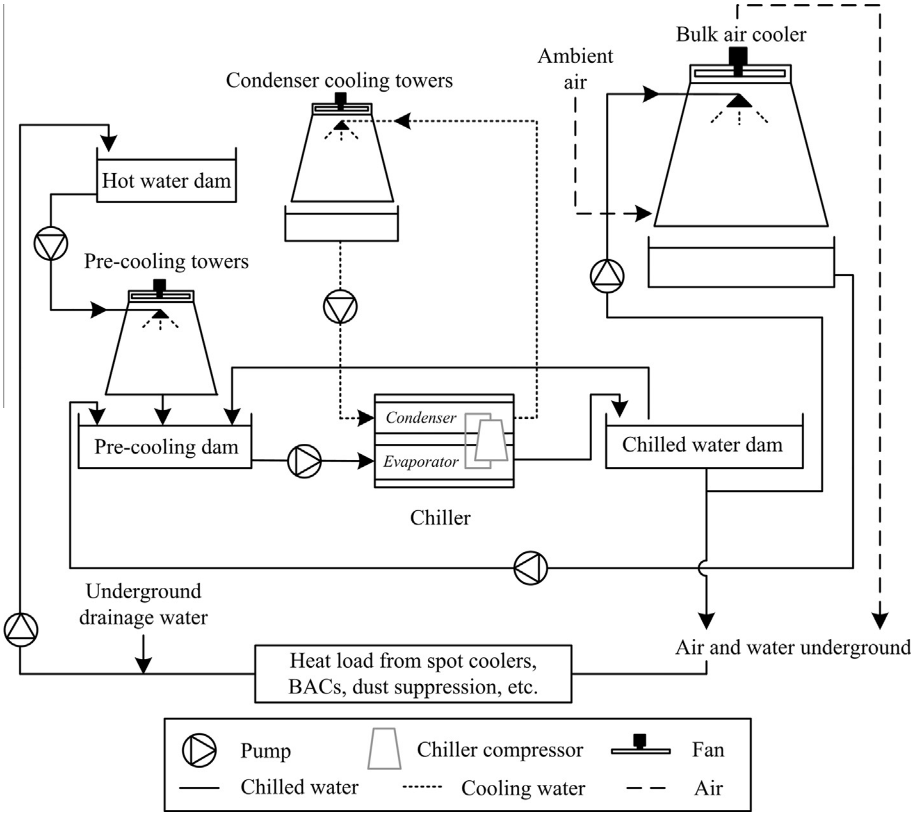

Fig. 2. Typical mine surface cooling and chilled water supply system.

3.2. Energy audit

A comprehensive energy audit is a key step in systematic energy management [50]. Twenty mine cooling systems were audited to evaluate their present features, operation and energy consumption. Detailed site visits were conducted to evaluate the systems. Meetings were also held with relevant managers, foremen and operators to obtain further information.

Logged system data, typically over a period of 1 year or more, were obtained from mine personnel. This was used in conjunction with design specification sheets and other relevant material [51,52] to analyse subsystem loading and energy consumption. Electrical energy consumed by a chiller and pump or fan can be calculated from Eq. (4) [53] and Eq. (5) [54], respectively.

$$EC_{chiller} = (OH)(\dot{Q}_c)(LF_c)(COP^{-1}) \tag{4}$$

$$EC_{pump,fan} = (OH)(\dot{W}_{rated})(LF_p) \tag{5}$$

The chiller cooling load factor is the ratio of the actual thermal load to the full design cooling load. The power load factor of a pump or fan electric motor is the ratio of actual capacity to rated capacity. Average load factors of the subsystems on each site were used in Eqs. (4) and (5) and were calculated from measured loads and load profiles. The key results of the evaluation are shown in Table 3.

It can be seen from Table 3 that 112 large chillers were evaluated with individual cooling capacities varying between 3 MW and 16.4 MW, with COP values between 3 and 6.5. Chiller loading factors varied somewhat depending on seasonal effects and operation methods of the individual mines. The average cooling load factor was 75.7%. Chillers account for 66% of mine cooling system electricity consumption.

Standard equipment on the audited sites included chilled water pumps, condenser cooling water pumps and various transfer pumps supplying water to pre-cooling towers and BACs. These are low-voltage centrifugal pumps with installed capacities varying between 50 kW and 600 kW. These pumps operate at an average loading factor of 82.4% and account for 27% of total cooling system electricity consumption.

Axial fans were found to be installed on pre-cooling towers, condenser cooling towers and BACs. Installed capacities varied between 40 kW and 400 kW. Some of these fans, such as those on BACs, were shut down during winter months when they were not required. The fans operate at an average load factor of 85.4% and comprise only 7% of the total electricity consumption.

A typical mine cooling system consists of 4–5 chillers, 5 chilled water pumps, 5 cooling water pumps, 4 transfer pumps and 5 cooling tower fans. The average site installed capacity was 10.8 MW and the average annual electricity consumption was 65,911 MW h. The total annual electricity consumption of the evaluated sites was 1,318,225 MW h. This is 4.0% of the total electrical energy used by all mines in South Africa and 0.6% of the total national electricity supply.

No VSDs were installed on any of the electric motors of these mine cooling systems. These mines comprise about 80% of deep mines in South Africa and include all the leaders regarding mining innovation and technology. It can therefore be assumed that no deep-mine cooling system in the country uses VSDs.

Possible reasons for the lack of VSD acceptance were investigated. At some mines personnel were concerned about the technical problems that VSDs might cause. In most cases however, it was found that there was a general lack of awareness and initiative. It is believed that this can be attributed to the historically low electricity tariffs in South Africa. Energy efficiency was not a priority on mines until the late 1990s, leading to most personnel not actively

Table 3
Annual electrical energy consumption of selected South African mine cooling systems.

Site	Chillers				Pumps			Fans			Total
	Qty.	Cooling capacity (kW)	Cooling load factor (%)	Total energy consumption (MW h/year)	Qty.	Load factor (%)	Total energy consumption (MW h/year)	Qty.	Load factor (%)	Total energy consumption (MW h/year)	Total energy consumption (MW h/year)
1	4	13,300	76	46,719	14	74	10,996	4	90	2120	59,835
2	6	6500	80	41,099	19	82	13,679	8	75	4504	59,282
3	4	5000	69	19,320	10	75	7406	5	93	3478	37,158
	1	6000		6955							
4	4	6000	67	25,292	15	70	10,499	4	74	2650	38,440
5	4	11,500	79	44,436	14	86	14,010	9	94	11,526	78,827
	1	5500		8855							
6	3	5000	92	15,807	16	97	12,619	13	81	8280	59,923
	2	5000		10,538							
	1	14,000		12,679							
7	3	7500	74	20,700	19	81	16,858	13	89	7187	71,379
	1	10,500		9660							
	1	16,400		16,974							
8	2	10,000	78	18,400	12	83	7525	7	79	6359	47,924
	1	5000		4600							
	1	12,000		11,040							
9	3	11,000	84	31,878	15	91	9505	12	99	9539	55,172
	1	4400		4250							
10	4	10,100	62	34,949	16	69	21,859	7	71	8280	98,949
	6	3700		33,861							
11	4	6600	71	27,821	11	88	8214	4	87	5299	41,334
12	4	4150	92	25,319	10	95	23,846	1	94	1656	88,801
	6	4150		37,979							
13	2	5000	89	16,100	6	86	10,433	2	96	2517	29,050
14	3	6450	82	24,923	8	80	13,116	3	75	3974	42,013
15	6	3000	61	29,808	22	79	51,005	4	91	1855	112,476
	3	6000		29,808							
16	5	5340	65	26,914	12	78	25,171	4	78	4306	56,390
17	2	10,000	73	21,955	8	79	20,137	3	74	3974	46,066
18	8	6000	90	84,562	7	91	12,321	1	99	874	97,757
19	12	4000	58	86,940	16	81	42,394	4	96	5299	134,633
20	4	10,000	71	38,640	10	83	22,190	2	73	1987	62,818
Total	112		75.7	868,780	260	82.4	353,781	110	85.4	95,664	1,318,225
(%)				66			27			7	100

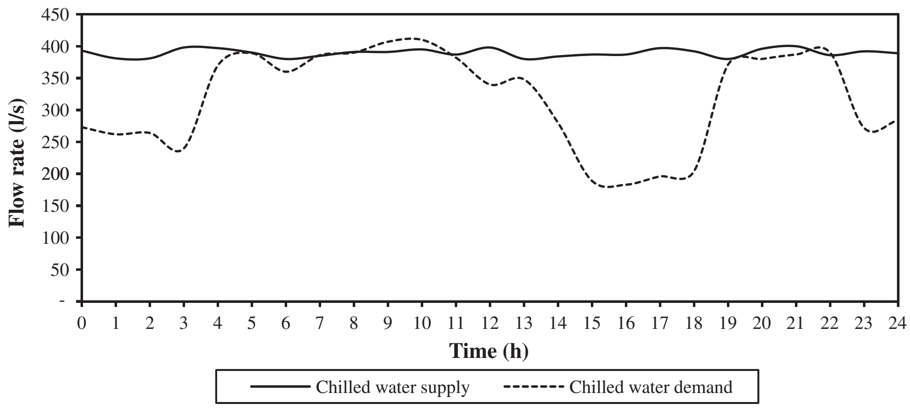

Fig. 3. Typical measured daily profile of mine chilled water demand and supply at present.

pursuing energy saving measures. This appears to still be the case among most technical personnel.

Loading and scheduling operations were observed to be mostly inefficient on mine cooling systems. Typically inefficient flow control measures are common, most motors are oversized and operate at moderate loading factors and chillers are not operated optimally for given loading conditions. Furthermore, part-load conditions were identified on all systems. This was primarily due to daily ambient condition fluctuations and the intermittent nature of water usage underground. For example, Fig. 3 shows the typical daily profiles of the chilled water demand and supply measured at one of the audited sites.

Fig. 3 shows that the supply flow is constant while the demand flow is intermittent. The fluctuations in the demand profile are caused by scheduled water-consuming underground operations, such as drilling and cleaning shifts. The supply flow is maintained constant at the maximum possible flow and all overflow water is recycled to the chiller inlet. In this example, the average demand is 18% lower than the supply. One could consider applying optimal pump scheduling techniques [55]. However, most mine personnel and energy managers indicated that they would prefer continuous flow control because of the added process control benefits of VSDs. The frequent starting and stopping of fixed speed equipment should also be avoided when possible due to the increased wear associated with it. It is thus apparent that there is definite potential for flow modulation by VSD to match the actual load profile of the chilled water demand.

From the energy consumption results, inefficient operations and part-load conditions it is apparent that there should be significant potential for changing over to VSDs on these cooling systems. However, viability must be investigated by estimating savings and feasibility parameters.

3.3. Saving estimates

It is of utmost importance that savings estimations are made correctly and conservatively so as to not make poor business decisions [56]. Various methods have been used to estimate potential savings that can be realised after installing VSDs on chiller compressor, pump and fan motors. A simplified approach described by Saidur et al. [57] was adopted because of its suitability to large-scale evaluations.

Energy consumption of variable speed chillers can be estimated by using Eq. (4) and considering variable speed chiller performance changes regarding the COP for different loading factors [51,52]. The energy savings that can be realised under the same operating conditions are then calculated from Eq. (6) [58].

$$ES_{chiller} = EC_{chiller} - EC_{chiller,VSD} \tag{6}$$

Estimates for pump or fan energy savings when using VSDs can be calculated using Eq. (7) [35]. Energy saving percentage (*ESP*) values associated for various speed reductions can be found in Ref. [35].

$$ES_{pump,fan} = (OH)(\dot{W}_{rated})(ESP) \tag{7}$$

Reductions in energy usage also result in reduced GHG emissions associated with electricity generation [59]. Estimates for the reduction in CO_2, SO_2 and NO_x emissions as a result of relevant energy savings (*ES*) can be calculated from Eqs. (8)–(10) [1].

$$ER_{CO_2} = (ES)\sum(\%F \times EF_{CO_2}) \tag{8}$$

$$ER_{SO_2} = (ES)\sum(\%F \times EF_{SO_2}) \tag{9}$$

$$ER_{NO_x} = (ES)\sum(\%F \times EF_{NO_x}) \tag{10}$$

Emission factors are based on electricity generation by burning coal [14]. This accounts for 92% of South Africa's electricity [60]. Emission reduction estimates are therefore conservative but expected to be sufficiently accurate.

4. Results and discussion

The potential electrical energy, emission and cost savings that can be realised by installing VSDs on chillers, pumps and fans of mine cooling systems were estimated from all relevant data collected during the investigation, using Eqs. (1)–(10). Feasibility indicators were also calculated. Various loading and operational conditions were considered for different system groups to investigate viability and relevance to different decision makers.

A pilot study was also done by installing VSDs on the pumps of one site and evaluating the performance after 1 month. The key results are shown in support of the large-scale evaluation.

4.1. Chillers

Savings and feasibility factors were calculated when installing VSDs on all chiller compressor motors at various chiller thermal loading factors. The results for all the sites combined are given in Table 4. The first three columns show the savings that can be realised if chillers operate at various loading factor ranges. The last column shows the savings that can be realised if chillers typically continue running under the present average loading conditions.

An annual energy saving of 168,633 MW h, or 19.4% of the total chiller energy consumption, is possible for the typical operational loads of the chillers. This amounts to a reduction in CO_2 emissions of 153,590,958 kg/year and an annual cost saving of US$8,084,510. However, the costs of the medium-voltage VSDs that are required for chiller compressors are high in South Africa. The viability indicators are therefore high, with the payback period being 4.2 years and cost of conserved energy US$203/MW h.

Chiller savings and feasibility factors are shown to improve at lower loading factors. This is attributed to chiller compressor VSDs having more scope to modulate refrigerant flow rates than at high loading factors. 90–100% chiller thermal loading is shown to be particularly unfeasible for VSDs, with a payback period of 15.5 years.

It is clear that the large-scale introduction of VSDs to mine chillers will result in significant savings, but that it is not an economically feasible option. This is mainly as a result of high VSD costs and relatively high loading factors imposed on mine chillers by large and continuous mine cooling demands. It might be worthwhile to consider replacing selected oversized compressor motors by smaller energy efficient motors instead as this usually implies lower costs [61].

Table 5 shows the potential savings and feasibility factors when implementing VSDs on all the chillers of a typical mine cooling system with a combined cooling capacity of 40 MW. Mine energy managers can use these results as a guideline to the potential savings and drawbacks of chiller VSDs. An energy saving of 7013 MW h/year, or 19.1%, is possible for typical chiller operations.

Table 4
Chiller energy consumption, energy and emission savings and cost analysis (all sites combined).

	Chiller loading			
	50–70%	70–90%	90–100%	Typical operation
Energy consumption without VSD (MW h/year)	717,928	920,421	1,104,505	868,780
Energy consumption with VSD (MW h/year)	524,620	773,154	1,058,484	700,147
Energy saving (MW h/year)	193,288	147,267	46,021	168,633
CO_2 emission reduction (kg/year)	176,047,078	134,131,107	41,915,971	153,590,958
SO_2 emission reduction (kg/year)	1,403,670	1,069,463	334,207	1,224,622
NO_x emission reduction (kg/year)	741,690	565,097	176,593	647,082
Cost savings (US$/year)	9,266,525	7,060,210	2,206,315	8,084,510
Cost (US$)	34,209,375	34,209,375	34,209,375	34,209,375
Payback period (years)	3.7	4.8	15.5	4.2
Cost of conserved energy (US$/MW h)	177	232	743	203

Table 5
Chiller energy consumption, energy and emission savings and cost analysis (typical site with 40 MW combined chiller cooling capacity).

	Chiller loading			
	50–70%	70–90%	90–100%	Typical operation
Energy consumption without VSD (MW h/year)	31,943	41,136	48,987	36,736
Energy consumption with VSD (MW h/year)	24,234	35,281	47,314	29,723
Energy saving (MW h/year)	7709	5856	1673	7013
CO_2 emission reduction (kg/year)	7,021,604	5,333,199	1,523,359	6,387,241
SO_2 emission reduction (kg/year)	55,985	42,523	12,146	50,927
NO_x emission reduction (kg/year)	29,582	22,469	6,418	26,910
Cost savings (US$/year)	369,594	280,722	80,185	336,203
Cost (US$)	1,459,836	1,459,836	1,459,836	1,459,836
Payback period (years)	3.9	5.2	18.2	4.3
Cost of conserved energy (US$/MW h)	189	249	873	208

Table 6
Chiller energy consumption, energy and emission savings and cost analysis (typical chiller with 5 MW cooling capacity).

	Chiller loading			
	50–70%	70–90%	90–100%	Typical operation
Energy consumption without VSD (MW h/year)	4591	5886	7063	5259
Energy consumption with VSD (MW h/year)	3355	4944	6769	4140
Energy saving (MW h/year)	1236	942	294	1119
CO_2 emission reduction (kg/year)	1,125,794	857,748	268,046	1,018,797
SO_2 emission reduction (kg/year)	8976	6839	2137	8123
NO_x emission reduction (kg/year)	4743	3614	1129	4292
Cost savings (US$/year)	59,258	45,149	14,109	53,626
Cost (US$)	176,073	176,073	176,073	176,073
Payback period (years)	3.0	3.9	12.5	3.3
Cost of conserved energy (US$/MW h)	142	187	598	157

Table 7
Pump and fan energy consumption, energy and emission savings and cost analysis (all sites combined).

	Pump and fan speed reduction			
	10%	20%	30%	Typical operation
Energy consumption without VSD (MW h/year)	449,445	449,445	449,445	449,445
Energy consumption with VSD (MW h/year)	350,567	251,689	175,284	304,724
Energy saving (MW h/year)	98,878	197,756	274,161	144,721
CO_2 emission reduction (kg/year)	90,057,996	180,115,992	249,706,262	131,812,158
SO_2 emission reduction (kg/year)	718,057	1,436,113	1,990,975	1,050,974
NO_x emission reduction (kg/year)	379,416	758,833	1,052,018	555,328
Cost savings (US$/year)	4,740,349	9,480,699	13,143,696	6,938,148
Cost (US$)	9,798,394	9,798,394	9,798,394	9,798,394
Payback period (years)	2.1	1.0	0.7	1.4
Cost of conserved energy (US$/MW h)	99	49	36	68

This is equivalent to a site cost saving of US$336,203/year. However, the payback period of 4.3 years and cost of conserved energy of US$208/MW h indicates the impracticality of changing over to VSDs. Chiller VSDs are therefore only recommended on sites where chillers have low loading factors and where sufficient funds are available.

Table 6 shows the same savings and feasibility analysis for one chiller with a 5 MW cooling capacity. The typical operational results indicate an energy saving of 1119 MW h/year, or 21.3%, with a payback period of 3.3 years. These results are better than shown in Tables 4 and 5. This is because better relative improvements in COPs can be achieved when using VSDs on smaller chillers and the lower VSD costs associated with 6600 V chillers, as used in this example. Plant managers can therefore expect significant savings when implementing VSDs on selected chillers, especially smaller chillers with suitably low loading factors. However, initial capital outlay, cost-effectiveness and trade-offs with pump and fan VSDs must be carefully considered.

4.2. Pumps and fans

Savings and feasibility factors were calculated when installing VSDs on all pump and fan motors at various speed reductions. The results for all the sites combined are given in Table 7. The 10–30% speed reduction scenarios show the savings that can be realised if pumps and fans operate only at the given reduced speeds. The typical operation scenario shows the average savings that can be realised if pumps and fans operate at average daily part-load profiles to match the supply to the load demand. These partial loads differ from one site to another, but a typical example is the chilled water flow demand profile shown in Fig. 3.

An energy saving of 144,721 MW h/year, or 32.2% of the total pump and fan energy consumption, is shown to be possible for typical speed reduction profiles. This amounts to a reduction in CO_2 emissions of 131,812,158 kg/year and an annual cost saving of US$6,938,148. Viability indicators are low, with a payback period being 1.4 years and the cost of conserved energy US$68/MW h.

Table 8
Pump and fan energy consumption, energy and emission savings and cost analysis (typical site with 3.4 MW combined pump and fan installed capacity).

	Pump and fan speed reduction			
	10%	20%	30%	Typical operation
Energy consumption without VSD (MW h/year)	22,455	22,455	22,455	22,455
Energy consumption with VSD (MW h/year)	17,515	12,575	8758	15,225
Energy saving (MW h/year)	4940	9880	13,698	7231
CO_2 emission reduction (kg/year)	4,499,515	8,999,030	12,475,929	6,585,654
SO_2 emission reduction (kg/year)	35,876	71,752	99,474	52,509
NO_x emission reduction (kg/year)	18,957	37,913	52,561	27,746
Cost savings (US$/year)	236,839	473,679	656,691	346,647
Cost (US$)	460,754	460,754	460,754	460,754
Payback period (years)	1.9	1.0	0.7	1.3
Cost of conserved energy (US$/MW h)	93	47	34	64

The average payback period indicates feasibility since it is less than the suggested benchmark of 2 years.

These results are significantly better than those shown for chiller VSDs in Table 3. This is because relatively larger energy reductions can be achieved more easily by reducing pump and fan motor speeds. Furthermore, low-voltage VSDs incur lower costs. This is illustrated by the cost of conserved energy of pump and fan VSDs that is almost one third of the cost of conserved energy of chiller VSDs.

The typical daily part load profiles used for the typical operation condition take into account the various mine site water requirements, working schedules and storage dam capacities. It has been shown that a variable water flow strategy does not adversely affect performance or mine service delivery requirements [39].

Savings and payback periods improve with speed reduction and it is shown that 274,161 MW h/year, or 61%, can be saved with a payback period of 0.7 years for a constant speed reduction of 30%. It has been shown experimentally that chilled and cooling water flow reductions of this order do not reduce chiller COPs by more than 5% [20]. The pump savings of up to 61% are generally found to outweigh possible chiller COP reductions, depending on the installed capacities. However, reducing the chilled or cooling water flow by more than about 40% of design flow causes transition into the laminar flow region, reducing heat transfer rates and increasing water-side fouling. This usually results in automatic chiller shutdowns and a significant decrease in chiller COPs that outweigh pump benefits and impede viability [51,62]. Pump speed reductions of more than 30% have thus conservatively not been included in this investigation.

The additional savings that will be realised by opening flow control valves fully and maintaining design flows are difficult to quantify since it depends on the specific valve opening. This is expected to be significant and will increase the reported savings.

It is clear that it will be feasible to install VSDs on all low-voltage pumps and fans on mine cooling systems. Reported savings and payback periods are conservative but significant and indicate that this is a more rewarding option than chiller VSDs.

Table 8 shows the potential savings and feasibility factors when installing VSDs on all the pumps and fans of a typical mine cooling system with a combined pump and fan installed capacity of 3.4 MW. Mine energy managers can use these results as a guideline to the saving potential of pump and fan VSDs. An energy saving of 7231 MW h/year, or US$346,647/year, is possible for typical speed reductions. The low payback period of 1.3 years and cost of conserved energy of US$64/MW h indicates feasibility. Installing VSDs on all pumps and fans of a typical mine cooling system can therefore be recommended, especially if large speed reductions are possible or where existing electric motor specifications have been significantly overestimated.

Table 9 shows a savings and feasibility analysis for single 75 kW and 200 kW pump or fan VSDs.

Table 9
Pump and fan energy consumption, energy and emission savings and cost analysis (typical operation of a 75 kW and 200 kW pump or fan motor).

	Motor rating	
	75 kW	200 kW
Energy consumption without VSD (MW h/year)	497	1,325
Energy consumption with VSD (MW h/year)	337	898
Energy saving (MW h/year)	160	427
CO_2 emission reduction (kg/year)	145,700	388,534
SO_2 emission reduction (kg/year)	1162	3098
NO_x emission reduction (kg/year)	614	1637
Cost savings (US$/year)	7669	20,451
Cost (US$)	14,993	24,918
Payback period (years)	2.0	1.2
Cost of conserved energy (US$/MW h)	94	58

Typical operational results indicate energy savings of 160 MW h/year and 427 MW h/year, respectively. The payback period for a 75 kW unit is 2 years while it is only 1.2 years for a 200 kW unit. While both seem viable, the 200 kW VSD application is more feasible because of the reduced US$/kW values for larger drives. If plant managers want to implement VSDs on only selected pumps or fans and funding is available, it is recommended that they start with larger units, provided that sufficient speed reduction is possible.

4.3. Pilot implementation

VSDs were installed on 19 pumps of the South Deep gold mine surface cooling systems as a pilot study to experimentally evaluate energy savings. The key results can be used to validate the findings of the saving potential study discussed in the previous sections. Power ratings of the pump groups that were fitted with VSDs as well as the relevant costs are given in Table 10.

The electrical energy consumption of the various pumps was monitored over a period of 1 month after implementation. These results were then compared to the electrical energy consumption of the same pumps, over the same number of running hours, before VSD installation. As commonly done during measurement and verification, only running hours were compared for which operating conditions such as ambient conditions and service requirements were comparable [63]. The results for the different pumps motor sizes are shown in Fig. 4.

Fig. 4 shows that there was a clear reduction in energy consumption of all the pump motors. The 132 kW motors showed the greatest reduction in energy consumption because the largest number of VSDs was installed on these motors. The total site electrical energy saving after 1 month amounted to 250 MW h, or 29.9% of the baseline energy consumption. This correlates closely to the estimated 32.2% saving shown in Table 7 for the large-scale use of VSDs. CO_2 emission reductions amounted to 227,893 kg.

Table 10
Power ratings and costs of VSDs retrofitted to pumps at the South Deep mine surface cooling systems.

	Qty.	Individual power rating (kW)	Total cost (US$)
Chilled water (evaporator) pumps	4	55	42,370
	3	132	43,331
	1	200	20,117
Cooling water (condenser) pumps	4	132	57,775
	3	110	39,648
	1	200	20,117
Transfer water pumps	3	75	34,846
Total	19		258,203

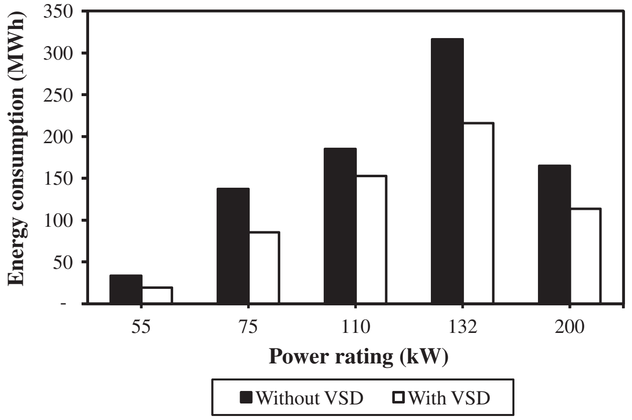

Fig. 4. Energy consumption of pump motor groups with different power ratings (1 month of pilot implementation).

The total cost savings for the month amounted to US$11,996. This implies a payback period of 1.8 years, indicating feasibility. However, the pumps were not operated continuously. It is worth noting that had this been the case, the cost savings would have been US$22,054 with a payback period of only 1 year. Increased VSD usage will therefore reduce the payback period and the cost of conserved energy. Also, the average future value of the savings is expected to be higher as a result of annual increases in electricity tariffs, depending on the expected life of the VSDs [56]. The reported savings for 1 month are therefore conservative.

The realised energy savings of the various types of pumps are shown in Fig. 5. It can be seen that the largest contribution to the savings was made by the chilled water pumps, realising 49% of the total savings. This was followed by the cooling and transfer water pumps with 30% and 21%, respectively. The major share of the chilled water pumps can be attributed to the drives that modulated the primary water flow rates in quick response to part load conditions and to the fact that the chilled water lines were throttled significantly by control valves before implementation. Cooling water VSDs generally took longer to modulate the secondary water flow relative to part load changes. Furthermore, these water supply lines were not throttled by valves before implementation.

Fig. 6 shows the average chilled water flow rate and electrical power input for full load conditions of one of the chilled water pumps. This shows the effect of replacing valve control with VSD control, even before any flow modulation takes place. While the design flow rate remained relatively constant, the electrical input power was reduced by 54%. Although the extent of this reduction depends on the extent of pump motor over-specification, the benefit of VSD control is clear.

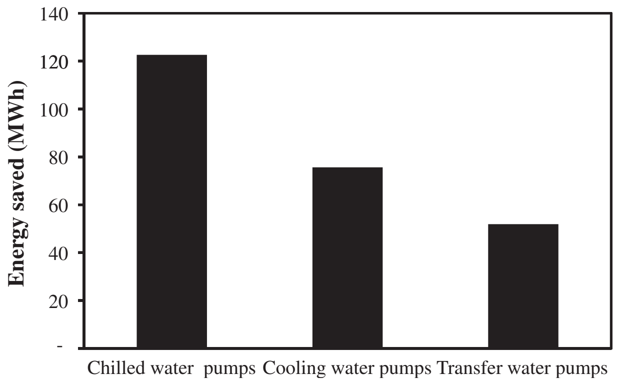

Fig. 5. Energy savings of chilled, cooling and transfer water pump motors (1 month of pilot implementation).

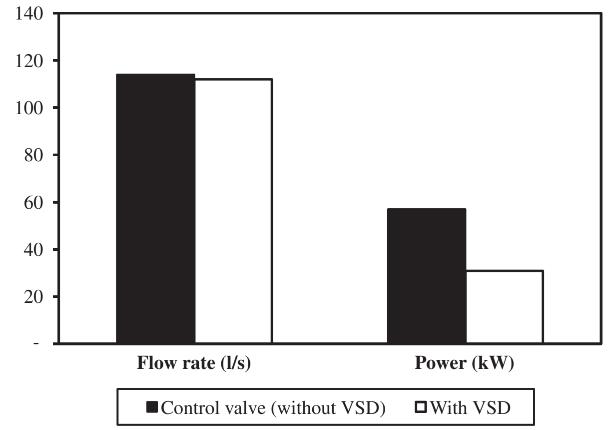

Fig. 6. Chilled water flow rate and pumping power when controlling flow with a control valve (without VSD) or with a VSD.

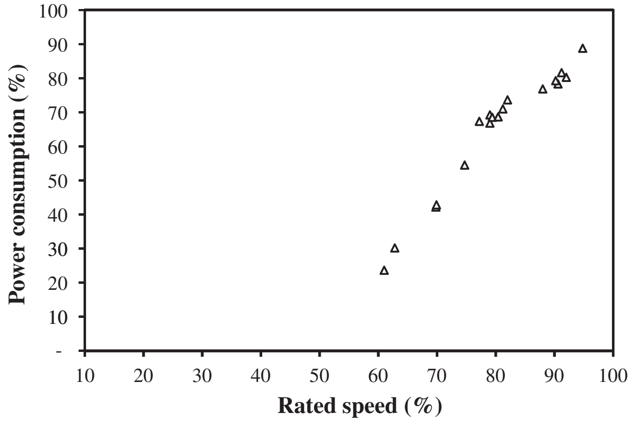

Fig. 7. Relationship between average motor power reduction and rated speed after VSD implementation (1 month of pilot implementation).

The average speeds and electrical power consumed by the various motors are shown as percentages in Fig. 7. It can be seen that the speed mostly varied between 75% and 95%. The general trend of the profile corresponds well to that shown in Fig. 1 [31]. The power reductions associated with different speed reductions estimated in the previous section are therefore realistic.

There were no adverse effects on the chilled water and ventilation air service delivery of the South Deep mine after VSD installation. No technical problems such as harmonic distortion and radio frequency interference were introduced. Preventative methods such as input and motor chokes and correctly shielded cables were applied. The benefits of VSDs also showed greater acceptance among plant personnel, especially after the actual energy savings were made available. These observations prove that technical and awareness concerns should not prevent the implementation of VSDs on mine cooling systems.

5. Conclusions

There is a global and South African drive for industrial energy efficiency improvement and GHG emission reduction. Large cooling systems on South African mines were identified to have the potential for significant energy efficient improvements by the large-scale introduction of VSD technology. An overview of VSD state-of-the-art highlighted its energy saving potential, especially when applied to chillers, pumps and fans. A summary of VSD costs in South Africa was given and the potential barriers to large-scale applications were discussed.

Mine cooling systems were reviewed and the results of an energy audit on 20 mine systems were presented. It was shown that the electrical energy consumption of these systems amounts to 1,318,225 MW h/year, or 4% of the total electricity supplied to all mines. Chillers account for 66% of this energy consumption while pumps and fans account for 34%.

Potential electrical energy savings, cost savings, emission reductions and feasibility indicators were calculated for various situations when implementing VSDs on the chiller compressors, pumps and fans of the evaluated cooling systems. The following conclusions can be drawn from the results that were obtained:

- An electrical energy saving of 168,633 MW h/year (19.4%), cost saving of US$8,084,510/year and CO_2 emission reduction of 153,590,958 kg/year will be realised if VSDs are implemented on all chiller compressor motors evaluated. However, the payback period of 4.2 years indicates that chiller VSDs are not a cost-effective option for widespread use on mine cooling systems. Investigating the replacement of selected oversized chiller motors with energy efficiency motors is recommended instead.
- It may be viable for mine energy managers to consider chiller VSDs for smaller chillers (below 6 MW cooling capacity), especially when the chillers are operating at low loading factors and if sufficient funds are available.
- An electrical energy saving of 144,721 MW h/year, or 32.2%, cost saving of US$6,938,148/year and CO_2 emission reduction of 131,812,158 kg/year will be realised if VSDs are implemented on all pump and fan motors evaluated. The payback period of 1.4 years indicates that pump and fan VSDs are cost-effective options for widespread use on mine cooling systems.
- Pump and fan VSDs can be recommended for most mine cooling systems, especially in cases where large speed reductions are possible and where motors are significantly oversized. In cases where only a limited number of pumps can be retrofitted with VSDs, it is more cost-effective to consider larger motors first.

VSDs were installed on pumps of the South Deep gold mine surface cooling systems as a pilot study to support the generalised findings. The following conclusions can be drawn from the results from 1 month:

- An electrical energy saving of 250 MW h, or 29.9%, cost saving of US$11,996 and emission reduction of 227,893 kg were realised. The payback period of 1.8 years indicates feasibility and it was shown that this can be reduced to 1 year if pumps are operated for longer periods. These results support and validate the general estimates made for large-scale VSD usage.
- Chilled water pumps realised 49% of the total energy savings. This was largely as a result of the significant improvement when replacing valve flow control with VSD flow control on the specific cooling system.
- No adverse effects such as harmonic distortion, radio frequency interference or reduction in service delivery requirements were introduced by the VSD installations.
- It can be concluded that there is a definite potential benefit, both financial and in energy efficiency, for the large-scale use of VSD technology on mine cooling systems in South Africa. It is recommended that decision and policy makers seriously consider VSDs implementation on pumps and fans of these systems. The potential impact on mine cooling systems is significant and it will contribute considerably to the improvement of South African and global industrial energy efficiency and sustainability.

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