CHAPTER 3. THE POTENTIAL FOR NEW VARIABLE SPEED DRIVE APPLICATIONS

3.1 Introduction

The general potential for variable speed drive (VSD) application on mine cooling systems has been discussed in previous chapters. A review of typical mine cooling system operations indicated that the elimination of common operations such as unnecessary water recirculation and valve flow control should lead to energy savings. Before the capital expenditure could be made to develop, simulate and implement VSDs using a new variable-flow strategy and energy management system, it was decided to do a preliminary investigation and energy audit of mine cooling systems. The main purpose of this investigation was to gain deeper insight into VSDs, to quantify the electrical energy usage of mine cooling systems, to estimate the savings that can be attained by installing VSDs on the cooling systems and to identify the most viable target area on which to implement VSDs.

First, an overview of VSDs is given as background to the investigation. The energy consumption of the main energy users of 20 mine cooling systems is then evaluated in an energy audit. These users included chillers, pumps and fans. The potential energy, cost and GHG emission savings are subsequently estimated. Feasibility indicators such as payback periods and the cost of conserved energy are also calculated.

The results of this preliminary investigation are valuable firstly because the potential large-scale impact of installing VSDs on mine cooling systems and its contribution to improving South African energy efficiency can be estimated. Secondly, the results can be used to make an informed decision regarding the viability of proceeding with the development of a new DSM method and the most feasible areas and components of cooling systems to focus on. The findings of this investigation are the focus of the article presented in Annexure A.1 (Du Plessis et al. 2013d).

3.2 Variable speed drives

The state-of-the-art in VSD technology, its benefits and considerations when evaluating its feasibility must be reviewed first. This is important in context of the effective investigation of its potential on mine cooling systems.

Energy saving potential

Electric motors have moderate to 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 efficiencies (Da Costa Bortoni 2009). 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 (Abbott 2006). As discussed in Chapter 1, it has been shown that switching to electric motors driven by VSDs is one of the most efficient and promising modern methods of operating a given load.

A VSD is connected between the driven electric motor and the power supply system, as indicated in Figure 16 (Teitel et al. 2008). Its basic principle of operation involves the use of power electronic components to control the driven motor speed by changing the motor input power frequency.

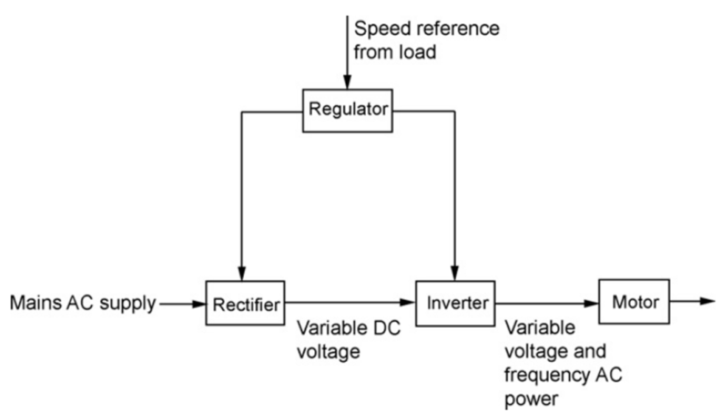

Figure 16 Main components of a variable speed drive (Teitel et al. 2008)

As shown in Figure 16, a VSD essentially consists of a rectifier, a regulator and an inverter. The rectifier converts the alternative current (AC) of the input power supply to direct current (DC) (Sueker 2005). Diode rectifiers are the most common and typically use six power diodes in a three-phase bridge configuration to produce a fixed DC voltage. The regulator controls the VSD by the exchange of data between the drive, the load and an external or internal control unit. The inverter generates an AC voltage by switching the DC voltage in alternate directions through the driven load (LLC 2003). It does so by using insulated gate bipolar transistor (IGBT) components. Pulse width modulation (PWM) is typically used to control the IGBT switches inside the inverter. PWM rapidly switches the IGBT components on and off so that pulses with variable width form a variable waveform. This therefore enables variable voltage, current and frequency as output to the motor and thereby allows the regulation of speed, torque and power (Saidur et al. 2012).

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 (Beggs 2002, Teitel et al. 2008, Johansson 2009). Successful implementation in various sectors has been vindicated, as shown by studies on a refinery (Euro Pump 2006), cement plant (Thirugnanasambandam et al. 2011), boiler house (Ozdemir 2004), petroleum plant (Irvine and Gibson 2000) and conveyor system (Zhang and Xia 2010).

As discussed earlier, 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 shown by the cubic power-flow affinity law in Figure 4 (Saidur et al. 2010).

VSDs can therefore be an important energy efficiency measure on integrated cooling systems that 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. (2012), realising energy savings of up to 13%. Crowther and Furlong (2004) showed how variable speed cooling tower fans can also save energy. Qureshi and Tassou (1996) confirmed that capacity modulation by applying VSDs to chiller compressors can lead to 12% to 24% energy savings. Energy savings of 19.7% were presented by Yu and Chan (2009) for all-variable speed chiller systems.

The variable-speed control of chiller compressors has been applied successfully to small and experimental refrigeration systems (Navarro-Esbrí et al. 2007, Romero et al. 2011). Some medium-sized chiller compressors have also been retrofitted with VSDs (US Department of Energy 2010). However, it has been indicated that for most chillers with cooling capacities larger than 1 000 kW it is not cost-effective to consider compressor VSDs as a primary energy saving measure. More cost-effective energy saving potential usually lies in first considering the use of VSDs on the various pumps in such cooling systems (Yao et al. 2004).

In addition to energy savings, VSDs also present other potential benefits. These include process control improvement (Rashid 2001), system performance and reliability improvement (Saidur et al. 2012), soft starting and stopping, reduced maintenance (Saidur 2010), electric motor and system life extension (Tolvanen 2008) and power factor correction (Pulkki 2004).

Economic considerations

It is important to consider economic factors when evaluating the viability of any energy efficiency improvement. 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 significant cost reductions in recent years. Low-voltage pump and fan VSD costs of about R850/kW for a 37 kW unit and R740/kW for a 745 kW unit were reported in the United States of America during 2011 (McKane and Hasanbeigi 2011). Typical cabling, installation and commissioning costs were shown to be about R1 150/kW in Turkey during 2004 (Ozdemir 2004). 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 cost per kW can be expected to be lower.

Table 1 shows typical costs associated with medium-voltage VSDs that would be applicable to mine chiller compressors in South Africa. 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 15 years and older. The shown installation costs include typical cabling, programming control adjustments and commissioning requirements.

Table 1 Typical chiller compressor VSD costs in South Africa (in South African Rand, March 2013 exchange rates)

	Voltage (V)	**800 kW**	**1 000 kW**	**1 500 kW**	**Average**
Company A	6 600	1 369 600	1 614 460	2 125 130	
Company B	6 600	1 452 105	1 721 820	2 210 346	
R/kW		1 764	1 668	1 445	**1 626**
Company A	11 000	1 965 702	2 210 540	2 964 912	
Company B	11 000	1 981 430	2 342 467	2 946 731	
R/kW		2 467	2 277	1 971	**2 238**
Installation	6 000-11 000	85 200	85 200	85 200	
R/kW		107	85	57	**83**
R/kW (6 600 V total)		1 871	1 753	1 502	**1 709**
R/kW (11 000 V total)		2 574	2 362	2 028	**2 321**

Table 2 shows typical costs of low-voltage drives applicable to most pumps and fans in South Africa. These costs include VSDs with standard panel protection and essential harmonic filtering equipment. Installation costs include typical cabling, programming and commissioning requirements.

Table 2 Typical pump and fan VSD costs in South Africa (in South African Rand, March 2013 exchange rates)

	Voltage (V)	**75 kW**	**132 kW**	**160 kW**	**200 kW**	**275 kW**	**Average**
Company A	525	153 996	205 110	233 485	278 105	397 330	
Company B	525	89 979	121 314	139 477	155 140	195 160	
Company C	525	74 569	115 170	131 731	168 277	203 140	
Company D	525	92 577	124 365	132 947	161 218	221 110	
R/kW		1 370	1 072	996	953	924	**1 063**
Installation	525	29 618	29 618	29 618	29 618	29 618	
R/kW		395	224	185	148	108	**212**
R/kW (total)		1 765	1 296	1 181	1 101	1 032	**1 275**

Table 1 and Table 2 illustrate that VSD costs per kW decrease with increasing power ratings, as can be expected. 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 the quoted prices abroad. This can be attributed to the expense of importing and the relatively low demand for VSDs in South Africa at present. However, installation costs are generally relatively low in South Africa.

Cost-effectiveness is commonly indicated by the simple payback period (*PBP*) as calculated by Equation 10 (Saidur et al. 2012) and Equation 11 (Abdelaziz et al. 2011).

$$PBP = \frac{C_{VSD}}{CS_{VSD}} \quad (10)$$

where $CS_{VSD} = (ES_{VSD})(ET)$ (11)

It is important that the total incremental cost of implementation (C_{VSD}) includes the cost of VSDs as well as the expense associated with necessary system changes, implementation and commissioning. Hourly energy savings and tariffs must also 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 (Abdelaziz et al. 2011). Typical feasible *PBP*s for VSDs have been reported as less than two years (Ozdemir 2004, Johansson 2009).

A further measure of cost-effectiveness is the annual cost of conserved energy (*CCE*) as calculated by Equation 12 (McKane and Hasanbeigi 2011).

$$CCE = \frac{C_{VSD}}{ES_{VSD}} \tag{12}$$

A *CCE* value of R383/MWh has been reported for VSD installations, indicating that it is one of the most feasible energy efficient measures available (McKane and Hasanbeigi 2011).

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.

VSDs generate noise in the process of internally switching between AC and DC power (Sen 1997). This noise is returned to the power supply system. The operation of VSDs thus 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. This may not only result in wasted power, but may also lead to overheating of equipment, reduced motor efficiencies, circuit breaker tripping, premature failure of old motors and communication network errors (Abbott 2006).

Distortion that has high frequency is called radio frequency interference (RFI) and is commonly corrected by RFI filters and shielded cables. Distortion with frequencies less than 3 kHz is referred to as harmonic distortion. The generation of harmonic distortion can be explained by considering Figure 17 (Schillinger 2011).

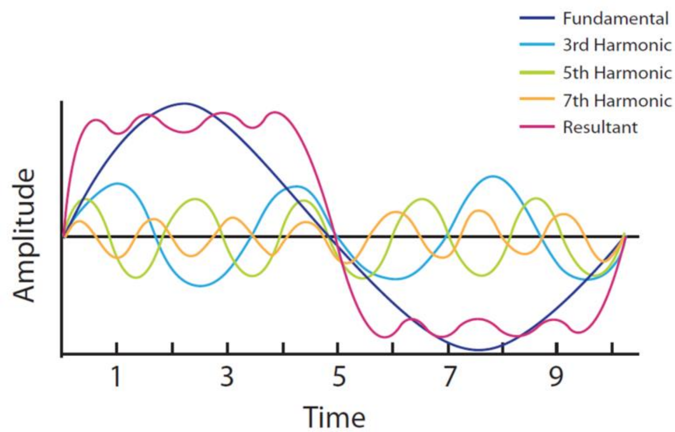

Figure 17 Harmonic current contributions when using a VSD (Schillinger 2011)

Figure 17 shows the fundamental current sine wave coming from the power supply at a frequency of 50 Hz (in South Africa). The switching current flow through the VSD rectifiers creates harmonics of the fundamental frequency. These harmonics add up to a resultant wave form that can be seen to distort the main power supply. In a typical six-pulse rectifier using six diodes, there are seven harmonic frequencies. The lower the harmonic frequency, the larger its amplitude and therefore the larger its contribution to harmonic distortion in the power supply.

The management of distortion introduced by VSDs depends on the degree of noise introduced to the existing system. The total harmonic distortion (THD) is usually measured at the point of common coupling at the power supply transformer to establish its effect on the power supply. Generally, THD of less than 40% (of the fundamental current or voltage wave) is acceptable for most robust systems, but levels below 5% can be obtained by advanced filters. Typical modern methods used to mitigate THD are shown in Figure 18 (Danfoss 2012).

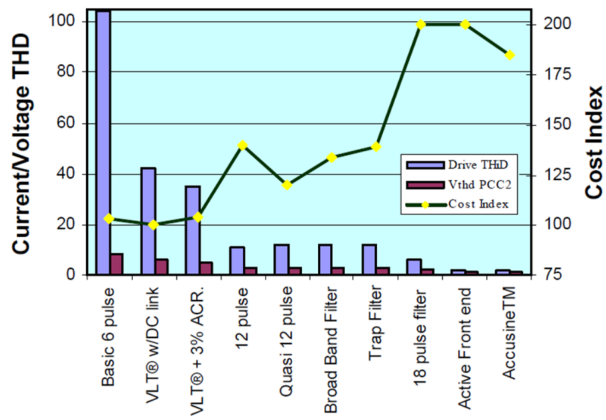

Figure 18 Typical THD mitigation measures for VSDs (Danfoss 2012)

Figure 18 uses a basic six-pulse VSD with no filtering as reference point. A standard modern VSD feature is the use of DC inductors, or DC links, between the rectifier and inverter. This reduces THD to about 40%. Adding a line reactor between the drive and the transformer reduces the THD further, but because this also reduces the voltage somewhat it is not recommended. Some manufacturers offer 12-pulse drives that theoretically cancel out problematic fifth and seventh harmonics. However, this is typically a very costly option. Passive or active harmonic filters can also be added between the drive and the transformer, but its necessity should validate the additional costs (Danfoss 2012).

It is important that the THD is measured before and after VSD implementation and that appropriate protective measures relevant to the specific system are installed. This will ensure that the equipment used in an energy saving strategy does not adversely affect the electrical power supply and equipment connected to it.

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 budgets are split between departments. This may lead to payback periods that exceed three years. These issues can be addressed by financial incentives such as rebate structures (Saidur et al. 2012) 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 (De Almeida et al. 2003).

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 (De Almeida et al. 2003).

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 R90/kW. It is thus apparent that after-sales concerns are generally unwarranted, given that the drives are suitably implemented.

It is apparent that VSDs show the potential to lead to significant savings, but that this must be weighed up against economic considerations to be feasible. Also, potential barriers to implementation should be addressed by considering proper THD and RFI preventative measures for each specific power supply system.

3.3 Energy audit

A comprehensive energy audit is a key step in systematic energy management (Bennett and Newborough 2001). It was decided to audit various different mine cooling systems to evaluate their present features, operation and energy consumption. The purpose was to get a general overview of mine cooling system operations on deep mines in South Africa so that problematic or energy inefficient areas can be narrowed down further. In this context, as large a sample size as possible was therefore preferred.

For confidentiality reasons not all mine groups allow access to information required in energy audits. The largest possible sample size of mine sites was therefore taken. This amounted to 20 different sites, accounting for about 80% of the leading deep and medium level mines in the country. The audited cooling systems were selected from various mines in the gold and platinum mining sectors of South Africa. They are collectively located in the Gauteng, North-West and Limpopo provinces.

As discussed by Saidur et al. (2011), a walkthrough energy audit is typically appropriate for a high-level evaluation such as this. The audit was therefore carried out by spending time on each site, obtaining technical specifications of all subsystems of the cooling systems, measuring important parameters (and comparing them to design values) and obtaining as much information as possible regarding the energy usage of the system through logged values, utility bills, etc. Meetings were also held with relevant managers, foremen and operators to obtain quantitative and operational information as required.

To assist in simplifying the process of gathering specifications and plant-specific data, a generalised questionnaire was compiled and filled in on each walkthrough site audit. This questionnaire was specifically designed to include key parameters and system specifications of common subsystems generic to all cooling systems. All these typical parameters are discussed in further detail in Chapter 2. The template of the general questionnaire that was used in the audits is shown in Table 3.

Table 3 Energy audit questionnaire template

	Value	Notes
Integrated system Water volume sent underground (Mℓ/day) Water temperature sent underground (ºC) Number of hot dams Hot dam temperature (ºC)		
Pre-cooling towers Number of cooling towers Inlet water temperature (ºC) Outlet water temperature (ºC) Design ambient wet-bulb temperature (ºC) Water flow rate per tower (ℓ/s) Number of fans Fan power (kW)		
Chillers Manufacturer Refrigerant Number of chillers Cooling capacity (kW) Design COP Compressor type Compressor installed capacity (kW) Evaporator flow rate (ℓ/s) Evaporator inlet temperature (ºC) Evaporator outlet temperature (ºC) Evaporator pump power (kW) Number of evaporator pumps Condenser flow rate (ℓ/s) Condenser inlet temperature (ºC) Condenser outlet temperature (ºC) Condenser pump power (kW) Number of condenser pumps		
Condenser cooling towers Number of cooling towers Inlet water temperature (ºC) Outlet water temperature (ºC) Design ambient wet-bulb temperature (ºC) Water flow rate per tower (ℓ/s) Number of fans Fan power (kW)		
Bulk air cooler Number of BACs Inlet water temperature (ºC) Outlet water temperature (ºC) Design ambient wet-bulb temperature (ºC) Water flow rate per tower (ℓ/s) Outlet air wet-bulb temperature (ºC) Number of fans Fan power (kW)		

Table 3 and basic system layouts were used to get a basic understanding of the operations and energy usage of each individual system. In addition, system data logged on the mine SCADA, preferably over a period of one year or more, were obtained from mine personnel. This typically showed key system parameters (such as temperatures and flows) and electricity consumption of main components. This data was used in conjunction with design specification sheets and other relevant material (Hartman 2002, Design Guide 2003) to analyse subsystem loading and energy consumption.

In cases where electricity usage was not logged (but system parameters and statuses were logged), the electrical energy consumed by chillers and pumps or fans were calculated from Equation 13 (Jayamaha 2008) and Equation 14 (Hasanuzzaman et al. 2011), respectively.

$$EC_{chiller} = (OH)(\dot{Q}_c)(LF_c)(COP^{-1}) \tag{13}$$

$$EC_{pump,\, fan} = (OH)(\dot{W}_{rated})(LF_p) \tag{14}$$

The chiller cooling load factor is the ratio of the actual thermal load to the full design cooling load. It was calculated by measuring the actual thermal load (Equation 2) and dividing it by the rated thermal load at the same average ambient and operational conditions, as published by the manufacturer.

The power load factor of a pump or fan electric motor is the ratio of actual capacity to rated capacity (Thirugnanasambandam et al. 2011). It was found by measuring the actual power of the electric motors with a multi-meter on site and dividing it by the rated power, as given by the manufacturer. Average load factors of the subsystems on each site were used in Equations 13 and 14 and were calculated from measured loads and load profiles.

A typical evaluated mine cooling system consisted of four to five chillers, five chilled water pumps, five cooling water pumps, four transfer pumps and five cooling tower fans. The average site installed capacity was 10.8 MW and the average annual electricity consumption was 65 911 MWh. The annualised energy consumption results of the evaluation are shown in Table 4. The results are presented in this form to account for operating hours and seasonal equipment scheduling.

Table 4 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 (MWh/year)	Qty.	Load factor (%)	Total energy consumption (MWh/year)	Qty.	Load factor (%)	Total energy consumption (MWh/year)	Total energy consumption (MWh/year)
1	4	13 300	76	46 719	14	74	10 996	4	90	2 120	59 835
2	6	6 500	80	41 099	19	82	13 679	8	75	4 504	59 282
3	4	5 000	69	19 320	10	75	7 406	5	93	3 478	37 158
	1	6 000		6 955							
4	4	6 000	67	25 292	15	70	10 499	4	74	2 650	38 440
5	4	11 500	79	44 436	14	86	14 010	9	94	11 526	78 827
	1	5 500		8 855							
6	3	5 000	92	15 807	16	97	12 619	13	81	8 280	59 923
	2	5 000		10 538							
	1	14 000		12 679							
7	3	7 500	74	20 700	19	81	16 858	13	89	7 187	71 379
	1	10 500		9 660							
	1	16 400		16 974							
8	2	10 000	78	18 400	12	83	7 525	7	79	6 359	47 924
	1	5 000		4 600							
	1	12 000		11 040							
9	3	11 000	84	31 878	15	91	9 505	12	99	9 539	55 172
	1	4 400		4 250							
10	4	10 100	62	34 949	16	69	21 859	7	71	8 280	98 949
	6	3 700		33 861							
11	4	6 600	71	27 821	11	88	8 214	4	87	5 299	41 334
12	4	4 150	92	25 319	10	95	23 846	1	94	1 656	88 801
	6	4 150		37 979							
13	2	5 000	89	16 100	6	86	10 433	2	96	2 517	29 050
14	3	6 450	82	24 923	8	80	13 116	3	75	3 974	42 013
15	6	3 000	61	29 808	22	79	51 005	4	91	1 855	112 476
	3	6 000		29 808							
16	5	5 340	65	26 914	12	78	25 171	4	78	4 306	56 390
17	2	10 000	73	21 955	8	79	20 137	3	74	3 974	46 066
18	8	6 000	90	84 562	7	91	12 321	1	99	874	97 757
19	12	4 000	58	86 940	16	81	42 394	4	96	5 299	134 633
20	4	10 000	71	38 640	10	83	22 190	2	73	1 987	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**

It can be seen from Table 4 that 112 large chillers were evaluated with individual cooling capacities varying between 3 MW and 16.4 MW. Chiller COPs typically varied 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%. Most inlet water temperatures have also increased by about 3 ºC to 4 ºC from original design conditions due to mine deepening. In many cases the chillers could not obtain the required chilled water temperature during summer at design flows, leading to significant volumes (20% to 50%) of chilled water being recirculated at design flow to lower the average inlet temperature. Chillers were shown to 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. In general, these pumps operated almost continuously at low loading factors. Most of the pumps were found to be significantly oversized for their applications, as indicated by manual throttle valves used for flow control that were often up to 60% closed. 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.

The total annual electricity consumption of the evaluated sites was 1 318 225 MWh. 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.

VSDs were not installed on any of the electric motors of the audited mine cooling systems. These mines comprise about 80% of deep mines in South Africa and include all the leading mines regarding mining innovation and technology. It can therefore be assumed that no deep-mine cooling system in the country widely 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. As discussed earlier, energy efficiency was not a priority on mines until the late 1990s, leading to most personnel not actively pursuing energy saving measures. This appears to still be the case among most technical personnel.

As is usually the case with cooling systems, evidently unutilised part-load conditions could be identified on the evaluated systems. These are summarised below.

- *Intermittent underground water demand.* Chilled water was often found to be recirculated to the pre-cooling dam when the chilled water dam becomes full and demand is less than supply. The chillers and pumps were therefore clearly working harder than was necessary.

- *Changing ambient conditions.* Even though ambient conditions fluctuate daily and are below design ambient conditions of equipment most of the time, the equipment controls were not found to take these fluctuations into account. This pertained more specifically to condenser cooling towers, pre-cooling towers and BACs. This means that the BAC was supplying air at lower temperatures than truly necessary for large portions of the day and that cooling towers and associated pumps were often working harder than required.

From the energy consumption results, inefficient operations and part-load conditions identified in the energy audit it is apparent that there should be significant potential for changing over to VSDs on large mine cooling systems.

3.4 Variable speed drive potential

The viability of implementing VSDs on the evaluated cooling systems was investigated. This was done by estimating energy and cost savings as well as GHG emission reductions, and by calculating payback periods and costs of conserved energy. The objective was to obtain a rough idea of whether VSDs will realise viable savings and on what systems to focus in the development of a DSM strategy.

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. (2011) was adopted because of its suitability to large-scale evaluations such as this.

Energy consumption of variable speed chillers can be estimated by using Equation 13 and considering variable-speed chiller performance changes regarding the COP for different loading factors (Hartman 2002). The energy savings that can be realised under the same operating conditions are then simply calculated from Equation 15 (Saidur et al. 2011).

$$ES_{chiller} = EC_{chiller} - EC_{chiller,VSD} \quad (15)$$

Estimates for pump or fan energy savings when using VSDs can be calculated using Equation 16 (Saidur et al. 2010). Energy saving percentage (*ESP*) values associated for various speed reductions were used as given by Saidur et al. (2010).

$$ES_{pump,fan} = (OH)(\dot{W}_{rated})(ESP) \quad (16)$$

Reductions in energy usage also result in reduced GHG emissions associated with electricity generation (Mustaffah and Azma 2006). 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 Equations 17 to 19 (Abdelaziz et al. 2011).

$$ER_{CO_2} = (ES)\sum(\%F \times EF_{CO_2}) \tag{17}$$

$$ER_{SO_2} = (ES)\sum(\%F \times EF_{SO_2}) \tag{18}$$

$$ER_{NO_x} = (ES)\sum(\%F \times EF_{NO_x}) \tag{19}$$

Emission factors are based on electricity generation by burning coal (Eskom 2011). This accounts for 92% of South Africa’s electricity (Amusa et al. 2009). Emission reduction estimates are therefore conservative, but expected to be sufficiently accurate for the purpose of this evaluation.

Using Equations 10 to 19 and the relevant logged data obtained during the audit, the applicable estimates were made. Chillers were separated from pumps and fans because chiller compressors need medium-voltage VSDs while most pumps and fans require low-voltage drives. Results are given for various scenarios and loading cases to investigate the potential as broadly as possible.

Chillers

Savings and feasibility factors were calculated when installing VSDs on all chiller compressor motors at various chiller cooling loading factors. The results for all the sites combined are given in Table 5. 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.

Table 5 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 (MWh/year)	717 928	920 421	1 104 505	868 780
Energy consumption with VSD (MWh/year)	524 620	773 154	1 058 484	700 147
Energy saving (MWh/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 (R/year)	81 814 149	62 334 590	19 479 559	71 378 143
Cost (R)	302 034 576	302 034 576	302 034 576	302 034 576
Payback period (years)	3.7	4.8	15.5	4.2
Cost of conserved energy (R/MWh)	1 563	2 051	6 563	1 791

Table 5 shows that an annual energy saving of 168 633 MWh, or 19.4%, 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 R71 378 143. However, the costs of the medium-voltage VSDs that are required for chiller compressors are high in South Africa, as was shown in Table 1. The viability indicators are therefore high, with the payback period being 4.2 years and the cost of conserved energy R1 791/MWh.

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. As is to be expected, 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 a very cost-effective option. This is mainly due to high VSD costs and relatively high loading factors imposed on mine chillers by large and continuous mine cooling demands.

Table 6 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. An energy saving of 168 633 MWh/year, or 19.1%, is possible for typical chiller operations. This is equivalent to a site cost saving of R2 968 335/year. However, the payback period of 4.3 years and cost of conserved energy of R1 838/MWh indicates the impracticality of changing over to VSDs. Chiller VSDs are therefore only recommended on specific sites where chillers have low loading factors and where sufficient funds are available.

Table 6 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 (MWh/year)	31 943	41 136	48 987	36 736
Energy consumption with VSD (MWh/year)	24 234	35 281	47 314	29 723
Energy saving (MWh/year)	7 709	5 856	1 673	7 013
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 (R/year)	3 263 142	2 478 491	707 949	2 968 335
Cost (R)	12 888 889	12 888 889	12 888 889	12 888 889
Payback period (years)	3.9	5.2	18.2	4.3
Cost of conserved energy (R/MWh)	1 672	2 201	7 706	1 838

Table 7 shows the same savings and feasibility analysis for a single chiller with a 5 MW cooling capacity. The typical operational results indicate an energy saving of 1 119 MWh/year, or 21.3%, with a payback period of 3.3 years. These results are better than shown in Tables 5 and 6. This is because better relative improvements in COPs can be achieved when using VSDs on smaller chillers and the lower VSD costs associated with 6 600 V chillers, as used in this example. Plant managers can therefore expect significant savings when implementing VSDs on single chillers, especially smaller chillers with low loading factors. However, initial capital outlay, cost-effectiveness and trade-offs with pump and fan VSDs must be considered.

Table 7 Chiller energy consumption, energy and emission savings and cost analysis (typical 6 600 V chiller with 5 MW cooling capacity)

	Chiller loading			
	50-70%	**70-90%**	**90-100%**	**Typical operation**
Energy consumption without VSD (MWh/year)	4 591	5 886	7 063	5 259
Energy consumption with VSD (MWh/year)	3 355	4 944	6 769	4 140
Energy saving (MWh/year)	1 236	942	294	1 119
CO_2 emission reduction (kg/year)	1 125 794	857 748	268 046	1 018 797
SO_2 emission reduction (kg/year)	8 976	6 839	2 137	8 123
NO_x emission reduction (kg/year)	4 743	3 614	1 129	4 292
Cost savings (R/year)	523 189	398 620	124 569	473 464
Cost (R)	1 554 545	1 554 545	1 554 545	1 554 545
Payback period (years)	3.0	3.9	12.5	3.3
Cost of conserved energy (R/MWh)	1 258	1 651	5 282	1 390

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 8. The 10% to 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 more realistic savings that can be realised if pumps and fans operate at average daily part-load profiles. These profiles were estimated based on existing system data showing when there was significant water recirculation and when the ambient conditions were below design values (indicating the potential to reduce flows).

Table 8 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 (MWh/year)	449 445	449 445	449 445	449 445
Energy consumption with VSD (MWh/year)	350 567	251 689	175 284	304 724
Energy saving (MWh/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 (R/year)	41 852 545	83 705 091	116 045 694	61 256 907
Cost (R)	86 510 025	86 510 025	86 510 025	86 510 025
Payback period (years)	2.1	1.0	0.7	1.4
Cost of conserved energy (R/MWh)	875	437	316	598

Table 8 shows an energy saving of 144 721 MWh/year, or 32.2%, 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 R61 256 907. Viability indicators are low, with a payback period being 1.4 years and the cost of conserved energy R598/MWh. The average payback period indicates feasibility since it is less than the previously suggested benchmark of two years.

These results are significantly better than those shown for chiller VSDs in Table 5. 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, as shown by Table 2. 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.

Savings and payback periods improve with speed reduction and it is shown that 274 161 MWh/year, or 61%, can be saved with a payback period of 0.7 years for a constant speed reduction of 30%. 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 large-scale option than chiller compressor VSDs.

Table 9 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. An energy saving of 7 231 MWh/year, or R3 060 543/year, is possible for typical speed reductions. The low payback period of 1.3 years and cost of conserved energy of R563/MWh 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 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 (MWh/year)	22 455	22 455	22 455	22 455
Energy consumption with VSD (MWh/year)	17 515	12 575	8 758	15 225
Energy saving (MWh/year)	4 940	9 880	13 698	7 231
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 (R/year)	2 091 054	4 182 109	5 797 923	3 060 543
Cost (R)	4 068 000	4 068 000	4 068 000	4 068 000
Payback period (years)	1.9	1.0	0.7	1.3
Cost of conserved energy (R/MWh)	823	412	297	563

Table 10 shows a savings and feasibility analysis for single 75 kW and 200 kW pump or fan VSDs. Typical operational results indicate energy savings of 160 MWh/year and 427 MWh/year, respectively. The payback period for a 75 kW unit is two 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 R/kW values for larger drives. If VSDs can be implemented on only selected pumps or fans (due to funding limitations for example), it is recommended that larger units are considered first, provided that sufficient speed reduction is possible.

Table 10 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 (MWh/year)	497	1 325
Energy consumption with VSD (MWh/year)	337	898
Energy saving (MWh/year)	160	427
CO_2 emission reduction (kg/year)	145 700	388 534
SO_2 emission reduction (kg/year)	1 162	3 098
NO_x emission reduction (kg/year)	614	1 637
Cost savings (R/year)	67 711	180 563
Cost (R)	132 375	220 000
Payback period (years)	2.0	1.2
Cost of conserved energy (R/MWh)	828	516

3.5 Conclusion

An overview of VSD state-of-the-art highlighted its functional principles and 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, such as harmonic distortion and lack of personnel incentives, 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 MWh/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%. It was found that there are various inefficient operations and that unutilised part-load conditions prevail, such as variations in chilled water demand and ambient conditions.

Potential electrical energy and 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. An electrical energy saving of 19.4% (on chiller energy usage) might be realised if VSDs are implemented on all evaluated chiller compressor motors. However, the payback period of 4.2 years indicates that chiller VSDs are not the most cost-effective option for widespread use on mine cooling systems.

An electrical energy saving of 32.2% (on pump and fan energy usage) might be realised if VSDs are implemented on all evaluated pump and fan motors. The payback period of 1.4 years indicates that pump and fan VSDs are cost-effective options for widespread use on mine cooling systems.

It can be concluded that there are definite potential benefits, both financial and in energy efficiency, for the large-scale use of VSD technology on mine cooling systems in South Africa. It was shown that it would be most cost-effective to consider pumps and fans as a priority when developing a new energy efficient DSM strategy to implement VSDs.