Reducing the electricity cost of a Three-Pipe Water Pumping System – a case study using software

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Abstract

Efficient control is often the most cost-effective option to improve on the running cost of a Three-Pipe Water Pumping System. However, the effect of changing the control strategy (i.e. on energy consumption) is usually difficult to predict. A new simulation tool, QUICKcontrol, was used to investigate the energy cost savings potential in a Three-Pipe Water Pumping System. The influence of pump scheduling, dam level set points, control parameters and different combinations thereof were investigated. The simulation models were firstly verified with measurements obtained from the existing system to confirm their accuracy for realistic control retrofit simulations. With the aid of the integrated simulation tool, it was possible to predict savings of R195 000 per year with an average 3.8 MW of load shifted out of peak times. These control strategies can be implemented in the pumping system with a direct payback period of less than 6 months.

Keywords: energy simulation; simulation software; energy cost saving; electrical load shifting

1 Introduction

The objective of this project was to reduce the electricity running costs of a Three-Pipe Water Pumping System installed at a South African gold mine with the use of a software system. This software system had to be able to carry out an optimisation of the system components by means of a simulation model of those components.

The project was a part of Eskom's Demand Side Management (DSM) Programme. This programme seeks to encourage clients to shift load out of peak periods, and thus free up some capacity in the national grid, by Eskom paying the full cost of such projects (www.EskomDSM.co.za.).

The DSM programme is supported by a specific Tariff Policy, (called Real Time Pricing) which charges clients for electricity as near as possible to the costs of generation. Under this tariff policy the cost of a unit of electricity during peak times can be as high as eight times that of the lowest off-peak cost (www.Eskom.co.za/Urban Tariffs/Megaflex/). By moving load out of peak times, a client can avoid these high costs and thus effect a substantial saving on their electricity account.

Since the South African mining industry consumes approximately 23% of all electrical power generated in the country (Eskom DSM 2003), and since up to 11% of the electricity cost on a mine can go to the pumping of water, this is a valid area for attention for energy efficiency interventions. Others have shown that the operation costs of a deep mine could be improved if the water pumping systems were made more energy efficient (De Ruiter 1992). This study uses the DSM programme of shifting load to effect energy cost savings.

2 Three Chamber Pipe Feeder System

A Three Chamber Pipe Feeder System (3CPFS) is widely used in the mining industry to circulate water from the mine surface (ground-level) to designated points inside the mine itself. The water is mostly used for the cooling of air. The water is cooled on the surface and then channelled down into the mine. After use, the water has to be pumped out of the mine again.

This system is so popular because it uses little electrical energy to achieve this cycling (Butterworth 2001). In principle, a 3CPFS extracts potential energy from water going down into the mine and uses this energy to pump used water out of the mine.

The mathematical model for the 3CPFS was built to simulate its overall working. It was not the focus of this study to go into an in-depth investigation of the valves and flow dynamics that govern the internal working of a 3CPFS itself. This was therefore not coded into the mathematical model.

An explanation on how a 3CPFS works is given with the aid of Figures 1 and 2, which are schematic representations of a 3CPFS installed in a typical mine situation.

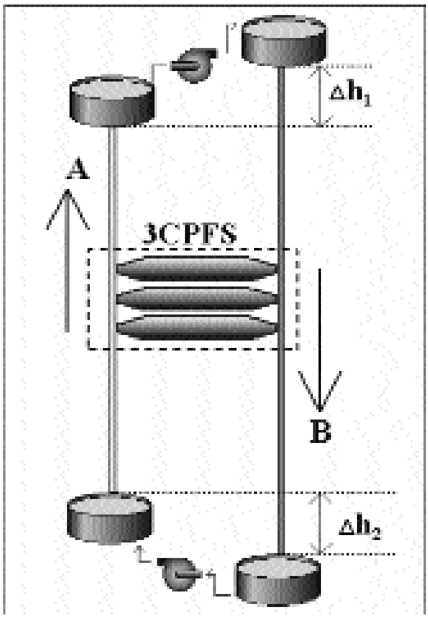

Figure 1: Energy principles of a 3 Chamber Pipe Feeder System (3CPFS)

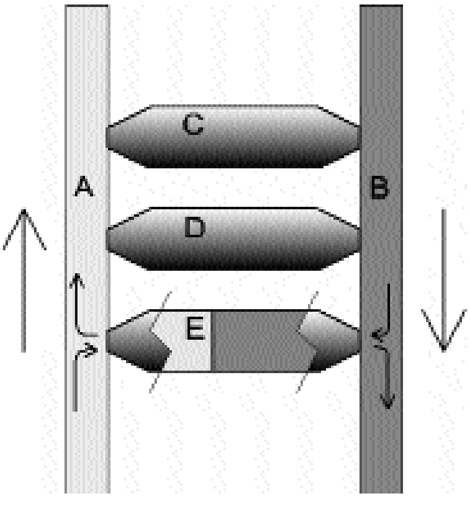

Figure 2: Schematic representation of a 3CPFS

Column B is cold water being channelled down into the mine where it is will be used for cooling, drilling, etc. Column A is hot, used water being pumped out of the mine where it will be cleaned and re-cooled. The 3CPFS uses potential energy derived from the water in column B to pump the water in column A. This energy is obtained from Δh_1 and Δh_2 and powers the 3CPFS.

The energy that is necessary to produce Δh_1 and Δh_2 can be described by

$$E_p = mgh \qquad (1)$$

where: E_p – potential energy,
m – mass,
g – gravitational constant,
h – height.

In a typical mine, Δh_1 is created by pumping the water that is to be channelled down into the mine, into a reservoir several meters above the ground. The water coming out of the mine goes into a dam built at ground level. Δh_2 is obtained by letting the water in column B flow to the bottom of the mine. The dam out of which water is pumped is deeper than this.

The 3CPFS can be seen as a closed energy system. The energy going into the system is obtained through Δh_1 and Δh_2 as explained above. The energy is consumed inside the system by overcoming the flow losses and kinetic and potential energy that end up in the water itself.

This is described by the equation

$$E_{in} = E_{out} \qquad (2)$$

where: E_{in} – energy going into the system,
E_{out} – energy going out of the system.

Equation (2) can therefore be expanded to

$$mg(\Delta h_1 + \Delta h_1) = E_{hf} + E_k \qquad (3)$$

where: E_{hf} – head/flow loss as result of flow,
E_k – kinetic energy that ends up in the water.

The kinetic energy in the water can be described by

$$E_k = \tfrac{1}{2}mv^2 \qquad (4)$$

where: m – mass,
v – speed.

The head loss is a result of friction during flow. The head loss in the piping and in and around the valves, elbows, links, etc. is calculated using the Hazen-Williams head loss equations (LMNO 2000).

$$h_f = SL \qquad (5)$$

where: h_f – head loss,
L – length,
S – head loss / length of pipe.

S is calculated

$$S = \left(\frac{v}{kCR_h^{0.63}} \right)^{\frac{1}{0.54}} \tag{6}$$

where: k = Minor loss coefficient,
C = table of Hazen-Williams coefficients,
R_h = hydraulic radius.

R_h is specific to the shape of the ducting. R_h for circular tubing can be calculated as

$$R_h = \frac{D}{4} \tag{7}$$

where: D – inside diameter of the tubing.

The values for k and C can be obtained from the Hazen-Williams Coefficient tables.

The 3CPFS consists of three chambers, marked C, D and E, which link column A and B. During the pumping process, these three chambers go through the same cycle, but in sequential phases.

For clarity, a section cut has been made into the chamber marked E. The cycle that each chamber goes through is as follows. Let's assume the chamber is filled with used hot water. The first stage of the cycle will be when valves open in such a way that cold unused water can flow, because of Δh_1, out of column B into this chamber. This cold unused water will then push the hot used water up into column A.

The chamber is now filled with cold water. The second stage will be when certain valves open in such way that this cold water is pulled, due to Δh_2, further down into column B. This will result is used hot water being sucked out of column A into the chamber. After this phase the chamber is again filled with used hot water and the cycle is completed, ready to start all over again.

There is no physical separation between the used and un-used water in the chambers, but there is a huge amount of water being pumped compared to the amount of mixing. The mixing is tolerated because this system can pump water out of the mine without using any electricity.

However, there are many problems associated with this system. Experience has shown that the biggest problem is the maintenance of the valves that govern the flow inside the 3CPFS. These valves undergo extreme stresses when opening and closing. This hammering on the valves can cause substantial downtime of the system, which can be costly and time consuming.

The simulation model of the systems creates the opportunity to build an optimisation engine. The heart of the optimisation engine is the system simulation upon which a component scheduler is built. The output of the component scheduler is an operation schedule for every controllable component in the system.

3 Tshepong – a case study

The Three-Pipe Water Pumping System upon which this case study was conducted is situated at the Harmony Mine, Tshepong, near Welkom in South Africa. The case study was conducted during August and September 2004.

The Three-Pipe Water Pumping System is responsible for delivering all the used water in the mine to the surface. This water is then cooled and again channelled down into the mine where it is used to cool air, prevent dust etc. From there it is collected and again fed into the Hot Water Pumping System, thus, completing the water cycle. (see Figure 3).

The Three-Pipe Water Pumping System starts with the dams '66 Hot dam 1' to '66 Hot dam 6'. All the used water in the mine is channelled to these dams where it is to be delivered to the surface for re-cooling and cleaning. The pumps labelled '66-1' to '66-7' pump the water out of these dams to the next two dams in the system labelled '45 Hot dam 1' and '45 Hot dam 2'.

From there, the water is pumped via the pumps '45-1' to '45-3' and the 3CPFS labelled '3CPFS' to a dam on the surface labelled 'Pre-Cool dam 1'. This is where the Three-Pipe Water Pumping System ends. From these the water is re-cooled, cleaned and channelled down the mine again.

This entire system is situated underground. The dams '66 Hot dam 1' to '66 Hot dam 6' are set on 66-level, a level 6600 feet under ground. Dams '45 Hot dam 1' and '45 Hot dam 2' are situated on 44-level, 4400 feet under ground.

The Three-Pipe Water Pumping System is responsible for delivering 30 240 m^3 water out of the mine every day. The pumps on 66-level, which are pumps '66-1' to '66-7', are 1500 kW pumps each, capable of delivering 120 l/sec each. The pumps on 45 level, which are pumps '45-1', '45-2', and '45-3' are 2500 kW pumps each, capable of delivering 120 l/sec each.

The simulation tool QUICKcontrol, was used to perform the required simulations (Mathews et al 1999). In order to verify the simulation, it was run for a couple of days where the simulation status was synchronised with the real-word status at the beginning of each day.

Figure 4 shows the actual and simulated levels of one of the dams in the circuit. (the correspondence between the actual and simulated levels of the other dams were very much the same and are not reproduced here to avoid duplication.) These figures give results for a 24-hour period and show that, on average, a less than 3.5% deviation accumulated in a 24-hour time period. This gives an indication of the accuracy of the simulation.

It is important to point out here that load shift

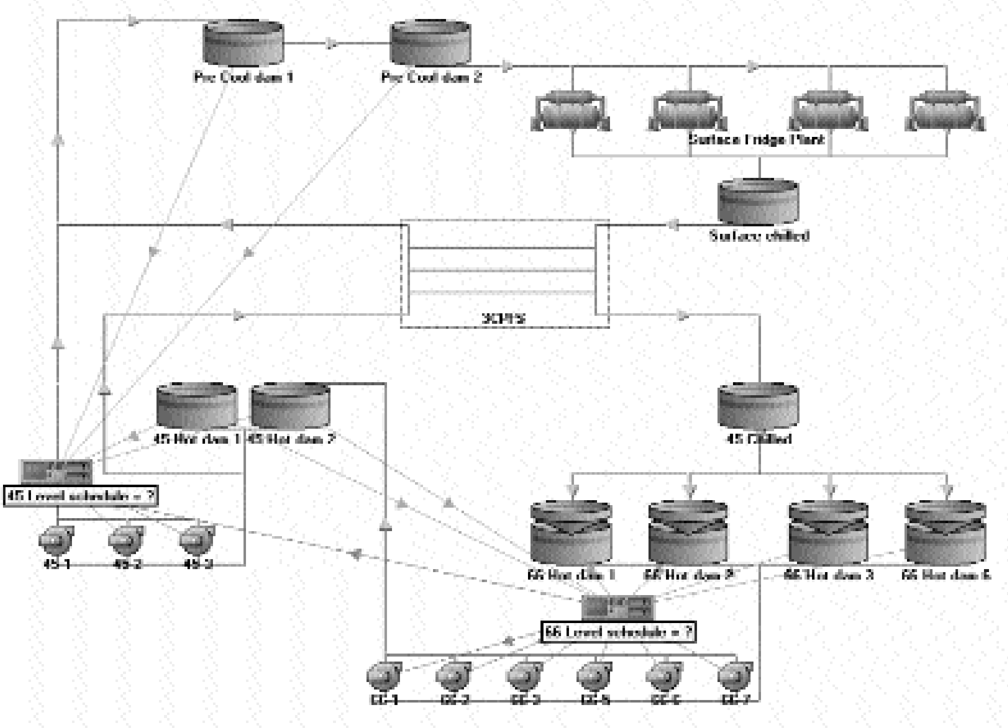

Figure 3: Tshepong water cycle

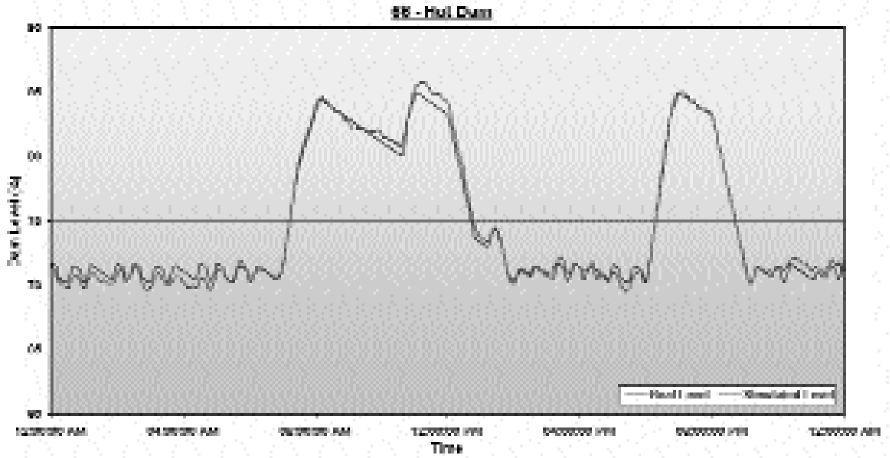

Figure 4: Simulation and verification of the model

can only be achieved if there is adequate storage capacity for the water during peak periods. This was indeed the case at Tshepong, where the 66 level hot water dams were large enough to accommodate all the water flowing into the dam during the peak period when pumps are switched off.

No other operational parameters of the mine are affected by shifting load in the hot water pumping system. The water-flow used for cooling the workings continues exactly as operational schedules demand (with or without load shift). There is also no net energy *consumption* saving, since the same amount of energy required to pump the water remains unchanged. The only factor that generates energy *cost* savings is the fact that water is now pumped mainly during off-peak hours, and not during the peak demand (high tariff) hours.

4 Calculating the energy savings

4.1 Calculation of the base line

In order to be able to calculate any savings or load shift of the new system after implementation, it was first necessary to determine the existing electricity usage base line of the pumping system before the control was implemented.

This base line is a 24-hour profile that describes the electricity usage for the 24 hours of the day. Each value gives the accumulated kW electricity used for that specific hour that was consumed by a system.

In this case study, three different base lines were required, of which the first was base line A. This was the base line for the system when the 3CPFS was *fully operational* on a 24-hour basis. The 3CPFS carried a part of the workload, but without using any electricity.

The second was base line B. This was the base line for the system when the 3CPFS was *not* operational. The electrical pumps were therefore solely responsible for carrying the full workload. Two pumps in the 45-level pump station must be started to compensate for the workload that the 3CPFS usually carries.

The pumps on 45-level are 2500 kW each. Base line B must therefore be altered with 5000 kW as this is the extra amount of energy needed to compensate for the 3CPFS not working.

The third base line was base line C. This was a base line for the system when the 3CPFS was operational for only a section or sections of the day. This base line is comprised of sections of base line A and base line B, depending on whether the 3CPFS was working or not.

Figure 5 shows base lines A and B and an example of base line C. This figure would be valid for a day when the 3CPFS is not operational between the hours 4:00 am to 6:00 am and 1:00 pm to 4:00 pm.

During the case study base line C was inevitably used, as there were only few days during which the 3CPFS was either fully operational or totally out of order. As the 3CPFS experiences significant down time as a result of maintenance, the operation of the 3CPFS was therefore carefully logged to make the calculation of every day's base line possible.

4.2 Electrical cost savings

To calculate the running electricity cost savings that were realised on a specific day as a result of the software control, two things are needed. The first is the cost of electricity that would have been consumed as a result of the base line profile for that specific day. This can be obtained by multiplying the base line with the variable electricity tariff. The result of this is a 24-hour cost profile. Adding these 24 values gives the total electricity cost for that day.

The second is the electricity cost as a result of the new electricity usage profile for that specific day. This is calculated in the same way as described above, except that the real electricity usage profile is used instead of the base line. The savings realised per day is then calculated by subtracting the electricity cost related to the real electricity profile from the electricity cost related to the base line.

4.3 Electrical load shifting

To calculate the load that was shifted for a specific day as a result of the software control, the base line and the actual electricity consumption for that specific day is needed.

The peak demand period, as specified by Eskom, is between 6:00 pm and 8:00 pm. The aim is therefore to shift load out of this period.

The 'electricity usage' line on Figures 6 and 7 gives the accumulated electricity that was consumed during the relevant hours. For example, the value on this line corresponding to the 6:00 pm mark, is the total electricity used during the hour from 6:00 pm to 7:00 pm.

The load that was shifted during a particular hour can be calculated by subtracting the actual electricity consumption from the base line value for that hour. The Load shifted for that day will be the average between of the values for the two hours in which load can be shifted.

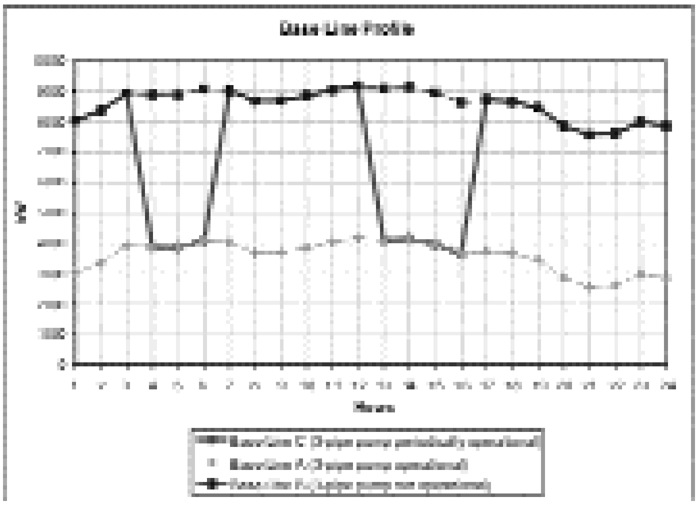

Figure 5: Baselines A, B and C

5 Results

A new electricity usage profile was drawn up during the period when the Three-Pipe Water Pumping System was controlled using the software as described. As with the base line profile, this current usage profile was drawn up using empirical measurements.

Figure 6 shows the average results achieved for the month of August, 2004. It can be seen that the electricity usage dropped below the base line during the periods when the electricity tariff was the highest.

The total savings realised during August was approximately R42 200.00. The average saving was R1 425.75 per day.

It is also clear that the average electricity consumption is below the base line during peak hours. This resulted in an average of 3.9 MW load shifting per day.

Figure 7 shows the average results for September 2004.

The total savings realised in September were R7 150. This relates to an average savings of R238.10 per day. Since September falls under the summer period of the MegaFlex pricing structure (which is more lenient, since peak demand in summer is not such a big problem for Eskom), the savings in September are far less than during August (winter). However, the load shifted on average was still significant at a calculated 3.4 MW per day.

There are three winter and nine summer months in the MegaFlex pricing structure. The predicted

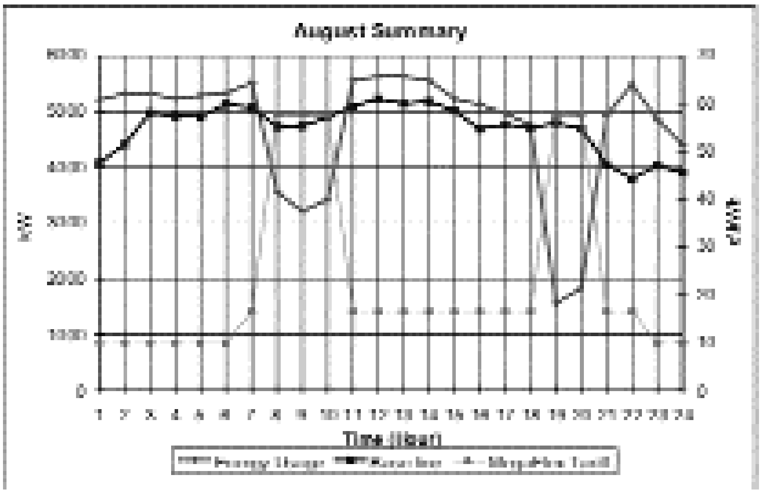

Figure 6: Summary results for August 2004

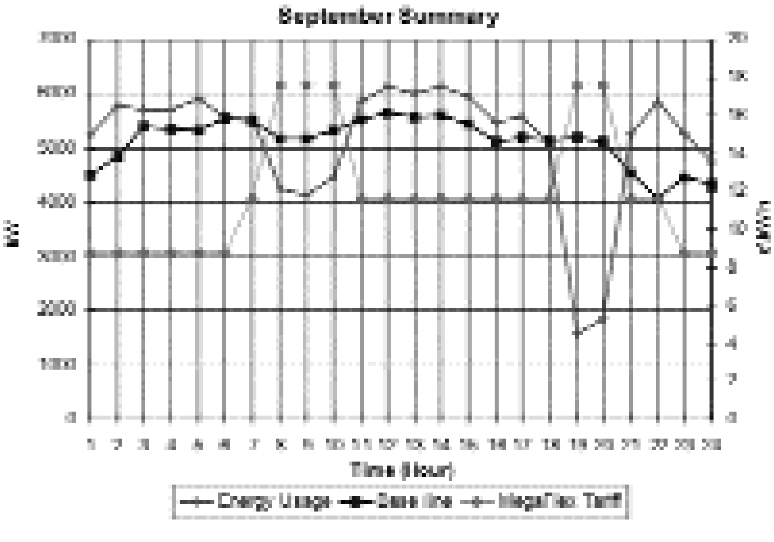

Figure 7: Summary results for September 2004

savings for one year is approximately R195 000.00. Since the study has not yet run for a full year, this prediction cannot yet be verified. A predicted 3.8 MW can be shifted on average each month.

6 Conclusion and recommendations

A study was conducted to determine the realistic retrofit energy cost savings of the water pumping system of Tshepong Mine. This study showed satisfactory results for the use of the simulation model. It is estimated that the proposed control strategies will incur electricity cost savings in the order of R 195 000 per year.

Recommendations for further study in this field are firstly to conduct an investigation on how to increase the availability of the 3CPFS. The downtime of this system has a detrimental effect on the saving and load shifting capacity. It will therefore have a financial impact if the availability of the 3CPFS can be improved.

Secondly, it is suggested that a database system be incorporated into the software. The loggings of all statuses and flows into this database would improve the investigations that can be conducted on the control system. The software can be engineered to automatically calculate savings and load shift figures from this data.

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