A variable water flow strategy for energy savings in large cooling systems

Volume 1: Thesis monograph

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Abstract

Large cooling systems consume up to 25% of the total electricity used on deep level mines. These systems are integrated with the water reticulation system to provide chilled service water and cool ventilation air. Improving the energy efficiency of these large cooling systems is an important electrical demand-side management initiative. However, it is critical that the service delivery and system performance be maintained so as to not adversely affect productivity.

A novel demand-side management strategy, based on variable water flow, was developed to improve the energy efficiency of large cooling systems like those found on deep mines. The strategy focuses on matching the cooling system supply to the demand through the use of modern energy efficient equipment, such as variable speed drives. The strategy involves the modulation of evaporator, condenser, bulk air cooler and pre-cooling water according to partial load conditions.

A unique central energy management system was developed to integrate the proposed strategies on large cooling systems. The system features a generic platform and hierarchical network architecture. Real-time energy management is achieved through monitoring, optimally controlling and reporting on the developed strategy. The system is robust and versatile and can be applied to various large cooling systems.

The feasibility of the strategy and energy management system was first investigated through the use of an adapted and verified simulation model and a techno-economic analysis. The strategy was then implemented on four large mine cooling systems and its *in situ* performance was assessed as experimental validation. The results of the Kusasalethu surface cooling system are discussed in detail as a primary case study while the results of the Kopanang, South Deep South Shaft and South Deep Twin Shaft cooling systems are summarised as secondary case studies. The potential to extend the variable water flow strategy to other industrial cooling systems is assessed through an investigation on the cooling system of the Saldanha Steel plant.

Results indicate that, over a period of three months, average electrical load savings of 606-2 609 kW (29.3-35.4%) are realised on the four systems with payback periods of 5-17 months. The average electrical load saving between the sites is 33.3% at an average payback period of 10 months. The service delivery and performance of the cooling system and its critical subsystems are not adversely affected. The potential to extend the method to other large cooling systems is also shown. The developed variable water flow strategy is shown to improve the energy efficiency of large cooling systems, making a valuable contribution towards a more sustainable future.

This thesis is presented as a detailed discussion of the entire research process. The key results have also been summarised in a series of five research articles attached as independent annexures. Three articles have been published in international scientific journals, one has been presented at and published in the proceedings of an international conference and one is still under review.

Keywords

Energy efficiency; energy management; electrical demand-side management; large cooling systems; variable water flow

Samevatting

By diep myne dra groot verkoelingstelsels tot 25% van die totale elektrisiteitsverbruik by. Die verkoelingstelsels is met die waterverdelingstelsel geïntegreer om aan die myn koue water en lug vir ventilasie te verskaf. Die verbetering van die energiedoeltreffendheid van hierdie groot verkoelingstelsels is ’n belangrike vraagkant-bestuursinisiatief. Dit is egter krities dat die dienslewering van die stelsel behoue bly sodat produktiwiteit nie geraak word nie.

’n Nuwe vraagkant-bestuurstrategie, gebaseer op veranderlike watervloei, is ontwikkel om die energiedoeltreffendheid van groot verkoelingstelsels, soos die wat op diep myne gevind word, te verbeter. Die strategie fokus daarop om die verskaffing van koue water by die aanvraag aan te pas deur middel van energiedoeltreffende tegnologie, soos veranderlike spoed motors. Dié strategie behels die modulasie van watervloei deur die verdamper, kondensator, grootmaatlugverkoeler en voorafverkoelde stelsels, soos deur gedeeltelike beladingstoestande bepaal.

’n Unieke, sentrale energiebestuurstelsel is ontwikkel om die strategie op groot verkoelingstelsels te integreer. Die stelsel behels ’n generiese platvorm en hiërargiese netwerkargitektuur. Intydse energiebestuur word deur die kontrolering, optimale beheer en verslaglewering van die strategie bewerkstellig. Die stelsel is robuus en veelsydig en kan op verskeie groot verkoelingstelsels toegepas word.

Die lewensvatbaarheid van die strategie en energiebestuurstelsel is eerstens deur die gebruik van ’n aangepaste simulasiemodel en ’n tegno-ekonomiese analise ondersoek. Daarna is die strategie op vier groot mynverkoelingstelsels geïmplementeer en die *in situ* resultate as eksperimentele geldigheidsbepaling ontleed. Die resultate van die Kusasalethu-verkoelingstelsel is as ’n primêre gevallestudie gebruik terwyl die resultate van die Kopanang-, South Deep South Shaft- en South Deep Twin Shaft-stelsels as sekondêre gevallestudies opgesom is. Die potensiaal om die strategie na ander industriële verkoelingstelsels uit te brei is deur middel van ’n ondersoek op die verkoelingstelsel van die Saldanha Steel-aanleg bepaal.

Resultate oor ’n tydperk van drie maande toon gemiddelde verminderinge van 606-2 609 kW (29.3-35.4%) in stelselelektrisiteitsverbruik vir die vier gevallestudies asook gemiddelde terugbetaalperiodes van 5-17 maande. The gemiddelde vermindering in stelselelektrisiteitsverbruik tussen die gevallestudies is 33.3% met ’n terugbetaalperiode van 10 maande. Die dienslewering en verrigting van die verkoelingstelsels is nie negatief beïnvloed nie. Die potensiaal om die strategie na ander groot verkoelingstelsels uit te brei is ook getoon. Daar is bewys dat die ontwikkelde veranderlike watervloeistrategie die energiedoeltreffendheid van groot verkoelingstelsels verbeter en dat dit ’n waardevolle bydrae tot ’n meer volhoubare toekoms kan lewer.

Hierdie tesis is as ’n gedetailleerde bespreking van die volledige navorsingsproses uiteengesit. Die deurslaggewende resultate is ook as ’n reeks van vyf navorsingsartikels opgesom en as onafhanklike bylae aangeheg. Drie artikels is reeds in internasionale wetenskaplike joernale gepubliseer, een is voorgelê by en gepubliseer in die verrigtinge van ’n internasionale konferensie en een word tans vir publikasie geëvalueer.

Sleutelwoorde

Energiebestuur; energiedoeltreffendheid; elektriese vraagkant-bestuur; groot verkoelingstelsels; veranderlike watervloei

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Preface

This thesis is presented as a complete monograph discussing the research done (Volume 1), as well as a summary of the key results in the form of a series of five research articles attached as annexures (Volume 2).

The details of the articles are as follows:

1. The use of variable speed drives for cost-effective energy savings in South African mine cooling systems
   - G.E. du Plessis, L. Liebenberg, E.H. Mathews
   - *Applied Energy 2013, 111, 16-27*
2. The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems
   - G.E. du Plessis, D.C. Arndt, E.H. Mathews
   - *Energy (under review)*
3. A versatile energy management system for large integrated cooling systems
   - G.E. du Plessis, L. Liebenberg, E.H. Mathews, J.N. du Plessis
   - *Energy Conversion and Management 2013, 66, 312-325*
4. Case study: The effects of a variable water flow energy saving strategy on a deep-mine cooling system
   - G.E. du Plessis, L. Liebenberg, E.H. Mathews
   - *Applied Energy 2013, 102, 700-709*
   - *Selected and featured in Renewable Energy Global Innovations 2013*
5. Improved energy efficiency of South African mine cooling systems
   - G.E. du Plessis, L. Liebenberg
   - *Presented at and published in the proceedings of the 5th International Conference on Applied Energy, 1-4 July 2013, Pretoria, South Africa*

The five articles have been written and are presented in such a way that they collectively encompass the entire scope of research work that was done. Table i provides an overview of the series of articles, summarising the key research objectives, methodologies and results in each case.

Table i Research articles overview

Article	Research objectives	Method	Main findings and conclusions
1. The use of variable speed drives for cost-effective energy savings in South African mine cooling systems	- To estimate the large-scale potential of variable speed drives (VSDs) on South African mine cooling systems - To identify the most important areas for VSD use - To validate the findings through a preliminary pilot case study	- Energy audit of 20 South African mine cooling systems - Calculation of estimated energy, cost and greenhouse gas emission savings - Implementation and results analysis of VSDs on the South Deep mine	- A total annual electrical energy saving of 32.2% (144 721 MWh) is estimated for the 20 mines - The most feasible VSD target areas are cooling system pumps and fans - Case study VSD implementation shows 29.9% saving
2. The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems	- To develop a variable water flow control strategy that enables energy savings through VSD implementation on mine cooling system pumps (as recommended by Article 1) - To simulate the developed strategy and validate the simulated results	- Strategies to control mine cooling evaporator, condenser and bulk air cooler water flow based on mine-specific cooling demands - Existing component-based simulation model adapted, verified and used to predict energy savings on the Kusasalethu mine	- An electrical energy saving of 33% is predicted by implementing the strategy at Kusasalethu - The simulation model predictions are shown to be accurate to within an average of 7%
3. A versatile energy management system for large integrated cooling systems	- To develop a robust and practical energy management system that integrates the control strategies developed in Article 2 - To experimentally evaluate the system by *in situ* application on four different mine cooling systems	- Real-time Energy Management System for Cooling Auxiliaries^{TM} developed as a hierarchical controller - Main features are to automatically control, optimise, monitor and report the variable-flow strategies - Implementation on four cooling systems	- System links to existing SCADA and writes out optimal set points to be controlled by PLCs in real-time - An average of 33.3% electrical energy saving is realised for the four different cooling systems - The average payback period is 10 months
4. Case study: The effects of a variable water flow energy saving strategy on a deep-mine cooling system	- To experimentally evaluate the effects of the strategy and energy management system described in Article 2 and Article 3 - To evaluate the energy savings as well as the effects on service delivery and system performance	- Strategy and energy management system implemented at Kusasalethu mine - Electrical energy savings measured - Changes in chilled water temperature, chilled water volumes, ventilation air conditions and coefficients of performance (COPs) evaluated	- An average electrical energy saving of 31.5% is realised for one month - Chilled water and ventilation air service delivery are maintained within acceptable limits - System performance and COPs are maintained within acceptable limits - Payback period of nine months
5. Improved energy efficiency of South African mine cooling systems	- To describe the improved energy efficiency through the newly developed variable-flow strategy and energy management system - To summarise the key findings of Article 1 to Article 4	- Large-scale energy audit and VSD potential investigation - Variable water flow strategy and simulation development - Energy management system development - Implementation on four cooling systems	- Pumps show best VSD potential - Strategy matches mine cooling supply with the demand - Energy management system integrates substrategies in real-time - Average energy efficiency improvement of 33.3% on all sites

The candidate is the lead author of all the presented articles. The various co-authors include Prof. L. Liebenberg, Prof. E.H. Mathews, Dr. D.C. Arndt and Mr. J.N. du Plessis. Permission to submit each respective article for degree purposes was obtained from all co-authors. Permission to submit the published articles was also obtained from the respective journal editors, namely Prof. J. Yan (Applied Energy) and Prof. M. Ahmad Al-Nimr (Energy Conversion and Management) through official Elsevier copyright license agreements (given in Annexures C.2 and D.2). Permission to submit the conference paper was also obtained (Annexure E.2).

The candidate's work is original and involved detailed literature studies, development of novel research contributions and compilation of articles. The candidate was responsible for making the original contributions in the complete energy audit, the development of the variable water flow strategies, the adaptation and application of the simulation model, the development of the new energy management system, the *in situ* implementation of the strategies, all data capturing and results analyses and discussions.

The series of articles is attached as an annexure with the specific journal editorial requirements and license agreement following each relevant article. The consolidating discussion of the articles is structured as an independent thesis monograph. However, some repetition of information summarised in the articles is unavoidable. This is supplemented by supporting detail and elucidating discussions where necessary. There is also a degree of repetition in the articles; this is as required for each to be considered independently in journals. However, they are integrated into the thesis to present a structured overarching discussion regarding the development of a variable water flow strategy for energy savings in large cooling systems.

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Nomenclature

%F	percentage of fuel used for electricity generation	(%)
A	flow admittance	(m^4)
Approach	approach of direct contact heat exchanger	(ºC)
ASC	annual service cost	(R)
C	average heat capacity rate	(W/ºC)
C	total implementation cost	(R)
CCE	cost of conserved energy	(R/MWh)
CS	total annual cost savings	(R)
c_p	specific heat at constant pressure	(J/kg.ºC)
e	control error	(-)
e_i	time-integrated control error	(-)
EC	energy consumption	(MWh)
EF	GHG emissions factor for fuel used	(kg/MWh)
ER	annual GHG emission reduction	(kg/year)
ES	energy savings	(MWh)
ESP	energy saving percentage	(%)
ET	electricity tariff	(R/MWh)
EXR	South African Rand/Euro exchange rate	(R/Euro)
f'	inflation rate	(%)
F	sample function	(-)
h	specific enthalpy	(J/kg)
IC	implementation cost	(R)
IRR	internal rate of return	(%)
k_d	derivative gain constant	(-)
k_i	integral gain constant	(-)
k_p	proportional gain constant	(-)
L	dam level	(%)
LF_c	cooling loading factor	(-)
LF_p	pump or fan power loading factor	(-)

$\dot{m}$	mass flow rate	(kg/s)
MARR	minimum attractive rate of return	(%)
NPV	net present value	(R)
o	control output	(-)
OH	operating hours	(h)
p	pressure	(Pa)
PBP	simple payback period	(years)
$PBP_{f'}$	inflation-adjusted payback period	(years)
PL	partial cooling load factor	(-)
$\dot{Q}$	heat transfer rate	(W)
RH	relative humidity	(%)
r	capacity ratio	(-)
Range	range of direct contact heat exchanger	(ºC)
T	temperature	(ºC)
UA	overall heat transfer coefficient $\times$ area	(W/ºC)
V	volume	(m^3)
$\dot{W}$	input electrical power	(W)

Abbreviations

AC	alternating current
ACHE	air-cooled heat exchanger
BAC	bulk air cooler
BEMS	building energy management system
COP	coefficient of performance
DC	direct current
DSM	demand-side management
ESCO	energy services company
FMCS	facility monitoring and control system
GHG	greenhouse gas
Global COP	coefficient of performance of combined cooling system
HMI	human-machine interface
HVAC	heating, ventilation and air-conditioning
IEA	International Energy Agency
IGBT	insulated gate bipolar transistor
L	mining level
NPSH	net positive suction head
OPC	object linking and embedding for process control
PC	personal computer
PID	proportional integral derivative
PLC	programmable logic controller
PWM	pulse width modulation
REMS-CA™	Real-time Energy Management System for Cooling Auxiliaries
RFI	radio frequency interference
SCADA	supervisory control and data acquisition system
THD	total harmonic distortion
VSD	variable speed drive

Greek symbols

Δ	change	(-)
δ	uncertainty	(-)
∂	derivative	(-)
η	efficiency	(-)
ρ	density	(kg/m^3)
τ	heat exchanger effectiveness	(-)
φ	water saturation enthalpy - water temperature ratio	(J/kg.ºC)
Σ	summation	(-)

Subscripts

a	air
actual	actual conditions
amb	ambient conditions
avg	average
c	condenser, compressor
chilled dam	chilled water dam conditions
cooling system	combined cooling system
daily avg	daily average
e	evaporator
f	fan
hot dam	hot water dam conditions
i	inlet
ideal	ideal conditions
loss	losses to ambient
o	outlet
p	pump
post-implementation	baseline measured after energy saving intervention
r	refrigerant
ref	reference design condition
sat	saturated water vapour
savings	savings realised by energy saving strategy
scaled baseline	baseline calculated by regression model
t	time
w	water
wb	wet-bulb