A simple demand-side management solution for a typical compressed-air system at a South African gold mine

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Abstract

Once designed, mine compressed-air systems tend to operate at peak levels throughout the life of the mine, despite there being significant periods when this air quantity is not required. This is mainly due to lack of appropriate compressor controls. Consequently, such compressed-air systems are inefficient and wasteful. A compressed-air system at a South African gold mine was retrofitted with an automatic compressor control system featuring compressor cascading and pressure bandwidth control. The goal was to implement a simple demand-side management (DSM) strategy to afford meaningful electrical energy savings. The automatic control strategy realised a saving of 1.25 MW (on a baseline of 7.22 MW) during Eskom's evening peak demand window. This represents a reduction of 17.3% in electrical power consumption during the evening peak period, and savings of nearly R2.9 million per year.

Keywords: demand-side management, compressed-air systems, gold mines

1. Introduction

Demand-side management (DSM) is a method applied to reduce electrical demand and therefore delay the time when new generation capacity will be required (Popp et al., 2009; Aufhammer et al., 2007; Gellings and Parmenter, 2006; Sioshansi, 2000; Ashok and Banerjee, 1995; Redford, 1994; Nilsson, 1994). DSM measures allow customers to use electricity less intensively or at times which do not coincide with unavoidable peak demand (Paulus and Borggrefe, 2010; Eskom, 2009; Gillingham et al., 2009; Strbac, 2008; Pelzer et al. 2008). With the South African mining industry consuming about 17% of the total electricity generated in South Africa (Winkler, 2006; Fawkes, 2005; Eskom, 2009), DSM can play a vital role in decreasing the national electricity demand (Winkler et al., 2007).

Air compressors at South African mines account for about 2.6% of Eskom-provided electricity (Eskom, 2009; Hughes et al. 2007). Compressed-air is a notoriously inefficient energy commodity, with typically only 19% of its power being usable (Bloch, 2006; NPCI, 2006; USDoE, 2003; CEA, 2007; Koski, 2002). Furthermore, analysis of the five-year life cycle of a new compressed-air system indicates that electricity consumption accounts for as much as 80% of total life cycle costs of the compressor (DeWitte and Boesmans, 2009; USDoE, 2004; Kaya et al., 2002; CEA, 2007). Industrial air compressors thus provide significant DSM potential based on their widespread use and implicit inefficiencies (Saidur et al., 2010).

Compressed-air systems represent a fundamental aspect of mining operations. Compressed-air is mainly used for ventilation, pneumatic rock drills, ore loaders, loading boxes, liquid agitation, and refuge bay air supply. All these compressed-air operations occur on different mining levels at different times and have different and varying air requirements.

At present, most mines use unsophisticated pressure control systems that ensure delivery of air at constant and equal pressure on all mining levels. The compressor delivery pressure set-point is usually set to meet the requirements of the highest pressure end-use load (D'Antonio et al., 2005; Kocsis et al., 2003). This results in unnecessary wastage of compressed-air and electrical power, with energy consumption being proportional to the cube of the air flow rate (Hartman et al., 1997).

The objective of an effective automatic compressor system control strategy is to match system demand with compressors' supply, while still operating at or near their maximum efficiency levels. This paper investigates a simple, automated DSM strategy to facilitate more effective compressor system operation and run-time scheduling at gold mines.

2. Control strategies for individual compressors at mines

Compressor control is aimed at maintaining the compressed-air discharge pressure within a specified range while the compressor plant is subject to variable rates of compressor air demand. The most common control options for centrifugal air compressors typically used at mines, comprise of load/unload control, inlet air modulation via throttle valves or control vanes, and variable speed control. Start/stop (on/off) control presents a low-cost control alternative (USDoE, 2003; Schmidt and Kissock, 2005). Oversized compressors, which are typical in mining applications (CAC, 2002), and compressors operating in inefficient control modes have the highest unit energy and the highest annual operating costs (Saidur et al., 2010).

Start/Stop control is the simplest control alternative. The electric motor driving the compressor is turned off and draws no power as long as the discharge pressure remains above a specified level. This type of control should not be used in an application that has frequent cycling (such as three or more start/stops per hour), as repeated starts might cause motor overheating and require more regular overhauling of compressor components (USDoE, 2003). The compressor duty cycle must be considered when using start/stop control and extreme care must be exercised when employing this control strategy with large centrifugal compressors.

Variable speed control is accepted as an efficient means of compressor capacity control, using integrated variable frequency AC or switched reluctance DC drives (USDoE, 2003). In both cases, the systems are started at a selected minimum pressure. The electric motors then operate along a characteristic curve to a speed which is specified by the ratio of actual pressure to control pressure. If the air consumption exceeds the control range of the compressor, the system is either shut down or switched to 'idling' mode, depending on the control schedule.

Load/unload control, also known as constant-speed control, allows the compressor's electric motor to run continuously, but unloads the compressor when the discharge pressure is adequate (USDoE 2003). When unloaded, the compressor no longer adds compressed air to the system, but the electric motor continues to run (i.e., idling or no-load condition). Load/unload control generates a distinctive step-like power signature, drawing between 105% to 115% of rated power when loaded and between 20% and 60% of full-load power when unloaded (Schmidt and Kissock, 2005; Aegerter, 1999).

Modulating (throttling) inlet control allows the compressor output to be continuously adjusted to meet flow demand. With centrifugal compressors, throttling is usually achieved by closing the inlet valve, thereby restricting inlet air to the compressor. When throttle control is combined with inlet guide vanes, the system dynamics and efficiency improve (i.e., fewer and smaller pressure fluctuations). Inlet guide vanes also reduce the mass flow but cause the air to be directed radially toward the impeller inlet in the same direction as the impeller rotation. This improves the efficiency compared to simple throttling (USDoE, 2003). The amount of capacity reduction is limited by the potential for flow surge (flow reversal) and minimum throttling capacity (Fink et al., 1992; Greitzer 1976a,b; Cohen et al., 1987). Inlet valve modulation is normally restricted to a range varying between 100% and about 40% of rated capacity (USDoE, 2003).

The energy penalty for operating with inlet modulation control, particularly at high loads, compared to load/unload control is small. However, it increases as the load declines relative to compressor capacity. As the load declines relative to compressor capacity, the energy penalty becomes greater (Schmidt and Kissock, 2005).

Inlet-modulation control has the lowest part-load efficiency of the various control strategies because it requires the largest fraction of full-load power compressed-air output. Start/stop control has the highest part-load efficiency because it requires the least fraction of full-load power per compressed-air output. Part-load efficiency is important since most centrifugal compressors are sized for the peak load, which generally occurs infrequently in mines, resulting in operation at part-load for most of the time (Schmidt and Kissock, 2005).

In some cases, discharge bypass or blow-off control is used to reduce the flow (load) delivered to the compressed-air system. Compressed-air is discharged to the atmosphere (USDoE, 2003). Although this represents a waste of energy, it is often used in air pressure controls on mines.

3. Control strategies for multiple compressors

Compressed-air systems at mines usually employ a number of compressors connected to an air ring. Most South African mines, however, do not employ sophisticated controls which are required to effectively control such compressor operation. The typical manual control strategy of compressor run-time

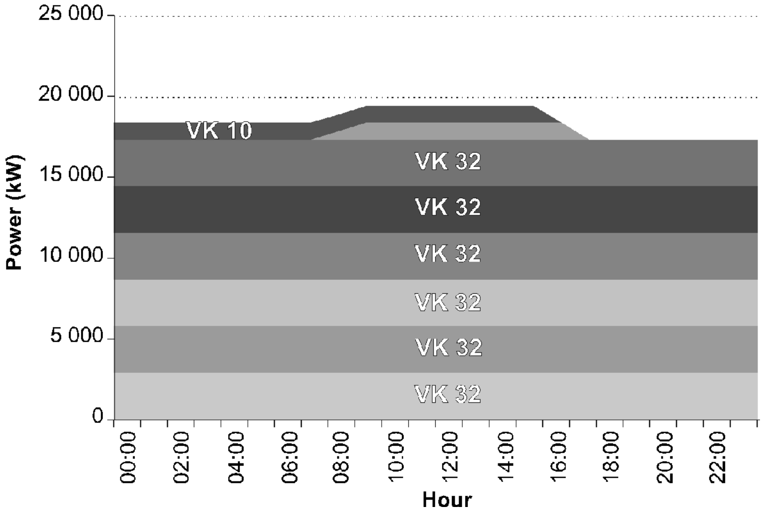


Figure 1: Typical weekday compressor operation at a South African gold mine. Manual compressor control implies that the eight compressors operate unnecessarily continuously

entails maintaining system pressure at a fixed, predetermined level. Manual operation of the system means that all the compressors run continuously at the specified pressure set point which is determined by the baseline pressure profile. However, this maximum demand is usually only required for approximately six hours per day, as shown in Figure 1. Under present operational procedures at most mines, surplus compressed-air is simply released into the atmosphere through compressor blow-off valves. This results in an unnecessary and preventable energy loss.

Under certain conditions, operators will start or stop one or more compressors manually, according to a predetermined schedule. A compressor should, however, only be stopped if the remaining on-line compressors are still able to maintain system demand. This requires pressure and flow transmitters and measurements which must be timely interpreted to ensure that an appropriate decision to stop or start a compressor can be made. If a compressor is prematurely stopped it may result in a drop in system pressure below the minimum requirement. This may necessitate the immediate restarting of one or more compressors (with the associated risk of compressor breakdown, as previously discussed) to maintain stable system pressure.

Automated compressor control will prevent or significantly reduce this wasteful compressed-air blow-off. The number of compressors required to maintain system pressure may also be reduced by synchronizing (in real-time) the compressed-air supply with demand, while maintaining the compressor system air demand parameters (Witrant et al., 2010). Electricity consumption and maintenance costs will be reduced because fewer compressors will be required to operate during the course of a normal working day. However, injudicious stopping and starting of compressors will result in greater compressor system maintenance costs (Neser et al., 2007; Pelzer et al. 2008).

The compressed-air system depicted in Figure 1 employs eight centrifugal compressors. Each compressor features individual controls, such as load/unload controls, throttle valves, inlet guide vanes, and blow-off valves. Variable speed drives are not used due to restrictive costs.

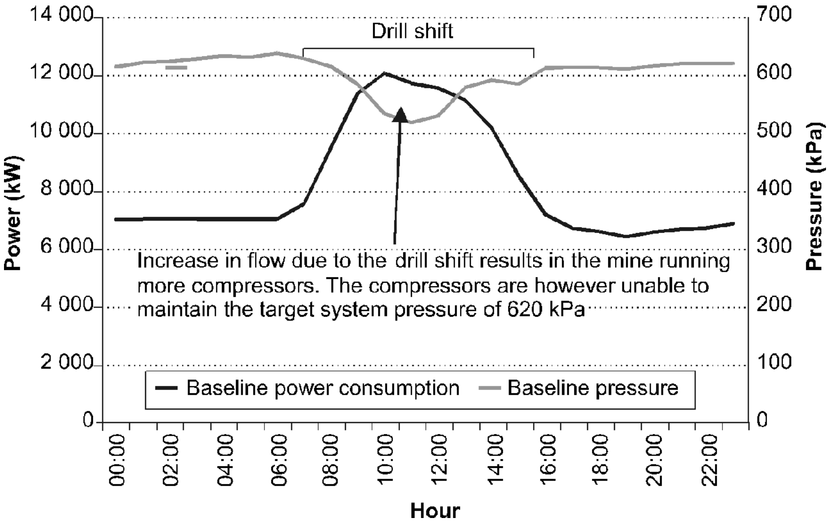
Figure 2 shows the average weekly compressed-air pressure profile, with the compressor system operating under manual control. Supply-side pressure at this mine was set at 620 kPa throughout the day with the compressors operating at full capacity, irrespective of demand. Air consumption reaches a peak during the relatively short drill shift (07:00 to 10:00) which is associated with a system pressure drop to 520 kPa.

Analysis of the mine's operational and production data showed that the drilling operations were still able to function effectively at 520 kPa. This is confirmed by the figures shown in Table 1, which reveal that critical pneumatic equipment can in fact operate effectively at 520 kPa. If it is possible to lower the overall system supply pressure, a general improvement in the overall energy efficiency can be expected.

Table 1: Pressure and flow requirements of gold mining equipment

Source: DeLa Vergne (2003)

Appliance	*Pressure requirements (kPa)*	*Flow requirements (m^3/h)*
Rock drills	400 – 600	310 – 430
Mechanical loaders	400 – 500	Up to 1010
Fans	400 – 500	70 -680
Diamond drills	400 – 500	Up to 510
Agitation	300	Up to 1700



Increase in flow due to the drill shift results in the mine running more compressors. The compressors are however unable to maintain the target system pressure of 620 kPa

Figure 2: Measured baseline power consumption of compressor system vs. pressure; compressor system under manual control

This corroborates that the initial pressure set-point of 620 kPa was too high, and that 520 kPa was a more realistic value. A general rule of thumb is that reducing pressure settings by 13 kPa will reduce energy consumption by 1% (Christina and Worrell, 2005; Risi, 1995). The reduction of pressure from 620 kPa to 520 kPa thus corresponds to an expected reduction of electrical energy consumption of 7.8%.

4. Improved control strategy

To improve the existing control philosophy, a simulation model was developed to test various control options (similar to the model of Gomes et al., 1999). The model can be customized to incorporate the specific constraints of a particular mine such as working pressure, number and capacity of the compressors, and system layout. Applying the characteristics of this simulation model, an improved control philosophy was developed, as shown in Figure 3.

The new control philosophy specifies a pressure set-point of 520 kPa. The base-load compressor runs throughout the day, whilst the trim compressors are actuated only during peak periods. When such a control strategy is employed, a new power profile is expected, as can be deduced from Figure 4. By comparing Figure 4 with Figure 1, the power saving potential of the new compressor control strategy can be ascertained.

Based on the airflow demand-profile shown in Figure 4, a compressor control philosophy was developed and simulated so that the mine would at all times be supplied with the correct pressure and airflow requirement. The simulation model continuously monitors and controls the number of compressors operating at any one time. System pressure and airflow supply could therefore be maintained at the correct operational requirement at all times.

Figure 5 illustrates the improved simulated compressor operation schedule that will supply the mine with sufficient air at the required system pressure at

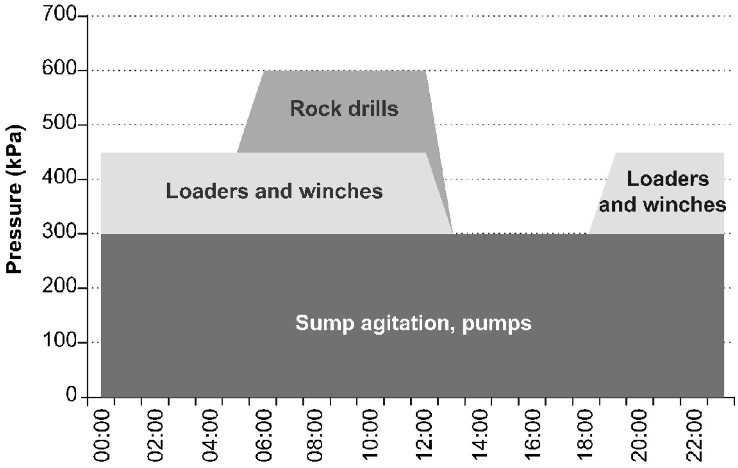


Figure 3: Improved compressor control strategy, showing pressure set-points for a typical production day

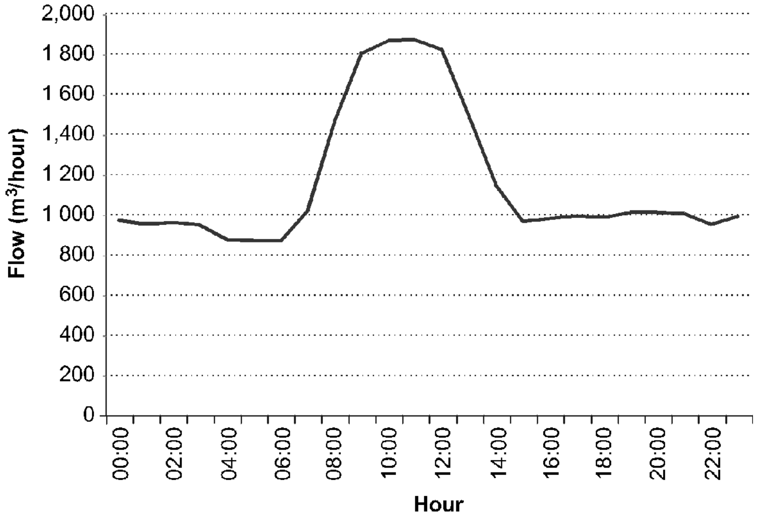


Figure 4: Measured daily compressed-air demand profile. The high airflow demand during the drill shift (07:00 – 10:00) is apparent

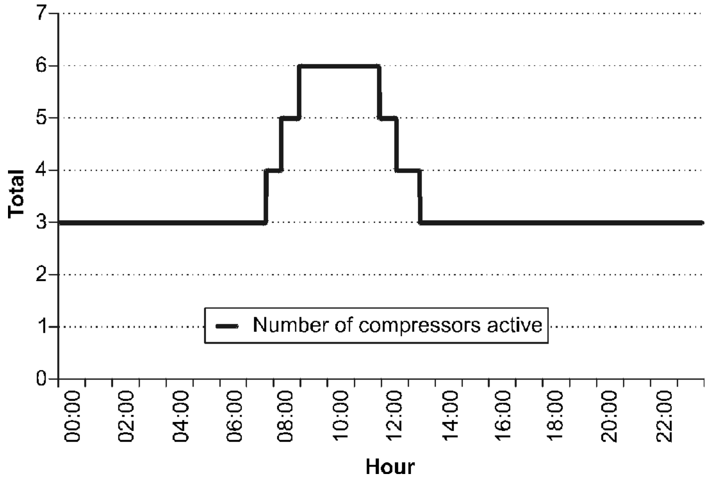


Figure 5: Improved compressor control schedule

any specific time. Three compressors are assigned base-load duties, whilst three other compressors fulfil trimming duties during the drill period.

Figure 6 illustrates the operation of the new control system. If the system air pressure increases above the maximum allowed pressure (520 kPa) the controller would be prompted to stop at least one compressor. However, the air demand of the system may be such that the remaining operating compressors cannot meet the demand with the reduced number of operating compressors. This might result in the system pressure falling below the minimum required operating pressure, signalling the controller to start the compressor up again.

Figure 6 further shows that the controller would control system pressure within a narrow band. The pressure variations within this band would be controlled by inlet air modulation (inlet guide vanes and throttle valves), (Radgen, 2003). Should the maximum allowable pressure be reached, a blow-off valve would be actuated releasing excess air, thus allowing the compressor to be placed in an unloaded ('idle') condition. If the minimum allowable pressure is reached during the no-load period, a compressor would be switched on and returned to full-load operation.

Compressors are usually placed in an offload state before they are completely shut down. When the inlet guide vanes or throttle valves are set at the fully closed position, the compressor will be running under no-load ('unloaded') condition (Radgen, 2003). The compressor would then essentially be isolated from the compressed-air ring. The compressor, operating in the no-load condition, consumes about 60% of its installed electrical capacity.

The compressor is kept in this offload condition for a predetermined period of time to ensure system pressure stability before completing the full shut down procedure. This eliminates the possibility of on-off cycling of the compressors, which reduces system wear and tear.

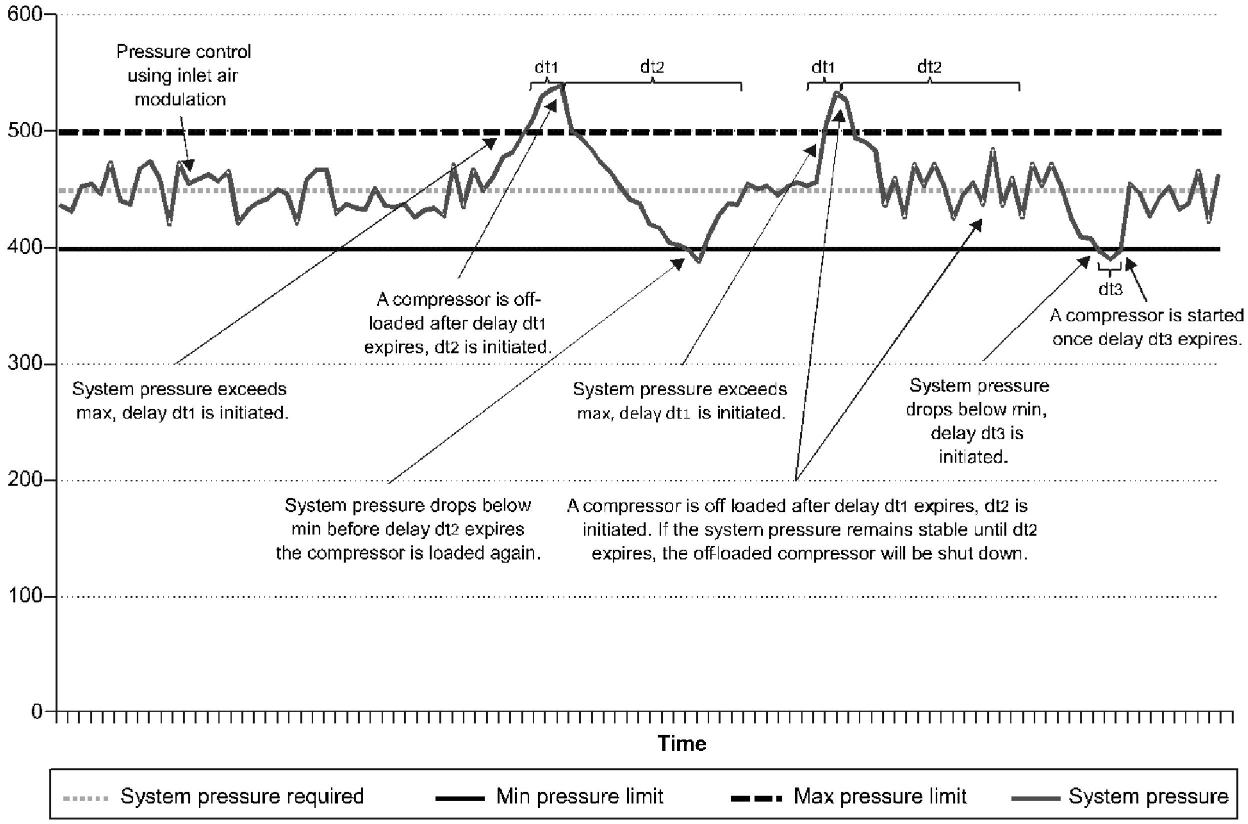


Figure 6: Illustration of control system regulating system pressure

5. Experimental verification

This new control strategy was experimentally verified at the specific gold mine under investigation. The new control schedule was implemented in an overhead computer controller, which interfaced with a supervisory control and dat acquisition (SCADA) system. Control signals were relayed to programmable logic controllers (PLC), which also acquired the required pressure and flow signals (Figure 7). The compressor energy management system was connected to the SCADA via object linking and embedding (OLE) for process control (OPC) connection. This connection to the SCADA gives the energy management system full control over the PLC. The overhead controller could initiate the following control actions: compressor start or stop; loading or unloading; inlet air modulation (actuating throttle valves and inlet guide vanes); actuate compressors in various combinations (sequencing).

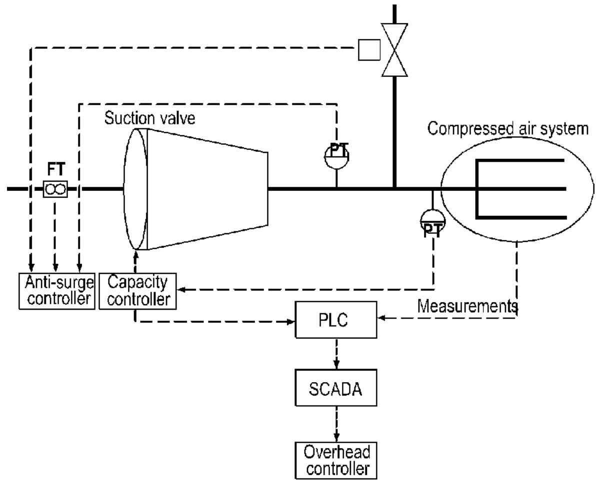


Figure 7: Automated compressor setup

Figure 8 shows the measured power profiles during a 24-hour workday. Compressor cycling is kept to a minimum due to effective modulation of inlet air (via control of throttle valves and inlet guide vanes). Some compressors are placed in an off-load condition instead of stopping and then restarting the compressors (see explanatory text boxes in Figure 8), as had previously been the case. This new control strategy therefore facilitates lower maintenance compared to the previous (manually-controlled) situation.

Figure 9 shows the measured power consumption using the new automatic control system. When compared with the power profile when the system operates under manual control (cf. Figure 1), the large power savings are apparent.

Figure 10 shows the new pressure profile as a result of automated compressor selection (or cascading) combined with capacity control (by actively controlling throttle valves, inlet guide vanes and blow-off valves) of individual compressors. The set-

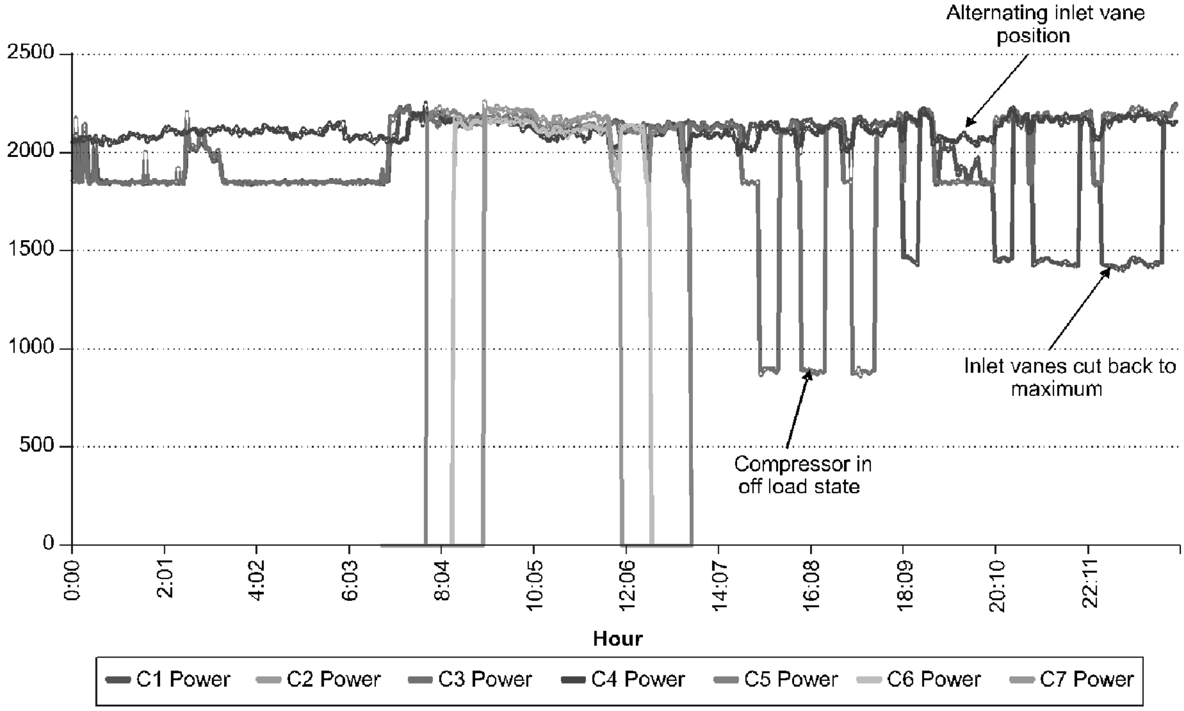


Figure 8: Individual compressor power curves illustrating computerized compressor control strategy

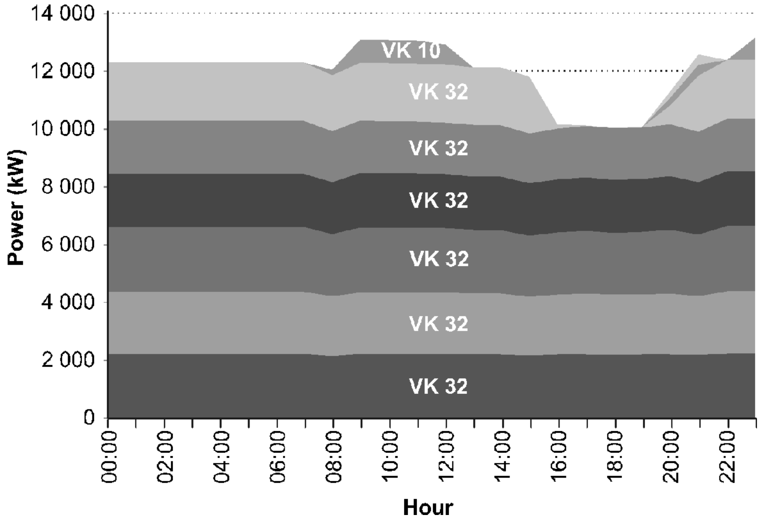


Figure 9: Measured compressor electrical power with new automatic control strategy, showing improved workday compressor operation (when compared to manual control set-up in Figure 1)

point of 520 kPa is well regulated with an acceptable pressure drop during the peak drilling period (07:00 – 10:00).

Figure 11 shows how the required airflow was obtained by cascading of compressors. Base load compressors worked throughout the day, whilst a combination of trimming compressors was employed during the peak drilling period. Compressors were activated based not only on their flow capability, but also on their mechanical efficiencies, downtime since last stop, total number of running hours since last maintenance, and the location of the specific compressor. An optimal compressor combination would of course result in effective pressure control and low maintenance, as well as savings inherent in both.

Figure 12 shows the electrical power profiles with and without the automated control strategy. The automatic control strategy realises a saving of 1.25 MW during Eskom's evening peak demand window. This saving was generated on a baseline of 7.22 MW, which represents a reduction of 17.3% in electrical power consumption during the evening peak period. The annual electricity cost saving by

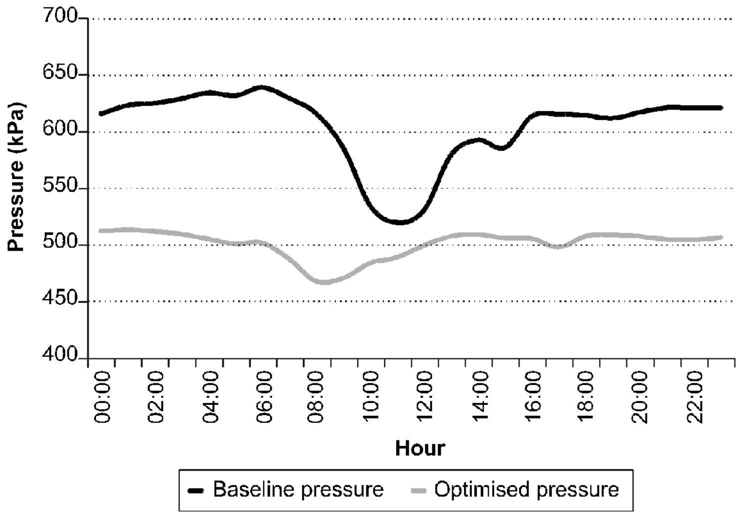


Figure 10: Measured pressure profile of optimized compressor control system vs initial (baseline) pressure profile

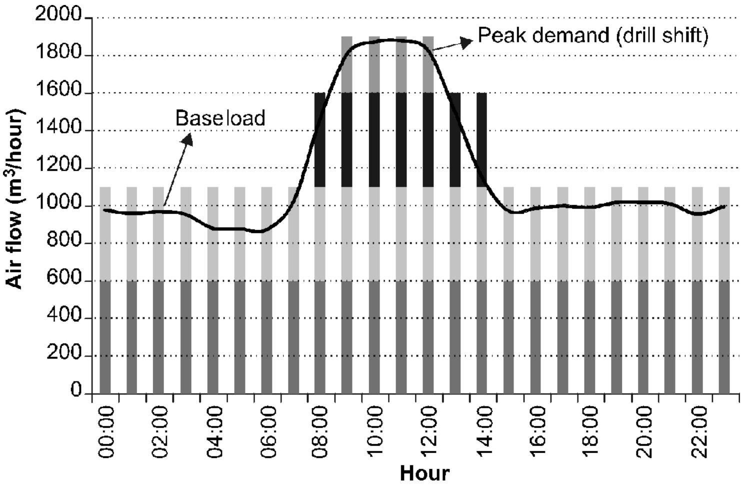


Figure 11: Measured air flow demand, superimposed on compressor sequencing strategy

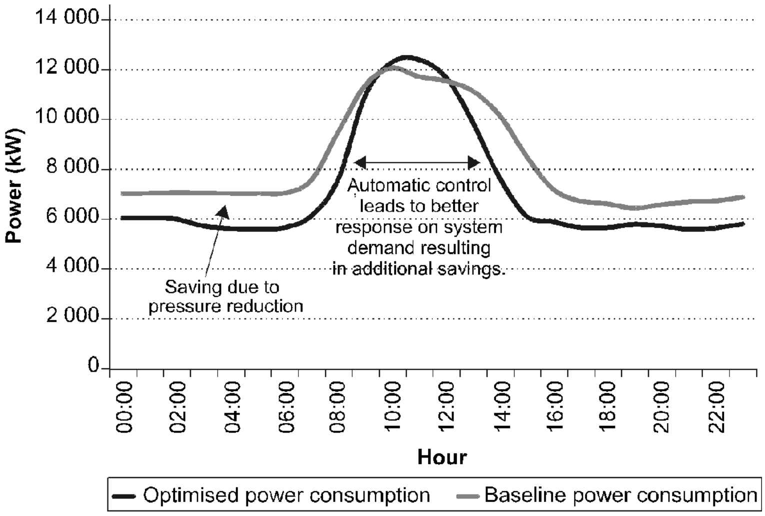


Figure 12: Measured electrical power profile of compressed-air system with automatic control, versus base-line power profile (i.e., compressed-air system with manual control)

means of optimised compressor control at this mine is an estimated R2.9 million (Eskom, 2010).

6. Conclusion

Compressed-air systems at South African mines have significant potential for electrical demand-side management (DSM). The system compressors typically feature unsophisticated and manually-operated control systems that control air pressure to peak levels. This represents significant wastage as peak conditions are experienced for only about the quarter of a typical workday.

The implementation of automatic control systems on these compressed-air systems has large electricity savings potential. The objective of an effective automatic compressor system control strategy is to match system demand with compressors' supply, while operating at or near their maximum efficiency levels. This can be done by retrofitting an existing mine compressed-air system with an overhead (computer) controller, interfacing with a conventional supervisory control and data acquisition (SCADA) system and programmable logic controllers (PLC's).

Such control systems can provide effective air supply by sequencing compressors in a cascade format, so as to meet the air demand as closely as possible. This implies that all compressors will only be activated for a limited period during the day, usually corresponding with the drilling period in a gold mine.

To ensure minimal start/stop cycling of such system compressors, it is essential to also employ pressure bandwidth control. This can be done by modulating inlet air to the compressors, by appropriately activating throttle valves, inlet guide vanes, and blow-off valves, when required. This results in fewer and smaller system pressure fluctuations, and hence, fewer compressor starts and stops, less compressor breakdowns, and an associated reduction in maintenance costs.

References

Ashok, S., and Banerjee, R., (1995). Load management – the role of the power utility. *Pattern Recognition*, 28(10): 1493-1497.

Aegerter, R., (1999). Compressed-air system optimization. *Proceedings of the 21st National Industrial Energy Technology Conference*, Houston, TX, May 12-13.

Auffhammer, M., Blumstein, C., and Fowlie, M., (2007). *Demand-side management and energy efficiency revisited.* Centre for the Study of Energy Markets, University of California Energy Institute, CSEM WP 165r, April.

Bloch, H., (2006). *A practical guide to compressor technology.* New York: Wiley-Interscience.

CAC, (2002). Compressed Air Challenge: Guidelines for selecting a compressed air system service provider and levels of analysis of compressed air systems. Available at www.compressedairchallenge.org (accessed 18 Nov. 2011).

CEA, (2007). Guide book: Compressed-air energy efficiency reference guide book. Canada: CEA Technologies.

Christina, G., and Worrell, E., (2005). Energy efficiency improvement and cost saving opportunities for the vehicle assembly industry. LBNL-50939.

Cohen, H., Rogers, G.F.C., and Saravanamuttoo, H.I.H., (1987). Gas turbine theory (3rd edition). Longman Scientific & Technical, London.

D'Antonio, M., Epstein, G., Moray, S., Schmidt, C., (2005). Compressed-air load reduction approaches and innovations. *Proceedings of the 27th Industrial Energy Pechnology Conference,* New Orleans, LA, May 10-13.

Da La Vergne, J.N., (2003). *Hard Rock Miner's Handbook*, 3rd ed. Ontario: McIntosh Engineering, p. 181.

DeWitte, M, and Boesmans, B., (2009). Activity Report: From innovation to operational assistance. Laborelec. www.laborelec.be/pages_files/AR2009.pdf (accessed 14 March 2011).

Eskom, (2009). The Energy Efficiency Series: Towards and energy efficient mining sector. Available from www.eskom.co.za/dsm (Accessed March 2011).

Eskom, (2010). Mega Flex tariffs, www.eskom.co.za/live/content.php?Category_ID=287 (Accessed June 2010).

Eskom, (2009). How are DSM initiatives costed? www.eskom.co.za (Accessed May 2010).

Fawkes, H., (2005). Energy efficiency in South African industry. *Journal of Energy in South Africa*, 16(4): 18-25.

Fink, D.A., Cumpsty, N.A., and Greitzer, E.M., (1992). Surge dynamics in a free-spool centrifugal compressor. *ASME J. Turbomachinery,* 114(2): 321-332.

Gellings, C.W., and Parmenter, K.E., (2007). Distributed generation and demand-side management. In: *Handbook of Energy Efficiency and Demand-Side Management* (eds. F. Kreith, D. Y. Goswami), New York: CRC Press, pp. 5.33-5.53.

Gillingham, K., Newell, R., and Palmer, K., (2006). Energy efficiency policies: a retrospective examination. *Annu. Rev. Environ. Resour.*, 31: 161-192.

Gomes, A., Martins-Gomes, A., and Figueiredo, R., (1999). Simulation-based assessment of electric load management programs. I*nt. J. Energy Res*., 23: 169-181.

Greitzer, E. M., (1976 a). Surge and Rotating Stall in Axial Flow Compressors, Part I: Theoretical Compression System Model, J. Engineering for Power, (98): 190-198.

Greitzer, E. M., (1976 b). Surge and Rotating Stall in Axial Flow Compressors, Part II: Experimental Results and Comparison with Theory, *J. Engineering for Power,* (98): 199-217.

Hartman, H.L., Mutmansky, J.M., Ramani, R.V., and Wang, Y.J., (1997). *Mine Ventilation and Air Conditioning,* 3rd edition. New York: Wiley.

Hughes, A., Howells, M.I., Trikam, A., Kenny, A.R., and Van Es, D., (2006). A Study of Demand Side Management Potential in South African Industries. Proceedings of the Industrial and Commercial Use of

Energy conference, Cape Town.

Joubert, R., and Liebenberg, L., (2010). Cost- and time efficient DSM on mine compressed-air systems. Proceedings of the Industrial and Commercial Use of Energy conference, Cape Town.

Kaya, D, Phelan, P., Chau, D., and Sarac, H.I., (2002). Energy conservation in compressed-air systems. *International Journal of Energy Research,* 26: 837-49.

Kocsis, C.K., Hall, R., and Hardcastle, S.G., (2003). The integration of mine simulation and ventilation simulation to develop a 'Life Cycle' mine ventilation system. Application of Computers and Operations Research in the Minerals Industries, South African Institute of Mining and Metallurgy, pp. 223-230.

Koski, M.A., (2002). Compressed-air energy audit, the real story. *Energy Engineering,* 99(3): 59-70.

Neser, H., Pelzer, R., and Kleingeld, M., (2008). Energy savings through the automatic control of underground air demand. Proceedings: Industrial and Commercial Use of Energy, Cape Town.

Nillson, H., (1994). The many faces of demand-side management. *Power Engineering Journal,* 8(5): 211-217.

NPCI, (2006). Electrical Energy Equipment: Compressors and compressed-air systems. Energy Efficiency Guide for Industry in Asia. National Productivity Council of India, p. 2.

Paulus, M., and Borggrefe, F., (2010). The potential of demand-side management in energy-intensive industries for electricity markets in Germany. *Applied Energy,* 88(2):432-441.

Pelzer, R., Mathews, E.H., Le Roux, D.F., and Kleingeld, M., (2008). A new approach to ensure successful implementation of sustainable demand-side management (DSM) in South African mines. *Energy,* 33(8): 1254-1263.

Popp, D., Newell, R.G., and Jaffe, A.B., (2009). Energy, the environment, and technological change. NBER Working Paper No. 14832, National Bureau of Economic Research, Cambridge, MA, April.

Radgen, P. (ed.), (2003). Druckluft Effizient: 'Compressed-air Facts', Fraunhofer ISI, available from www.druckluft-effizient.de (accessed 20 March 2011), Oct.

Redford, S.J., (1994). The rationale for demand-side management. *Power Engineering Journal,* 8(5): 211-217.

Risi, J.D., (1995). Energy Savings with Compressed-air. *Energy Engineering,* 92(6): 49-58.

Saidur, R., Rahim, N.A., and Hasanuzzaman, M., (2010). A review on compressed-air energy use and energy savings. *Renewable and Sustainable Energy Reviews,* 14: 1135-1153.

Schmidt, C., and Kissock, K., (2005). Modelling and Simulation of Air Compressor Energy Use. *American Council for an Energy Efficient Economy (ACEEE) Conference,* West Point, NY. Available from www.aceee.org/proceedings-paper/ss05/panel01/paper13 (accessed 15 March 2011).

Sioshansi, F.P., (2000). Demand-side management: the third wave. *Energy Policy,* 23(2): 111-114.

Strbac, G., (2008). Demand-side management: benefits and challenges. *Energy Policy,* 36(12): 4419-4426.

USDoE, (2003). Improving Compressed-air System Performance, a sourcebook for industry. US Department of Energy, Energy Efficiency and Renewable Energy, Washington, D.C., Nov.

USDoE, (2004). Energy Tips—Compressed-air, Tip Sheet #1, 'Determine the cost of compressed-air for your plant. US Department of Energy, Energy Efficiency and Renewable Energy, Washington, D.C.

Winkler, H. (ed.), (2006). Energy policies for sustainable development in South Africa; options for the future. Energy Research Centre, University of Cape Town, April.

Winkler, H., Howells, M., and Baumert, K., (2007). Sustainable development policies and measures: institutional issues and electrical efficiency in South Africa. *Climate Policy,* 7(3): 212–229.

Witrant, E., *et al.,* (2010). Wireless ventilation control for large-scale systems: the mining industrial case. *Int. J. Robust Nonlinear Control,* 20: 226-251.

Received 4 April 2011; revised 25 November 2011