

A control system for the efficient operation of bulk air coolers on a mine

S van Jaarsveld
24887080

Dissertation submitted in fulfilment of the requirements for the
degree *Magister* in [Computer and Electronic Engineering](#) at the
Potchefstroom Campus of the North-West University

Supervisor: Dr R Pelzer

May 2015

ABSTRACT

Title: A control system for the efficient operation of bulk air coolers on a mine
Author: Mr. S van Jaarsveld
Supervisor: Dr. R Pelzer
Degree: Master of Engineering, Computer and Electronic
Keywords: Bulk Air Coolers, Control systems, Refrigeration systems, Ventilation and Cooling (VC)

Eskom provides 98% of South Africa's ever increasing electricity demand. The mining sector is a vital contributor to the economy, but also consumes vast amounts of electricity. This sector is responsible for almost 15% of the country's electricity usage.

Mines heavily depend on the supply of cold water and air. Refrigeration systems are therefore constantly operational and can account for 25% of a mine's electricity costs. The need therefore exists to investigate possible energy savings initiatives.

Refrigeration systems are typically used to lower the temperature of water and air. Bulk Air Coolers (BACs) are used to produce cold air. The aim of this study is to investigate possible electricity cost savings in a mine refrigeration system. This can be achieved by enabling equipment to dynamically adapt to changes in their environment. Electricity usage reduction has the greatest financial impact if it occurs during Eskom peak periods. Time-dependent schedules of operation are therefore used to achieve this objective.

Due to the lack of such a controller in the mining industry, the focus of this study is a BAC control system. A BAC controller would be able to follow guidelines that could lead to electricity cost savings. It was therefore developed and incorporated in the Real-time Energy Management System (REMS). The BAC controller combines various inputs and constraints to determine the output. An electricity usage reduction during the Eskom evening peak period was consequently achieved.

The BAC controller was implemented on three sites. Electrical energy usage during the evening peak period was reduced via the load shifting method. This aids Eskom in their effort to reduce the peak period demand. Air temperature and dam levels were closely monitored during the peak period. If any preset condition was violated, the load shifting was abandoned for that day.

It was shown that a total power reduction of 7 MW is possible between the three sites. The electricity savings occurred in the evening peak period. A calculation was made to determine the possible annual savings by using the achieved daily cost savings. The winter months were not included in the calculation. An annual cost saving of R1 166 694.41 is therefore possible without having to reduce output quantities.

OPSOMMING

Titel:	'n Beheerstelsel vir die effektiewe gebruik van grootmaat lugverkoelers op 'n myn
Outeur:	Mnr. S van Jaarsveld
Studieleier:	Dr. R Pelzer
Graad:	Meester van Ingenieurswese, Rekenaar en Elektronies
Sleutelwoorde:	Beheerstelsels, Lugversorgers, Ventilasioe, Verkoelingstelsels

Eskom verskaf 98% van Suid-Afrika se toenemende vraag na elektrisiteit. Die mynbou-sektor se bydrae tot die land se ekonomie is van kardinale belang, maar dit gaan gepaard met 'n baie hoë kragverbruik. Hierdie sektor alleen is verantwoordelik vir bykans 15% van die land se verbruik van elektrisiteit.

Myne is baie afhanklik van 'n voorsiening van koue water en lug. Verkoelingstelsels word dus amper nooit afgeskakel nie en gebruik tot 25% van die totale kragverbruik. Dit is duidelik dat daar 'n behoefte bestaan om moontlike inisiatiewe vir energiebesparings te ondersoek.

Verkoelingstelsels word gebruik om die temperatuur van water en lug te verlaag. Grootmaat lugverkoelers (BACs) verskaf koue lug aan die mynsgate. Die doel van hierdie studie was om moontlike kostebesparings in 'n mynverkoelingstelsel te ondersoek. Dit kan bereik word deur toerusting in staat te stel om dinamies aan te pas by omgewingsveranderinge. 'n Vermindering in elektrisiteitsverbruik het die grootste finansiële impak wanneer dit gedurende die Eskom piekperiode plaasvind. Hierdie doel is bereik deur tyd-afhanklike skedules te implementeer.

Die fokus van die studie is 'n BAC beheerstelsel a.g.v. die gebrek daaraan in die mynbou-bedryf. 'n BAC beheerder sal in staat wees om riglyne te volg wat kan lei tot besparings op elektrisiteitskoste. Dit is dus ontwikkel en opgeneem in die *Real-time Energy Management System* (REMS). Die BAC beheerder kombineer verskeie insette en grense om die uitset te bepaal. Daar was dus 'n verlaging in die kragverbruik tydens die Eskom piektyd.

Die BAC beheerder is op drie mynaanlegte geïmplementeer. Energiebesparings gedurende die aand piekperiode is gerealiseer deur gebruik te maak van die lasskuif metode. Hierdie besparings dra by tot Eskom se poging om die piektyd vraag te verminder. Lugtemperatuur

en damvlakke is noukeurig gemonitor tydens die piekperiode. Indien enige meting nie voldoen het aan die voorvereistes nie, is die dag se lasverskuiwing beëindig.

'n Totale elektrisiteitsbesparing van 7 MW kan gerealiseer word tussen die aanlegte van die drie gevallestudies. Dit was gedurende die aand piekperiode wat elektrisiteit bespaar is. 'n Berekening is gemaak wat die daaglikse koste besparing gebruik om die moontlike jaarlikse besparing te bepaal. Die wintermaande is nie in die berekening ingesluit nie. 'n Jaarlikse koste besparing van R1 166 694.41 is dus moontlik sonder om produksie volumes te verminder.

ACKNOWLEDGEMENTS

I could not have finished this dissertation on my own and would like to express my sincerest gratitude to everyone who has made this possible.

I would like to thank Prof. Eddie Mathews and Dr. Marius Kleingeld for the opportunity to gain valuable experience while completing my Master's degree. Thank you to TEMM International (Pty) Ltd and HVAC International (Pty) Ltd for the opportunity, financial assistance and support to complete this study.

I appreciate the time and effort that my study leader, mentors and colleagues have put in to guide and assist me. Your inputs and contributions were invaluable.

To all the project engineers who helped with data collection, testing and implementation, thank you very much.

My family and friends whose prayers and support have carried me throughout this study. Thank you. Your love and friendship means the world to me. I would especially like to thank my parents. You have supported me throughout my life and made it possible for me to complete my studies. I will forever be grateful for everything you have done for me.

Finally and above all else, to my saviour Jesus Christ. God has blessed me with so much and I would like to honour Him. His love never fails.

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NOMENCLATURE

ACP	Air Cooling Power
BAC	Bulk Air Cooler
CA	Cooling Auxiliaries
COP	Coefficient of Performance
DLL	Dynamic Link Library
DSM	Demand Side Management
EE	Energy Efficiency
ESCo	Energy Services Company
GUI	Graphical User Interface
LS	Load Shifting
NMD	Notified Maximum Demand
PLC	Programmable Logic Controller
REMS	Real-time Energy Management System
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-use
UML	Unified Modelling Language
VC	Ventilation and Cooling
VRT	Virgin Rock Temperature
VSD	Variable Speed Drive

Units:

°C	degree Celsius	Temperature
kg/s	kilogram per second	Airflow
kJ	kilojoule	Heat
kJ/kg	kilojoule per kilogram	Enthalpy
kW	kilowatt	Power
kWh	kilowatt-hour	Energy
m ²	square metre	Area
m/s	metre per second	Velocity
MW	megawatt	Power
MWh	megawatt-hour	Energy
R	South African Rand (ZAR)	Currency

Formula Symbols:

A	Area of water surface
C_p	Specific heat capacity of water
G	Evaporation rate of water
$\dot{m}_{air}$	Mass flow of air
ϕ	Relative humidity
Q	Cooling capacity
S_{in}	Inlet enthalpy
S_{out}	Outlet enthalpy
T_{in}	Inlet temperature
T_{out}	Outlet temperature
v	Air velocity
W	Humidity ratio
W_{comp}	Work input from a compressor
X_{H_2O}	Rate of water removal

CHAPTER 1

INTRODUCTION

1.1 Preface

South Africa's largest provider of electricity, Eskom, is one of the top five energy suppliers in the world. Eskom provides 98% of South Africa's electricity and also exports electricity to neighbouring countries [1]. This is a challenging enterprise. Eskom's reserve margin is currently very small (below 3% during the winter peak periods) [2] and in March 2014 load shedding was employed [2]. It is therefore clear that efficient energy management is of utmost importance.

One of the largest consumers of electricity is the mining sector. 14.5% of the power that is generated by Eskom is sold to the mining industry [3]. The ventilation and cooling (VC) process can typically be responsible for one quarter of a mine's electricity costs [4]. This is the reason for investigating possible cost savings with regard to VC systems.

When mining at depths of over 2 km below surface, the cooling capabilities of the mine are considered to be one of the most important discussion topics. Mine cooling ensures that the underground working environment is acceptable. It is also important to provide the underground shafts with the necessary air quantity and air pressure. The VC systems limit the thermal stress of the workers to a safe threshold. Thermal stress refers to the physical and mental fatigue experienced by the workers due to their increased body temperatures [5].

A mine cooling system consists of various refrigeration machines that provide the cold water and air. Water moves through several cooling stages before it reaches the desired temperature. Cold water is used as mine service water in underground operations. It can then be filtered and pumped back to a hot dam. Bulk air coolers (BACs) also use cold water in the air conditioning process. Figure 1.1 shows the water cooling cycle.

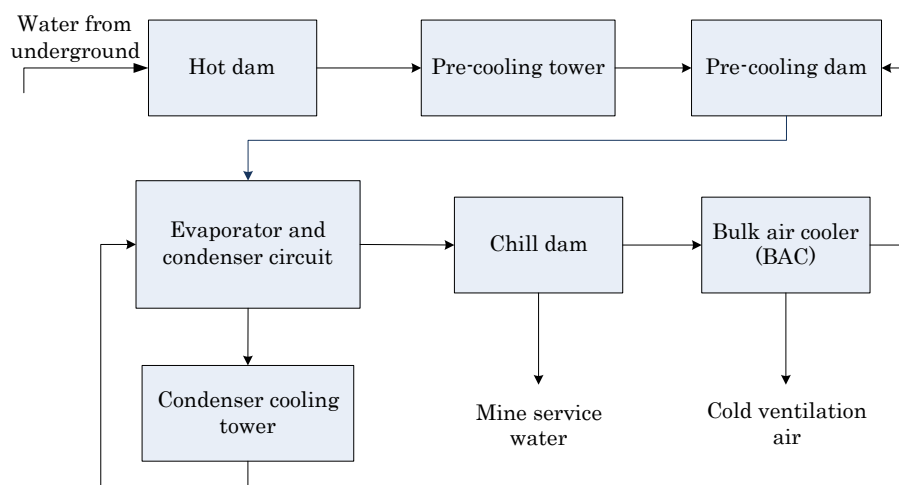


Figure 1.1: *Water cooling cycle*

1.2 Background on mine refrigeration systems

Introduction

The underground temperature in a mine plays an important part in the productivity of a mine. Productivity is directly affected by a change in temperature [6]. The dry- and wet-bulb temperatures determine the quality of the working environment. These measurements include air temperature, humidity and radiant heat. It is vital that the quality of the underground environment remains within acceptable levels. This is the reason for the large VC systems that are implemented on mines.

Refrigeration systems are responsible to maintain working conditions that not only adhere to safety regulations, but that also lead to higher levels of production. These systems provide the underground workers with cold water and air. This is an energy intensive task which results in substantial electricity costs. The refrigeration process can account for 25% of the mine's electricity usage [4]. Opportunities therefore exist to improve these systems and make the utilisation thereof more efficient.

Firstly, a cold water supply is vital in deep mine operations. As the mining depth increases, the virgin rock temperature (VRT) rises [7]. The VRT can exceed 55 °C in deep mines [8,9]. Cold water is used to lower the temperature of the rock to a level that is safe for the miners. The water is supplied from a chill dam on the surface. Fridge plants, or chillers, are used to supply these dams with cold water. These chillers extract heat from the water by using a compression refrigeration cycle [10].

Secondly, a continuous supply of cold fresh air is needed, for which the BACs are responsible. The mine's regulations regarding acceptable working conditions must be adhered to. It is very important that the underground air temperature is maintained within the prescribed levels. The underground wet-bulb temperature must always be between 10 °C and 25 °C [11]. When keeping in mind that mine shafts can extend to more than 3 km below surface, it is clear why this process requires so much electricity.

The installed capacity of the refrigeration plant on a mine usually exceeds the utilised capacity [12]. Redundant machines may be installed to enable scheduled maintenance which requires equipment to be switched off. A study was conducted to evaluate the percentage of the installed refrigeration capacity that was utilised on an average basis. Table 1.1 shows that it is not uncommon for a mine to only use about 50% of its capacity. This is an indication that energy management strategies might result in electricity savings. The utilised capacity

can be increased during low demand periods and therefore be decreased during high demand periods.

Table 1.1: *Percentage of mines' utilised capacities*

Refrigeration plant	Installed capacity (kW)	Average usage (kW)	% of capacity
Mine A	6 868	2 700	39.3
Mine B	7 185	3 100	43.1
Mine C	6 750	1 800	26.7
Mine D	11 130	6 870	61.7
Mine E	18 615	8 170	43.9

System layout and use

Refrigeration system components can be arranged and combined in various ways, depending on the requirements of the mine. Some mines have fewer chillers with larger installed capacities. Other mines rather choose to add smaller capacity chillers together to supply the demand. Both of these alternatives have advantages regarding maintenance and power efficiency. Figure 1.2 shows an example of a possible layout.

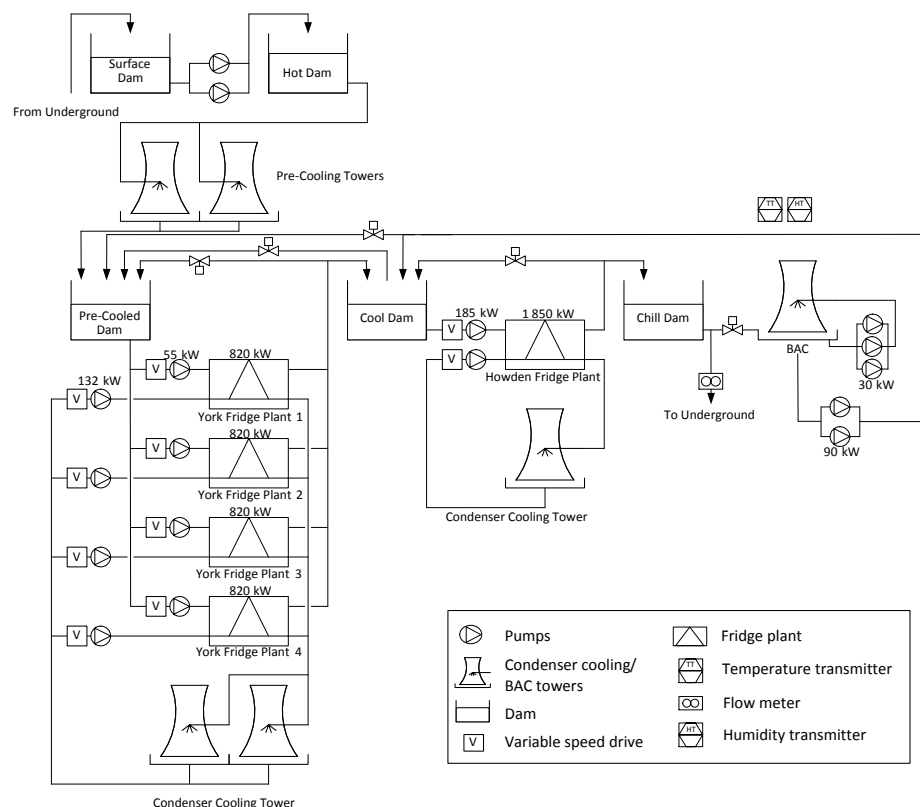


Figure 1.2: *Example of a refrigeration system layout*

BACs can be arranged in a closed loop, together with chillers and condenser cooling towers. Water is continuously recirculated and thus no hot or cold dams are used. Depending on the ambient temperature, the water can be used by the BAC for multiple cycles. As the water absorbs the heat of the air, the water temperature increases. It can then be pumped back to the chillers to cool down the water to the desired temperature.

Each mine is unique with regards to its environmental conditions. The depth of the mine contributes to the underground temperature. If the mine is located in a warmer geographic region the ambient temperature is higher. A geothermal gradient can be used to calculate the temperature at a specific depth [13]. Specialised instruments and meticulous calculations are needed to determine the required quantities of water and air. It is therefore important to tailor the approach accordingly.

Refrigeration plants can be located on either the surface or underground. It is common for deep mines to have cooling systems on both the surface and underground [14]. Due to the distance between the surface and the lowest level, having only a surface refrigeration plant would not suffice. A surface plant would not be able to maintain the temperature within the specified range on both the top levels and the bottom levels.

It is very important that the underground temperature does not fall below the specified minimum. In order for a surface refrigeration plant to maintain the temperature on the bottom levels can sometimes be impractical. It may require an initial output of much colder air with a higher velocity. Consequently the top levels would be overcooled and have air temperatures below the allowable minimum. It is also not feasible to pump water from 3 km underground back to the surface. Underground refrigeration is subsequently implemented.

Chillers, dams and BACs can be located on a mid-level in a mine. Water can be pumped into an underground hot dam and from there be pumped to a surface hot dam. Cold water is gravity fed down from the surface to the underground chill dam. These dams supply the underground BACs with cold water to provide the lower levels with ventilation. Several underground levels can also have booster fans to extract the warm air to the air outlet.

The ventilation system of a mine supplies the underground shafts with fresh air. This is an important task for a number of reasons. First and foremost is the oxygen supply which is critical for the mine workers. Mining equipment emits heat into the underground environment. This is accompanied by exhaust fumes from machinery and blasting fumes when detonating explosives. The air is therefore hot and contains gases such as carbon monoxide, nitrogen oxide and methane [15,16]. Fresh air removes the heat and maintains a safe vapour composition in the atmosphere. BACs are consequently a critical component in a ventilation system and it is very common for deep mines to have at least one BAC.

Refrigeration components

BACs use cold water in the air conditioning process. The two main electrical components of a BAC are a pump and a fan. Cold water is pumped from a chill dam to the BAC and is used to produce a vapour that is misted down from above. Air is then blown through the vapour which causes the mist to absorb the heat of the air (Figure 1.3). The result being that cold, dehumidified air exits the BAC outlet. Water can be recycled by pumping it back to the top of the BAC tower. When the water has reached a specific temperature it is pumped into a pre-cooling dam.

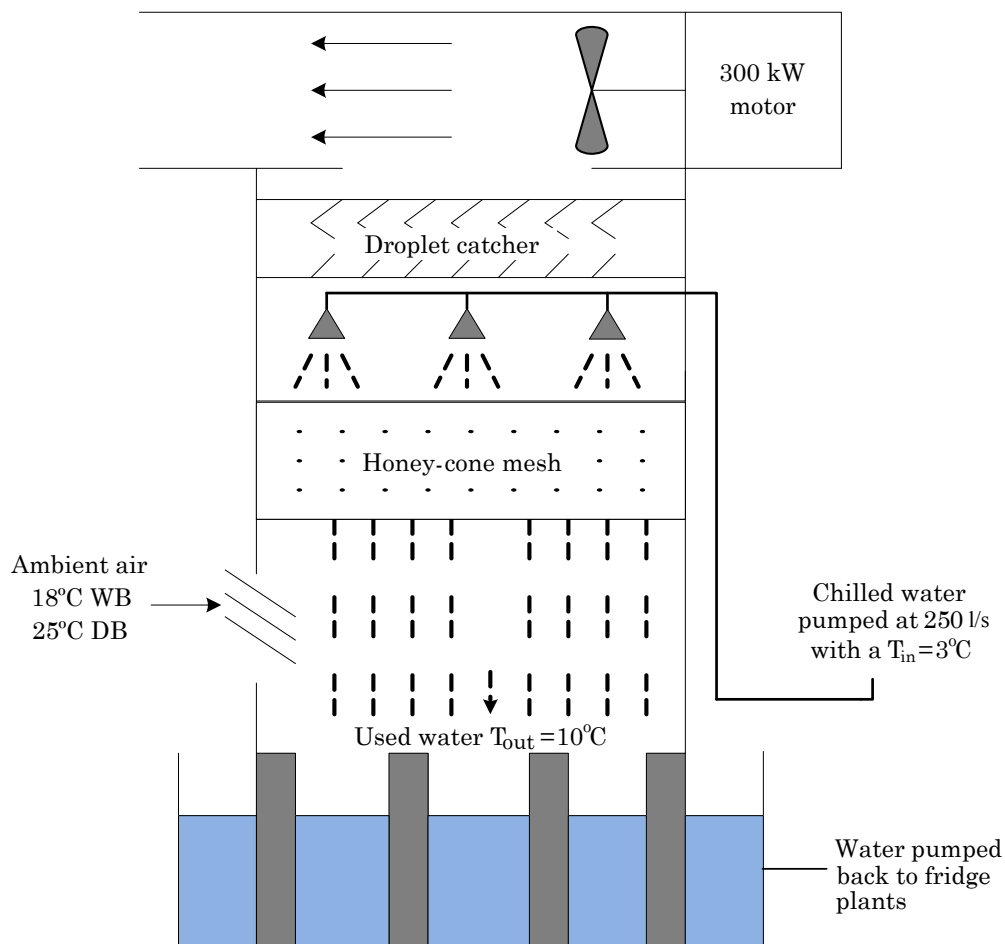


Figure 1.3: *Cross section of a typical BAC*

It is common for the BAC pumps to be switched off during the winter months [17]. During these periods the low ambient temperature means that additional cooling is unnecessary. The BAC fans would most likely be kept on to supply ventilation for the underground workers. Maintenance on equipment would also be scheduled to take place in winter. This allows

operators to retain refrigeration levels with only selected machines running simultaneously. Eq. 1.1 can be used to determine the energy that is absorbed by a BAC during operation [18].

$$Q = \dot{m}_{air}(S_{out} - S_{in}) \quad [kW] \quad (1.1)$$

Where:

$$\begin{aligned} Q &= \text{energy absorbed by the BAC (kW)} \\ \dot{m}_{air} &= \text{mass flow of air (kg/s)} \\ S_{out} &= \text{enthalpy out of the BAC (kJ/kg)} \\ S_{in} &= \text{enthalpy into the BAC (kJ/kg)} \end{aligned}$$

The pre-cooling dams are mainly supplied with water from the pre-cooling towers. Pre-cooling towers are designed to have an outlet temperature of 2 °C above the wet bulb temperature [19]. These towers can be very efficient in removing excess heat from warm water, if they are properly maintained. Convection as well as evaporation is used to transfer the heat to the air. The water is pumped into a pre-cooling dam where it is combined with the BAC outlet water. This process reduces the inlet temperature of the chillers making them more efficient [4, 20].

Chillers are at the core of refrigeration systems. The basic operation of a chiller consists of transferring heat from a source to a thermal sink. This is achieved by using a vapour compression cycle [21, 22]. A refrigerant with a specific pressure-temperature relationship is used to extract heat from the liquid (or gas) that is being cooled [22]. The refrigerant moves from the evaporator to the condenser via a compressor. The cooling capacity of a chiller can be calculated by using eq. 1.2 [23].

$$Q = \dot{m}_{air} \cdot C_p (T_{in} - T_{out}) \quad [kW] \quad (1.2)$$

Where:

$$\begin{aligned} Q &= \text{cooling capacity (kW)} \\ \dot{m}_{air} &= \text{mass flow of air (kg/s)} \\ C_p &= \text{specific heat capacity of water (liquid) (kJ/kg.K)} \end{aligned}$$

T_{in} = inlet temperature ($^{\circ}\text{C}$)

T_{out} = outlet temperature ($^{\circ}\text{C}$)

Evaporators operate at low pressure and temperature conditions where the refrigerant is vaporised. Condensers operate at high pressure and temperature conditions which causes the refrigerant to condense. This process is repeated to continually transfer heat from the water (source) to the air (sink). Common types of refrigerants that are used in chillers on a mine are Ammonia (R-717), R-12 or R-22 [24]. Different types of refrigerants have a trade-off regarding Coefficients of Performance (COP), stability, toxicity and availability [25].

The COP of a refrigeration cycle is a measure of the performance or efficiency of the equipment. It is defined as the useful cooling effect divided by the work input from the compressor, as shown in eq. 1.3 [20]. A higher COP indicates better efficiency. The COP can vary depending on the ambient temperature and load requirements [14]. Significant performance improvement is possible by reducing the inlet temperature of the refrigeration plant [4]. The case studies in [26] and [27] show a typical COP of between 3 and 5.

$$COP = \frac{Q_e}{W_{comp}} \quad (1.3)$$

Where:

Q_e = heat removed from system (kJ)

W_{comp} = work input from the compressor (kJ)

Environmental measurements

Several types of measurements are used to determine the temperature and composition of the air. Quantities such as dry-bulb temperature, wet-bulb temperature, enthalpy and relative humidity are measured. Wet-bulb temperature is commonly used to determine whether the underground conditions are acceptable. Wet-bulb temperature is defined as the temperature at which water will evaporate when an equilibrium between water and air exists [8, 20].

The composition of the ambient air differs during the summer months and the winter months. The air is much more humid during the summer. BACs are used to dehumidify the air before it is delivered to the mine shafts. This means the water vapour is removed from the air to

provide the underground miners with dry air. The rate at which a BAC dehumidifies the air was obtained from [28] and is given in eq. 1.4.

$$X_{H_2O} = \dot{m}_{air}(W_1 - W_2) \quad [kg/s] \quad (1.4)$$

Where:

X_{H_2O} = rate of water removal (kg/s)

$\dot{m}_{air}$ = mass flow of air (kg/s)

W_1 = humidity ratio (kg/kg)

W_2 = humidity ratio (kg/kg)

Teodoros and Andresen [29] compiled a simplified formula to determine the evaporation rate of water (Eq. 1.5). The rate of evaporation is impeded by increased levels of humidity [29]. That is why it is vital for the refrigeration system to supply sufficient airflow to keep the heat stress of the miners to a minimum. The air enthalpy is also an important measurement that can establish the level of heat stress. It is a measurement of a system's heat content [21]. When water vaporises, it absorbs heat from the atmosphere. Enthalpy of vaporisation refers to the heat that was absorbed by the water in order to evaporate.

$$G = C_1 A(1 - \phi)(1 + C_2 v) \quad [kg/s] \quad (1.5)$$

Where:

G = evaporation rate of water (kg/s)

C_1 = coefficient of the evaporation rate (kg/m²s)

A = area of water surface in contact with air (m²)

ϕ = relative humidity of air (%)

C_2 = coefficient of the dependency on air velocity v (m/s)⁻¹

v = air velocity over water surface (m/s)

Another parameter that is used to verify acceptable working conditions for underground miners is the Air Cooling Power (ACP) index [20, 30]. This index accounts for the velocity of the ventilation air. A combination of air temperature and velocity gives a better indication of the cooling effect on the miners. The ACP index can therefore be improved by increasing the air velocity or by reducing wet-bulb temperature [31]. For heavily clothed labourers working underground, the ACP index should be at least 300 W/m^2 [20, 27].

The safety of the miners is always regarded as a top priority. Before any attempt can be made to cut back on electricity usage, the safety regulations need to be studied. Demand Side Management (DSM) projects can generate energy savings by implementing load shifting (LS) methods. This means electrical equipment is switched off during the Eskom peak period. Load shifting can only be considered if the water resource reserves will sustain the demand during the peak period. Configured alarms alert the personnel if any measurement is approaching its pre-set minimum. This will result in the abandonment of load shifting for that day.

1.3 Existing DSM technologies

Introduction

DSM projects were introduced by Eskom to assist with managing South Africa's electricity demand. Mines are mostly billed for their power usage according to the Megaflex tariff structure. This structure links the price of electrical energy to the time of usage. As an incentive to implement DSM projects, Eskom awards certain rebates to the Energy Services Company (ESCO). The reduction in demand during peak times greatly reduces the pressure on the supplier. It is therefore mutually beneficial for the ESCOs, their clients and also for Eskom.

Types of DSM projects

Various DSM projects have been implemented over the past few years. Some DSM projects focus on implementing an improved energy usage strategy or on installing equipment that use less electricity [32]. These projects are known as electrical energy efficiency (EE) projects. Other projects are responsible for load shifting which takes time-of-use (TOU) tariffs into account. Substantial savings can be generated by following time-dependent schedules [33]. These schedules allocate equipment to operate during the Eskom off-peak time period.

EE methods focus on lowering the demand over a 24-hour period, whereas LS methods focus only on the peak periods [34,35]. DSM projects can realise cost savings by replacing existing equipment with machines that are energy efficient e.g. EE motors. EE motors would normally operate at higher speeds and have lower power factors. The operating voltage and load percentage of motors are important factors when calculating savings. Regular maintenance can also increase efficiency on mining equipment such as pumps and fans [19].

LS projects have a clear focus on minimising energy usage during the peak demand periods. Eskom uses different tariff structures for different types of customers. The tariff applicable to the user is dependent on their notified maximum demand (NMD). This is the contracted maximum demand of the client. If the usage of the client exceeds the NMD, the client is liable for penalty surcharges.

Tariff structures

The main TOU tariff structures that are used for urban enterprises are Nightsave, Megaflex, Miniflex and Businessrate [36]. Mines are typically billed according to the Megaflex tariff. This is because they normally have an NMD greater than 1 MVA as well as the ability to shift electrical loads. There are three time periods defined within the Megaflex tariff structure. Depending on the day of the week, each hour of the day can either be labelled as peak time, standard time or off-peak time. Figure 1.4 shows the hourly classification of these time periods for each day of the week.

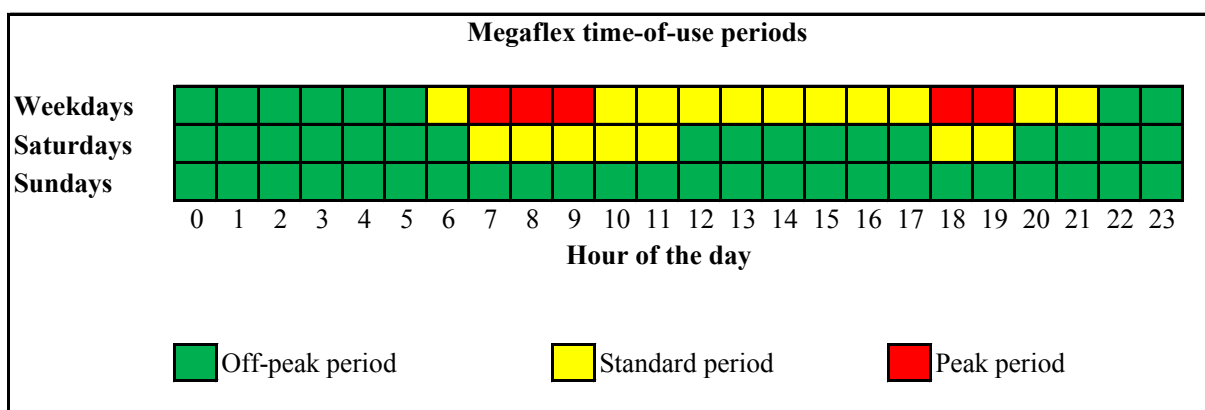


Figure 1.4: *Megaflex time period classification*

Table 1.2 below shows the active energy charge rates that are applicable to the Megaflex tariff structure. Prices are given in c/kWh and is dependent on the time of year, transmission zone and voltage level. Electricity is most expensive in the peak period of the high demand

season. This would be the red sections on Figure 1.4 during the winter months (June – August). It is over 200% more expensive than the peak period in the low demand season as well as the standard period in the high demand season. Therefore the need to limit peak-time usage cannot be overemphasised.

Table 1.2: Eskom’s Megaflex electricity tariff structure for 2013/2014 [36]

		Active energy charge [c/kWh]											
Transmission zone	Voltage	High demand season [Jun - Aug]						Low demand season [Sep - May]					
		Peak		Standard		Of Peak		Peak		Standard		Of Peak	
		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl	
≤ 300km	< 500V	204.55	233.19	62.23	70.94	33.97	38.73	66.98	76.36	46.22	52.69	29.46	33.58
	≥ 500V & < 66kV	201.33	229.52	60.99	69.53	33.12	37.76	65.68	74.88	45.20	51.53	28.68	32.70
	≥ 66kV & ≤ 132kV	194.96	222.25	59.06	67.33	32.07	36.56	63.60	72.50	43.77	49.90	27.77	31.66
	> 132kV*	183.75	209.48	55.66	63.45	30.23	34.46	59.94	68.33	41.25	47.03	26.18	29.85
> 300km and ≤ 600km	< 500V	206.21	235.08	62.48	71.23	33.93	38.68	67.27	76.69	46.31	52.79	29.38	33.49
	≥ 500V & < 66kV	203.34	231.81	61.60	70.22	33.45	38.13	66.34	75.63	45.65	52.04	28.96	33.01
	≥ 66kV & ≤ 132kV	196.88	224.44	59.64	67.99	32.38	36.91	64.22	73.21	44.19	50.38	28.04	31.97
	> 132kV*	185.58	211.56	56.22	64.09	30.52	34.79	60.53	69.00	41.66	47.49	26.43	30.13
> 600km and ≤ 900km	< 500V	208.27	237.43	63.08	71.91	34.25	39.05	67.94	77.45	46.76	53.31	29.66	33.81
	≥ 500V & < 66kV	205.38	234.13	62.22	70.93	33.79	38.52	67.00	76.38	46.11	52.57	29.25	33.35
	≥ 66kV & ≤ 132kV	198.88	226.72	60.25	68.69	32.71	37.29	64.87	73.95	44.65	50.90	28.32	32.28
	> 132kV*	187.45	213.69	56.78	64.73	30.84	35.16	61.15	69.71	42.08	47.97	26.70	30.44
> 900km	< 500V	210.36	239.81	63.74	72.66	34.61	39.46	68.63	78.24	47.23	53.84	29.97	34.17
	≥ 500V & < 66kV	207.43	236.47	62.83	71.63	34.11	38.89	67.66	77.13	46.56	53.08	29.54	33.68
	≥ 66kV & ≤ 132kV	200.88	229.00	60.85	69.37	33.04	37.67	65.52	74.69	45.10	51.41	28.61	32.62
	> 132kV*	189.29	215.79	57.37	65.40	31.17	35.53	61.78	70.43	42.53	48.48	27.00	30.78

Implementations

Energy management techniques such as load shifting have been implemented in mine refrigeration systems. Cost savings are generated by reducing the load during the evening peak period. One such example is documented by Schutte et al. [37]. A daily electricity usage reduction of 6 MW was achieved. This resulted in an annual electricity cost saving of R2 million (2008 tariffs). Other successful load shifting case studies are shown in [35,38,39].

Another DSM technique that was successfully implemented is variable water flow control. Du Plessis et al. [40] and Booysen et al. [41] have shown that savings can be generated by controlling the water supply of a mine cooling system. Du Plessis et al. [40] made use of a software tool called Process Toolbox. Their results showed an electrical energy saving of 33%. The average system COP of all four case studies were also improved.

Control systems

Software control systems have proven to be very effective to monitor and control the energy usage of a mine. Examples include Adroit, Wonderware Intouch and WinCC. These packages

can control and monitor the use of water in a refrigeration system [42]. They are, however, unable to simulate and optimise a production schedule. Other tools such as VUMA-coolflow is a sophisticated simulation program, but not a control system. The ideal would thus be a control system with simulation and optimisation capabilities.

One such control system is the Real-time Energy Management System (REMS). The REMS package consists of several platforms, each with a set of modules [42, 43]. A model can be created to represent the arrangement of components on site. Equipment on site is connected to a Supervisory Control and Data Acquisition (SCADA) system. Each software component is linked with the corresponding site component via a SCADA tag.

Communication between electronic equipment in a mine is enabled via instrumentation infrastructure. This allows the software control system to send information to the Programmable Logic Controller (PLC) and the SCADA system. A PLC is typically installed on-site and works alongside the SCADA system. It receives set point values from the SCADA and control the relevant equipment accordingly [44]. The software control system can communicate with the SCADA and PLC. It can override given control instructions in order to implement LS.

Application specific software platforms within REMS were developed to cater for different types of projects. For example, the REMS Pumps platform was specifically designed to be used for projects with a focus on pumps. It would also contain components such as a Variable Speed Drive (VSD) controller. This enables the operator to adjust the speed of a pump from the control room. The REMS system can therefore switch pumps on or off automatically if it is running in automatic mode.

The REMS software is continually improved by adding control components which can operate in automatic mode. The valve controller is an example of such an addition. It can be given position control limits that are used to specify an acceptable operating range. Permission can then be given to set the position at its maximum value during specific time periods. Safety measures are built in that will trigger an alarm when a value is approaching a preset limit. Equipment can also be shut down if necessary.

A variety of components which are specific to refrigeration systems have been developed and included in the REMS Cooling Auxiliaries (CA) suite. The user can, for example, create a simulation with BACs, fridge plants, dams and pumps. VSDs and valves can be added where necessary. A real-time graphical depiction of the underground system can be monitored, provided that all the SCADA tags are available. The software-based control system is therefore a fundamental part of DSM.

1.4 Opportunities for cost savings on bulk air coolers

Several types of DSM projects were discussed in the previous section. None of these projects have focussed on BAC control. Viljoen and Ranasinghe have shown that it is possible to save electricity by reducing the BAC chilled water supply [45]. A BAC controller that enables the mine to regulate the water supply and incorporate a tariff structure into the schedules of operation could realise cost savings. It would therefore be recommended to investigate possible opportunities that might lead to cost savings.

Within the REMS-CA platform there exists a BAC component which displays all the applicable tag values. Together with the rest of the refrigeration components, a control system can be developed for the BACs. By coordinating the usage of the BACs with the time of day, a reduction in electricity costs is possible.

There are two Eskom peak periods on weekdays. A morning peak and an evening peak. The evening peak time would be a feasible option to employ load management. This would give the BACs enough time during the day to provide sufficient cooling. Cold dam levels should be kept at a maximum to be able to supply enough water during the two hours downtime. Underground temperature levels must also be low enough to ensure that an acceptable cooling level is maintained.

A BAC controller would be able to determine whether peak time savings can be achieved. Daily averages of underground usage can be used to calculate the anticipated demand during the peak time. This can be used to plan ahead and exploit the off-peak period. The idea is to use the least amount of electrical energy during the peak period.

Another way in which the BAC controller can make the VC process more efficient, is by using the underground temperature. This can prove to be a valuable input to the controller. Equipment can therefore be switched off when the desired cooling level has been achieved. A trend line can also be used to determine the times when the supply of cold air is most important. Operating schedules could thus be pre-empted to minimise unnecessary usage.

Prior to the development and implementation of the BAC controller, several on-site investigations were conducted. Possible sites where load shifting or load clipping could be implemented were identified. The main focus was the effect on the underground temperature when refrigeration systems were shut down. The temperature needed to remain within the given limits for the site to be considered. Investigations consisted of manual intervention by operators during the peak period.

Two different types of site configurations were investigated. As mentioned earlier, a closed loop configuration does not supply water for underground operations. Refrigeration systems that use chilled water dams to provide the mining operations with cold water is known as an open loop (or open ended) configuration. The results presented here show the potential energy savings for two case studies.

The first investigation was done on a site where water is used in a closed loop. Table 1.3 lists the equipment that was used during the investigation. Figure 1.5 shows the resulting power profile which indicates the possible energy reduction during the peak period. The underground temperature was monitored throughout the investigation and it did not exceed the specified maximum.

Table 1.3: *Installed equipment used in the closed loop investigation*

Description	Quantity	Motor rating (kW)
Howden chiller		
Howden fridge plant compressor	2	2 000
Howden evaporator pumps	3	250
Howden condenser pumps	3	275
BAC		
Fans	4	300

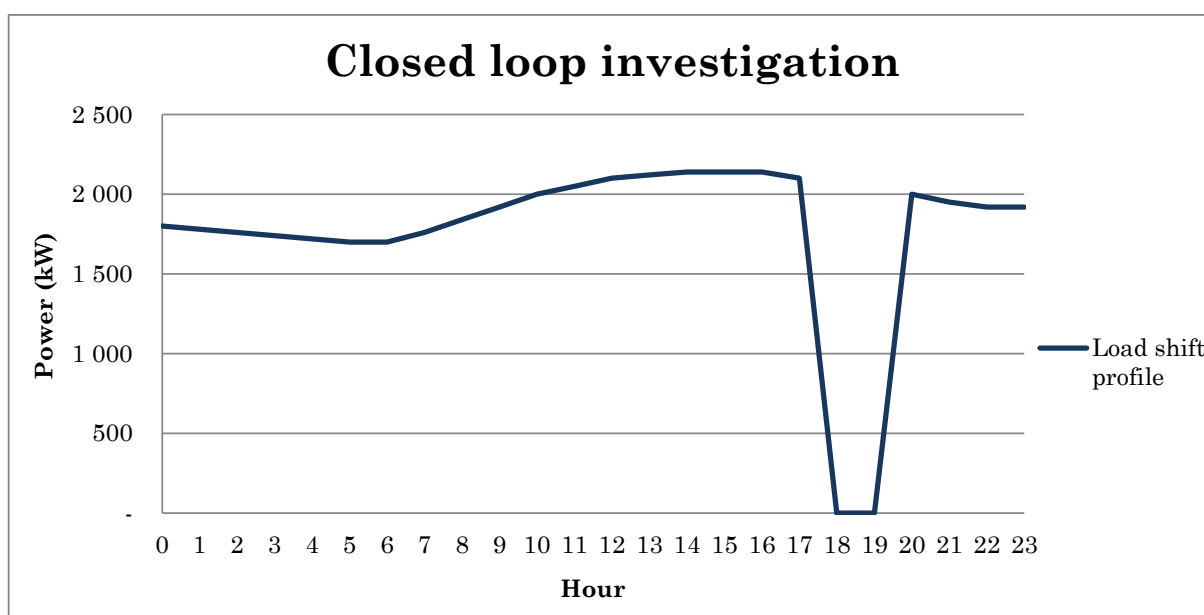


Figure 1.5: *Power profile of the closed loop investigation*

The second investigation was done on a site where the water is stored in a dam after it is chilled by the fridge plants. This is an open loop configuration where water is not only supplied to the BACs, but it is also used for underground cooling of rock and ore. Table 1.4 lists the equipment that was used during the investigation. Figure 1.6 shows the power profile that was realised by the load shifting investigation.

Table 1.4: *Installed equipment used in the open loop investigation*

Description	Quantity	Motor rating (kW)
York chiller		
York fridge plant compressor	4	820
York evaporator pumps	4	55
York condenser pumps	4	132
Howden chiller		
Howden fridge plant compressor	1	2 200
Howden evaporator pumps	1	185
Howden condenser pumps	1	185
BAC		
Return pumps	2	90
Recycle pumps	3	30

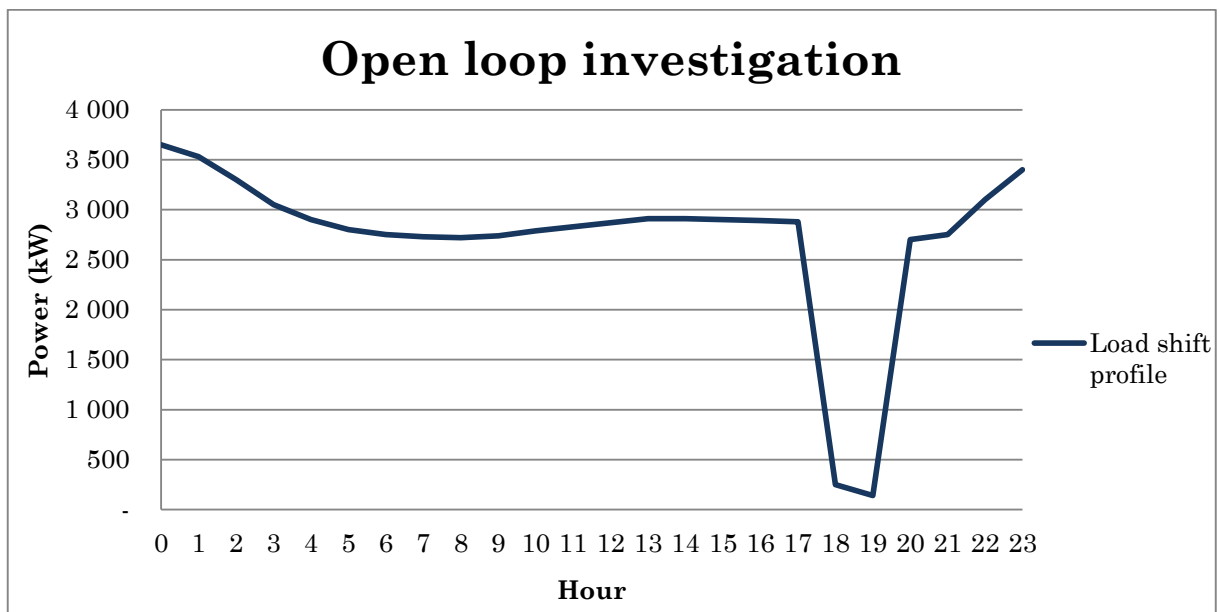


Figure 1.6: *Power profile of the open loop investigation*

The results obtained from the investigations show that an opportunity for electrical energy savings exists. A reduction of energy usage during the Eskom peak period results in substantial cost savings. This means that Eskom as well as the client will benefit from the implementation of such a DSM project.

1.5 Objective of this study

The main objective of this study is to implement a control system which could realise possible cost savings. BACs are the focus of the control system. Refrigeration components are all interconnected and would therefore be incorporated into the control philosophy.

The fact that mines are billed for their electricity usage according to TOU tariffs can be exploited. There is an opportunity to use more electricity when the cost thereof is at a minimum. Correspondingly the expensive peak-time usage can be limited as far as possible. This would dramatically reduce the monthly electricity expense of a mine.

In order to limit peak-time usage, the software must be able to monitor and control relevant components. The aim would be to generate savings without reducing monthly production quantities. Energy usage would be governed by the time of the day and therefore its cost.

1.6 Overview of this dissertation

This dissertation is divided into four main chapters. Below is a brief summary of the content of each chapter to give an overview of the study. References that were used are all listed in the bibliography at the end of the dissertation.

Chapter 1 is an introductory chapter. It contains a literature study on the subject of mine refrigeration. Relevant information regarding equipment and the underground environment is given. Existing DSM technologies and new opportunities are discussed.

Chapter 2 focusses on the development of a bulk air cooler controller. The design process is covered in detail. A discussion on the formulated control philosophy is also included in this chapter.

Chapter 3 presents the results that were achieved. The control system was implemented on three different mines. Each with its own layout and production specifications. The three case studies are discussed and compared.

Chapter 4 provides a conclusion, comparing the end results to the initial goals. Any discrepancies and possible reasons for them are discussed. Future opportunities that might build on this study are also included.

CHAPTER 2

DESIGNING AN EFFECTIVE CONTROL SYSTEM
FOR BULK AIR COOLERS

2.1 Foreword

This chapter discusses the design considerations that were relevant in the development of the BAC controller. The BAC controller was specifically designed to be incorporated into the REMS control system. Relevant refrigeration system components were modelled on a software platform. These software components are linked to actual equipment on site. The operation of the control system is governed by the control philosophy, which is also discussed. System verification was done with a simulation of a complete cooling system with automatic control.

2.2 Modelling of mine cooling systems

The design process started with the collection of the necessary site information. Each mine has its own configuration as well as infrastructure. These differences were taken into account to develop a generic controller. Operators of the control system are therefore able to decide which inputs are applicable to their arrangement. In order to achieve this, a comprehensive mine cooling system was modelled.

After various investigations the scope was established. The input and output requirements were identified. Discussions regarding existing component capabilities revealed additional component capabilities that needed to be developed. Existing on-site infrastructure and control functionality thereof were also reviewed.

One important factor to consider is the sequence of control procedures involved when stopping or starting electrical equipment. The on-site arrangement of equipment determines the control procedure priority. An example of this is that the pumps that have VSDs installed will typically be given a higher priority. Control procedure sequences are in some cases predetermined by the SCADA system. In other cases the control software needs to establish the sequence.

Some mines had temperature sensors installed on selected levels. These sensors measure the dry-bulb temperature and relative humidity. It is common for the underground temperature regulations to be specified as wet-bulb temperature. The control system therefore needs a wet-bulb temperature input. The formula given in [46] was used to determine the wet-bulb temperature from the dry-bulb temperature and the relative humidity. The wet-bulb temperature is therefore available and it enables control via the underground temperature.

The wet-bulb temperature calculation was incorporated into a weather station software component. Figure 2.1 shows the weather station icon which displays important temperature related values. Input values can be read from a SCADA tag or it can be a fixed (constant) value. Output values are written to a SCADA tag which is available for use by other components. The calculated wet-bulb temperature is written to a tag that can be used by the BAC controller as an input parameter .

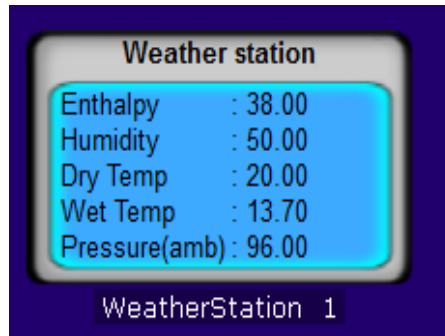


Figure 2.1: *Weather station icon display*

The REMS platform icons give feedback on current status values. This makes it easy to view the current state of the complete VC system. The BAC icon indicates the status of the BAC fans and BAC pumps. In Figure 2.2 the icon of BAC 1 has two green colour fills which indicates an on-status for both the fan and the pump. The red colour fills in the BAC 2 icon denotes that both the fan and the pump are switched off. It is also possible that only the fan or the pump is on (BAC 3 and BAC 4).

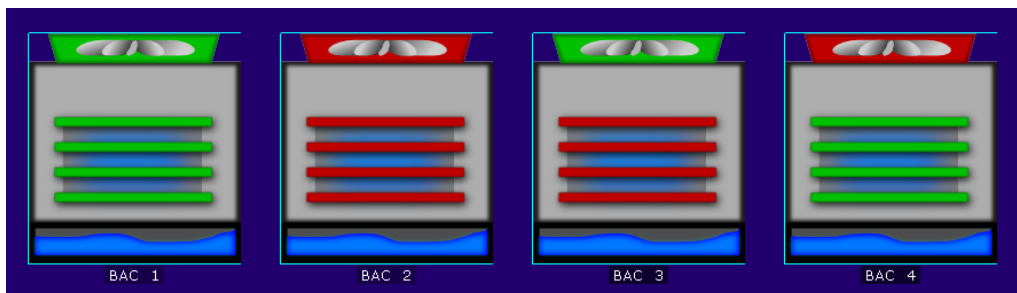


Figure 2.2: *BAC icon display*

Other components that would typically be used within the BAC platform are fridge plants and pumps. Fridge plants are the refrigeration systems that produce cold water. The fridge plant icon is colour-coded to indicate its status. FridgePlant 1 in Figure 2.3 is switched on,

while FridgePlant 2 is off. Similarly Figure 2.4 shows the icons used to represent the pumps on site.

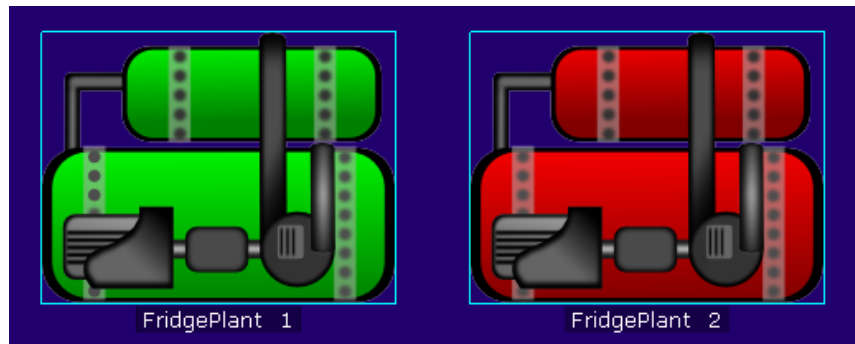


Figure 2.3: *Fridge plant icon display*

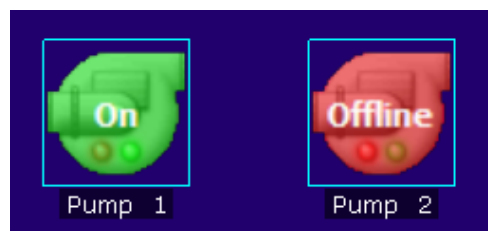


Figure 2.4: *Pump icon display*

Historical data is a valuable input in a control system. When considering the ambient temperature for instance, the norm is for the daily maximum to occur at 12:00. It is also useful to have a correlation between the underground temperature and the BAC on/off status. A steady increase in air temperature can be expected when the BACs or chillers are switched off. Historical data is created by logging tag values and saving the logged data in a text file.

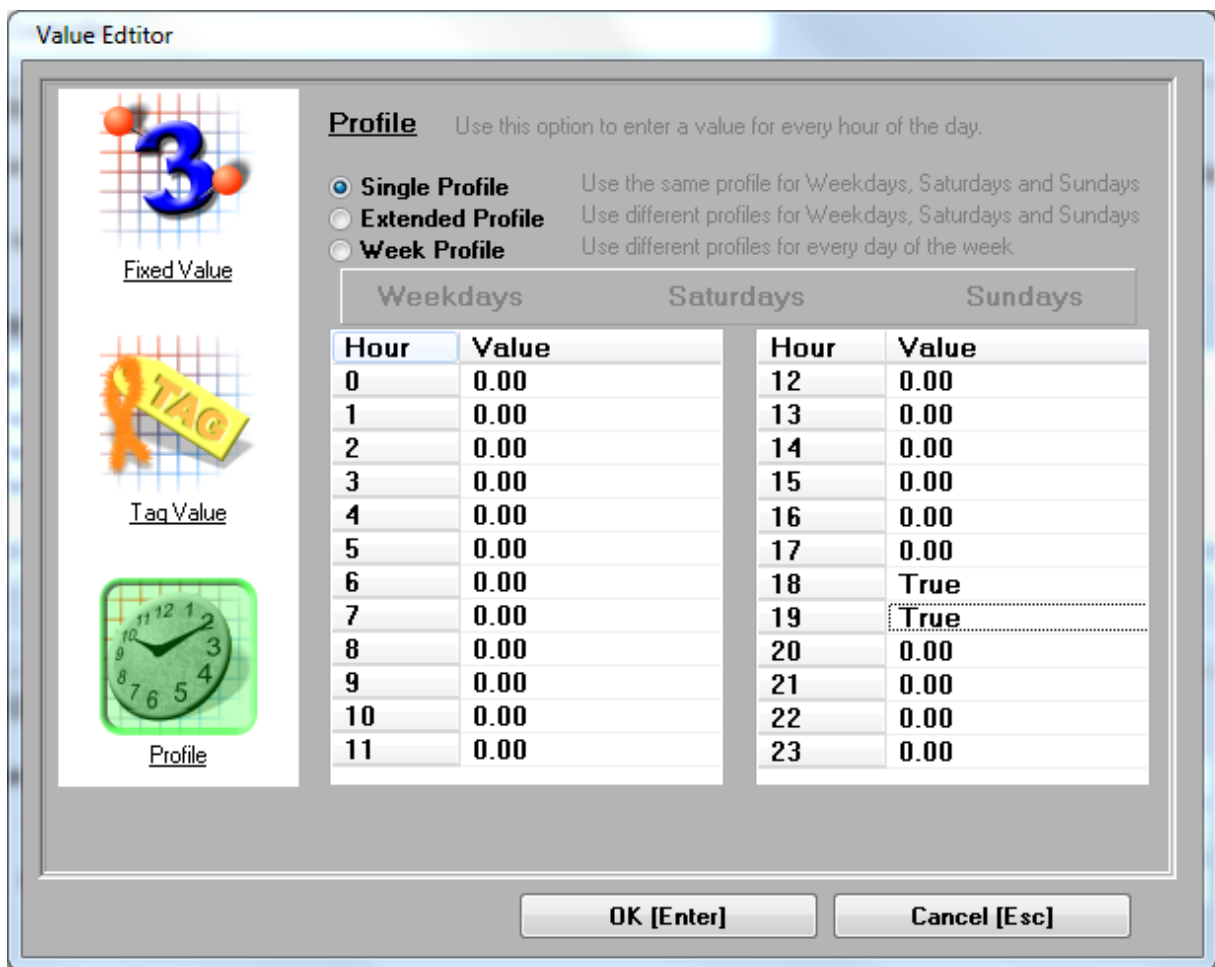
Input values can suddenly change drastically due to a number of reasons. These values are essentially just electrical signals. The hardware used to measure and transmit values can temporarily send a much larger or smaller value. Safety conditions may then be violated and cause shut down procedures to be executed. Control instructions are therefore based on average or stable values rather than instantaneous values. This is possible with internal tags, which are discussed next.

Internal tags are built into the software control system. It is a processing tool which can execute a preset procedure with a SCADA tag as input. An internal tag calculates an output according to the type of tag that was selected. Various types of internal tags can be used for

specific purposes. Internal tags enable the user to create very particular control conditions or limits. Examples include minimum, maximum, difference, average or stable values.

Average values or stable values can be generated by using the internal tag tool. An average value internal tag calculates the average of a SCADA tag over a specified period. This will therefore result in 24 values for the day if an hourly interval was selected. A stable value will only change the output once the input measurement has changed by the specified delta value.

The 24-hour profile tag function provides a table with 24 cells to specify discreet hourly output values. Figure 2.5 shows the interface of the profile tag. Selected cells can be marked as 'True' which translates to an output of '1' for the corresponding hourly interval. A controller can thus be permitted to only operate automatically during the peak period by marking the relevant cells. Control permission will consequently be disallowed for the rest of the day.



Value Editor

Profile Use this option to enter a value for every hour of the day.

☒ **Single Profile** Use the same profile for Weekdays, Saturdays and Sundays
☐ **Extended Profile** Use different profiles for Weekdays, Saturdays and Sundays
☐ **Week Profile** Use different profiles for every day of the week

Weekdays		Saturdays		Sundays	
Hour	Value	Hour	Value	Hour	Value
0	0.00	12	0.00		
1	0.00	13	0.00		
2	0.00	14	0.00		
3	0.00	15	0.00		
4	0.00	16	0.00		
5	0.00	17	0.00		
6	0.00	18	True		
7	0.00	19	True		
8	0.00	20	0.00		
9	0.00	21	0.00		
10	0.00	22	0.00		
11	0.00	23	0.00		

OK [Enter] Cancel [Esc]

Figure 2.5: Profile tag interface

The trend tool shows a graphical display of the day's measured values. This tool makes it possible to establish the effect of one measurement on another. For instance, the operator can visually see the rate at which the temperature increases when the chillers or the BACs are switched off. Figure 2.6 is an example of a trend tool that tracks the underground temperature measurement.



Figure 2.6: *Trend tool display*

These tools have been used to model a refrigeration system. Input values can be read and processed in order to make decisions and calculations regarding control. System performance can be tracked and compared to historical data. The control philosophy was implemented by creating a model of a mine cooling system. More information regarding the functioning of the control philosophy is provided in the following section.

2.3 Proposed control philosophy on bulk air coolers

Introduction

The performance and robustness of a control system are determined by the control philosophy. The control philosophy is the instruction set that contains all the conditions used for decision

making. The ideal is to make it generic or customisable as far as possible. This gives it the potential to be used on several types of site configurations.

As mentioned in the previous section, some underground levels were fitted with temperature sensors. These sensors measure the dry-bulb temperature and humidity. The weather station component converts the measurement from dry-bulb to wet-bulb. Underground temperature measurements form the foundation of the control philosophy.

Methods of control

The aim was to restrict the electricity usage during the evening peak period. Another objective was to limit the unnecessary use of refrigeration equipment. By monitoring the underground temperature it is possible to eliminate undesirable overcooling. Equipment is only switched on when the need for cooling exists. This reduces the peak-time usage as well as the overall electricity usage, which together result in cost savings for the client.

Due to the different site configurations and resource limitations, the control method differs for each site. Investigations, regarding the proposed control intervention, helped to determine which of the control options could be considered. The controller was therefore customised for the respective sites.

BACs, fridge plants and pumps can be added to the list of control items. Peak period control consists of switching off the listed components at the start of the peak period. This is only allowed if the underground temperature is within the specified range. The control system will start the peak period procedure when the *Control enabled tag* as well as the *Peak time tag* is set to '1'. The peak control procedure will end when the *Peak time tag* changes to '0' or if a start-up trigger is activated.

Off-peak control is used to prepare the refrigeration plant for the peak period. The focus of the off-peak control procedure is the chilled water dams. These dam levels should be close the specified maximum before the peak period starts. The reason for this is that chilled water is not supplied to the dams when the pumps and chillers are switched off. Having a maximum capacity of chilled water available when the peak period starts will enable the equipment to remain off during the peak period.

Dam level checking is an additional condition that is included in the philosophy of the control system. A low dam level measurement requires fridge plants and pumps to start. Once they are running, the chilled dams are supplied with cold water. A high dam level measurement may require a valve to open and enable water flow to the BAC sump or an underground

dam. Pumps and compressors can be shut down when the refrigeration system has been supplied with enough cold water.

Certain site configurations are closed loop systems. These sites do not have chilled water dams that supply cold water for underground operations. This means that the cold water is continuously recirculated between the refrigeration components. It is also customary to keep the BACs running throughout the day. Off-peak control is therefore not pertinent to closed loop systems. Control commands are thus only given to pumps and chillers during off-peak control.

Once a stop or start command is given by the BAC controller, the relevant tag value is changed to '1'. If the *Tag pulse time* is 0 s, the controller will apply status control. This causes the tag to remain high (1) until the status of the corresponding component has changed accordingly. Once the command has successfully been processed the BAC controller will reset the tag to '0'.

Alternatively, the tag pulse time can be set on the BAC controller edit form. Setting this parameter to a value greater than zero activates the use of pulse control. When using pulse control, the BAC controller will start a timer when tag values are set. The controller will then reset the relevant tags after the pulse time period has elapsed.

A flow chart illustrating how a stop command is executed can be seen in Figure 2.7. The only difference with a start command is that the controller writes values to a start tag and checks for an *On* status. An illustration for the start command procedure was therefore not included.

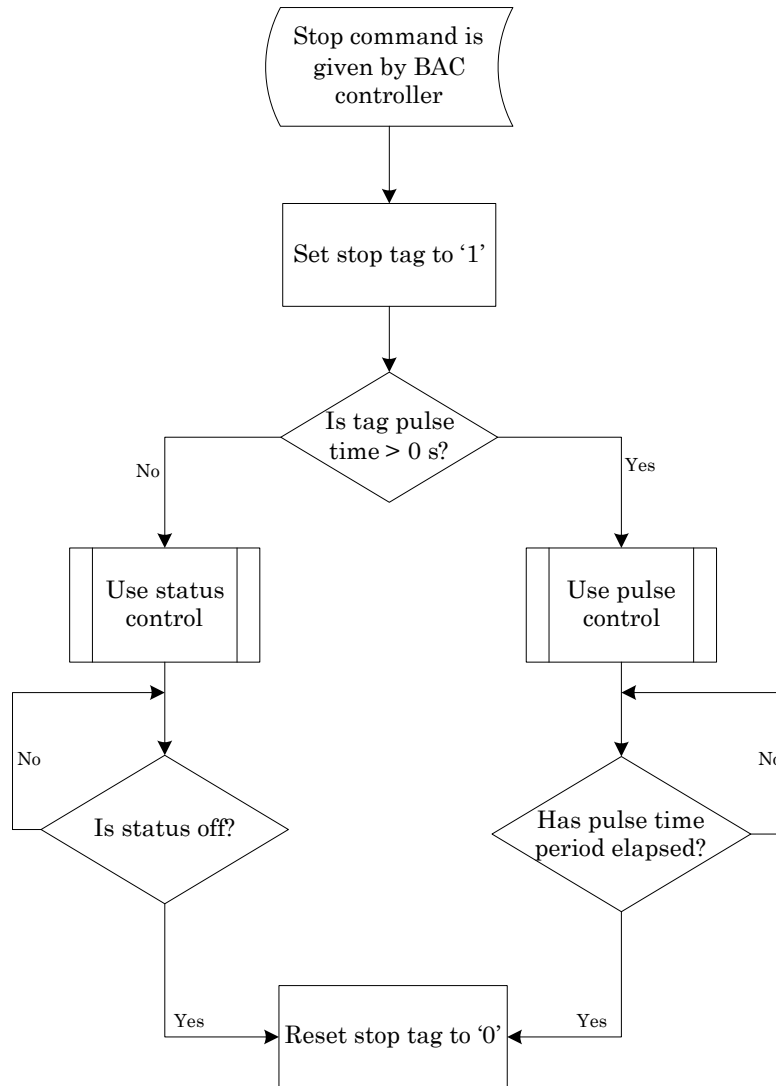


Figure 2.7: *Stop command procedure flow diagram*

Control parameters of underground equipment can be controlled either manually or automatically. Input values can be a fixed value or a variable tag value such as a dam level tag or underground temperature tag. The system operator chooses between fixed and variable values according to site specifications. BAC pumps and BAC fans are two separate inputs which can be controlled independently. Mines that do not wish to shut down the BAC fans can therefore assign a fixed value to the control tags.

The control philosophy consists of instructions and conditions that are supplementary to underground temperature control. Instructions such as opening or closing of valves and adjusting the frequency on VSDs are two examples. Existing components such as the valve controller and the VSD controller have the ability to execute these commands. They were therefore used in conjunction with the BAC controller.

Control sequences

The sequence of control decisions for a closed loop system is shown in Figure 2.8. Cold water is used by the BAC to produce cold air. The warm water is sent back to the condenser cooling towers and chillers for cooling. Dam level checking is not added to this sequence. Fans, pumps and compressors are controlled according to the temperature measurement.

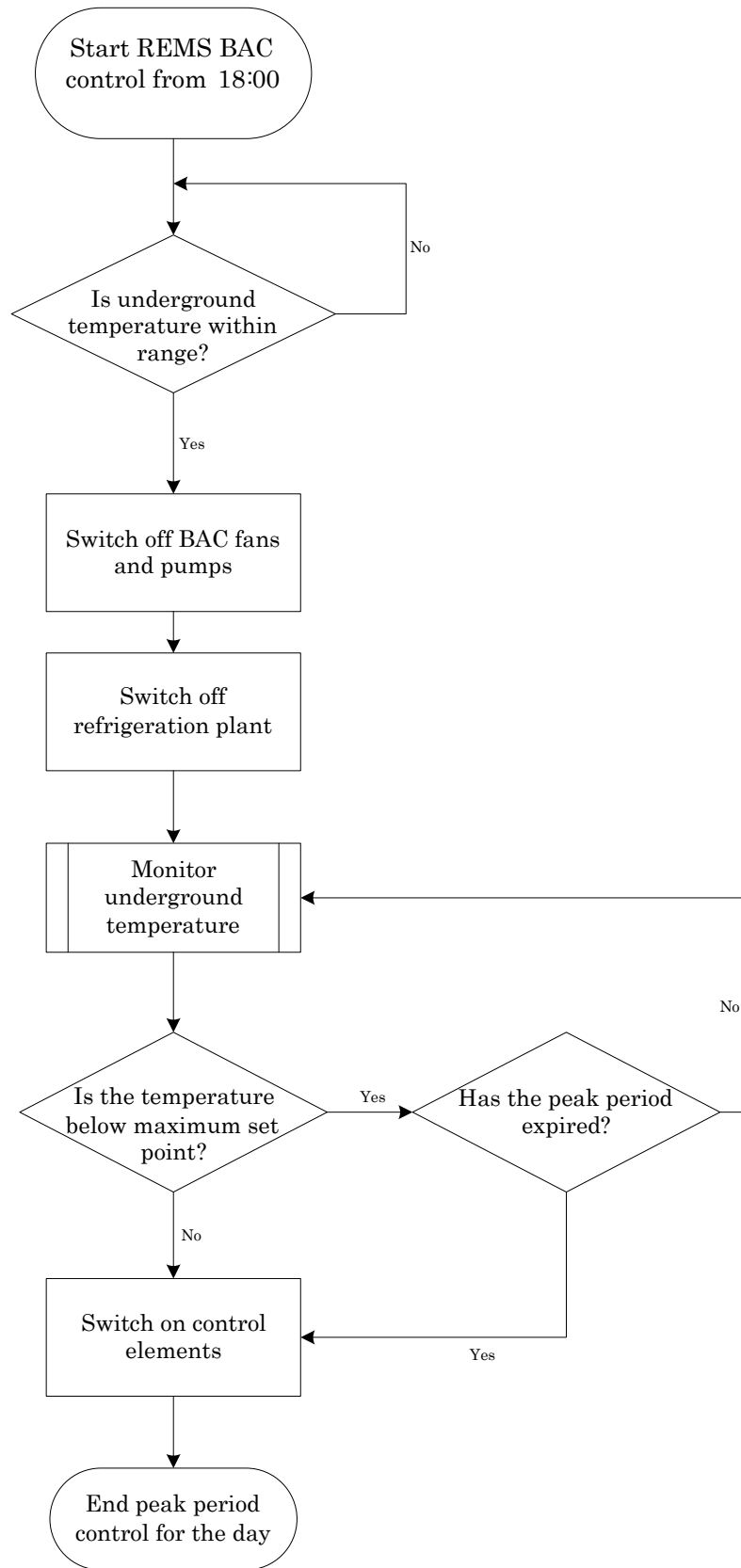


Figure 2.8: *Closed loop peak control flow diagram*

2.4 Software development of the control system

Introduction

Several types of requirements were taken into account during the development of the BAC controller. The controller's graphical user interface (GUI) was determined by the input and output requirements. Functionality requirements were built into the software operating procedures. Delphi® XE3¹ was used for the software development. Delphi is a Unified Modelling Language (UML) which is the core of object-orientated problem solving [47].

The BAC controller was developed as an addition to the REMS software package. The existing REMS platform was developed in Delphi® 6², however. The software package was therefore upgraded before the start of the development. All the existing components' dynamic link libraries (DLLs) were also recompiled using the updated software package.

REMS BAC platform

A BAC platform was created within the REMS software package. The BAC platform consists of all the necessary components to implement the control philosophy. Operating modes, user access levels and alarms are options that are available for site specific customisation. These platform options are discussed below. This section also provides more information regarding the relevant refrigeration system components and tools.

Four operating modes are used within the REMS platform. The platform can either be in Idle, Edit, Manual or Automatic mode. The operating mode determines the functionality of the system. Idle mode prohibits the user to alter the current settings. Edit mode enables the user to change the platform settings and layout parameters. Output values are not written to the SCADA during manual mode. This is only done during automatic operation. Switching between the operating modes can only be done if the required user access level has been granted.

User access groups are used to determine the privileges of the user. A user can log in as a Viewer, Operator, Supervisor or an Administrator. Each user group is given access to a set of the available actions. System operators are given a username and password to log in and access their account. A time-out feature is available to automatically log out a user after

¹Embarcadero® RAD Studio XE3

²Borland® Delphi 6

a period of inactivity. Table 2.1 shows which of the platform actions are available for each user group.

Table 2.1: *User group access control*

Platform action	Viewer	Operator	Supervisor	Administrator
Connect/Reconnect OPC	X	X	X	X
Log in	X	X	X	X
Switch modes	-	X	X	X
Save	-	X	X	X
Backup	-	X	X	X
Change component settings	-	-	X	X
User manager	-	-	-	X
Contacts	-	-	-	X
Alarms	-	-	-	X
Options	-	-	-	X
Tags	-	-	-	X
OPC options	-	-	-	X
Idle/Edit	-	-	-	X

The user group access control prevents any unauthorised personnel to change the system parameters. Only administrators have full access to control actions. This ensures that safety conditions are never bypassed unless the necessary permission is given. Alarm notifications can be set to alert the user when a preset safety condition has been reached. Notifications appear on the screen of the server. Off-site personnel can receive alarm notifications via email or SMS.

BAC controller

The BAC controller can be used to control BACs, pumps and fridge plants. Start and stop tag inputs were added for these three components. The fridge plant component consists of compressors, evaporator pumps and condenser pumps. Tag inputs are used by the BAC controller to send start and stop commands. Once a component's start or stop tag has been set, the SCADA and PLC on site execute the command.

Control parameters and conditions can be submitted or modified on the edit form of the BAC controller. Several BAC controllers can be added to the platform. Individual measurements need separate controllers to access the relevant equipment. Figure 2.9 shows the edit form of a BAC controller. The edit form is used to establish the relationship between the input values and the control elements.

Settings

Description
BACController 1

Control permissions

Permission tag 1 / Fix

Control enabled tag 1 / 24P / CH=14

Peak time tag 0 / 24P / CH=14

Force start tag 0 / 24P / CH=14

Control procedure status

☒ Enable dam level control for pumps and fridge plants

Tag pulse time 15 s

Elements to control

Pumps	Fridge plants	BACs
CAPump 1	CAFridgePlant 1	BAC 1
CAPump 2	CAFridgePlant 2	

Add Delete Add Delete Add Delete

Input limits

Temperature tag 18 / Tag / InternalTag Temp W/B calc

Min value 14 / Fix

Max value 25 / Fix

Dam level tag 69 / Tag / InternalTag DamLevel

Min value 50 / Fix

Max value 90 / Fix

OK Cancel

Figure 2.9: BAC controller edit form

The temperature tag input on the BAC controller edit form displays the measured wet-bulb temperature value. This can be an underground temperature measurement or the BAC air outlet temperature. Minimum and maximum inputs are used to specify the control range. Once the input measurement exceeds the given limit, the control procedure is initiated. The listed control elements are then switched on or off, depending on the control philosophy.

Each site has a unique configuration in terms of equipment and therefore measurements. Control elements are listed according to the site layout. One temperature measurement can, for instance, be associated with five refrigeration components. The operator can select which elements will form part of the control sequence. A list of all the BACs that were added to the platform is shown when the add BAC button is clicked. Figure 2.10 shows the BAC selection form.

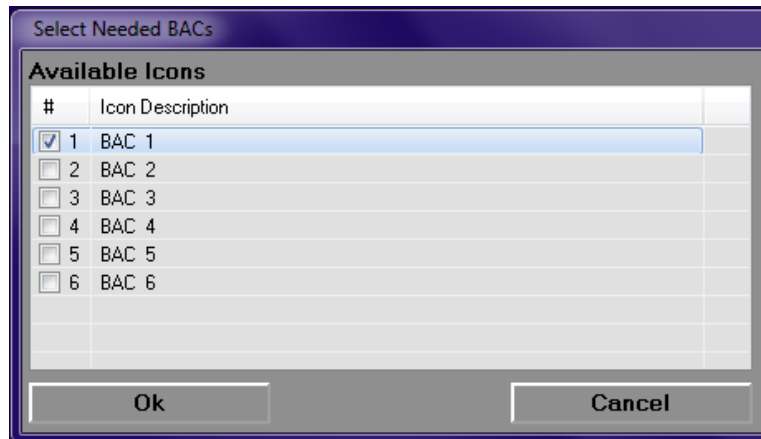


Figure 2.10: *BAC selection form*

The BAC controller edit form also includes buttons to add fridge plants or pumps. These buttons open the respective selection forms. Different BAC controllers can thus be used in parallel to control the plant collectively. Each BAC controller will write out commands to the elements listed on the respective edit forms. The peak time tag value can be extended to enable control before or after the evening peak period.

Control will only be enabled if the permission tag and the control enabled tag are both true. The software platform makes use of a ‘run procedure’ to determine if control has been enabled for the BAC controller. All the conditions in the run procedure are continuously checked while the platform is active. Only when the BAC controller is enabled, will it start to execute its control instructions. The run procedure will discontinue control once the control enabled tag value is false.

When all the prerequisites are met the control procedure will commence. The BAC controller will step through the listed elements to control. The controller will check the status of the component. If the unit is switched off, the controller will not make the stop tag true. This also applies to the start procedure. Another check is whether the limit of start or stop attempts has been reached. This is to prevent cycling of components (multiple starts or stops) that may damage equipment or even counteract the electricity savings.

Control elements

The first control element to be discussed is the BAC component. Separate start and stop tags can be assigned to the BAC pumps and the BAC fans. This enables independent control of the pumps and fans. The key measurements of a BAC can be seen on the BAC component

edit form, shown in Figure 2.11. These measurements are visible if the corresponding tags are available. Inlet and outlet temperatures of the BAC water and air is shown. The air that is cooled by the BAC and sent down to the shafts is represented by the air temperature out value.

The screenshot shows a 'Settings' dialog box for 'BAC 1'. It has three main sections: 'Description', 'Control permissions', and 'Inputs'. The 'Description' section contains a text field with 'BAC 1'. The 'Control permissions' section has a 'Priority tag' field with '1 / Fix'. Below this, there are two columns: 'BAC Fan' and 'BAC Pump'. Each column has 'Start tags' and 'Stop tags' fields, all with '0 / Fix'. The 'Inputs' section is a table with 8 rows and 3 columns. The first two columns are labels for various inputs, and the third column is a status field.

Inputs		
Water pressure	0 / Fix	
Flow rate	0 / Fix	
Water temperature in	0 / Fix	
Water temperature out	0 / Fix	
Air temperature in	0 / Fix	
Air temperature out	0 / Fix	
Fan status	0 / Fix	
Pump status	0 / Fix	

At the bottom of the dialog are 'OK' and 'Cancel' buttons.

Figure 2.11: *BAC edit form*

Secondly, the BAC controller is able to control fridge plant components. The fridge plant edit form is shown in Figure 2.12. Fridge plants added to the platform represent the chillers on site. Chillers consist of a condenser and an evaporator circuit. The measured values are displayed on the edit form. Evaporator and condenser pumps each have an inlet temperature, outlet temperature and a flow rate. The evaporator pump can also have inlet and outlet temperature set points.

Fridge Plant settings

Description
 CAFridgePlant 1

Fridge plant

Status tag

☒ Bit ☐ Byte ☐ Spec. Bits

Priority tag 1 / Fix

Start tag 0 / Fix

Stop tag 0 / Fix

Evaporator

Status

Inlet Temp

Outlet Temp

Flow tag

Inlet temp SP

Outlet temp SP

Condenser

Status

Inlet Temp

Outlet Temp

Flow tag

Figure 2.12: *Fridge plant edit form*

Lastly, it is possible to include individual pumps to the control elements. The site layout usually consists of separate stand-alone pumps such as transfer pumps. These pumps can also be controlled automatically. A pump component can be used to represent the pump of another system, for example a fridge plant evaporator pump. This allows the operator to determine how many pumps are presently running.

2.5 Theoretical results

In order to verify the correct operation of the BAC controller, several test conditions were used as inputs. Each test condition is a possible on-site event that can occur during the control procedure. The relationship between the input conditions and the resulting output

was compared to the expected outcome in each test case. This process illustrates the BAC controller's execution of control commands.

The BAC controller is responsible for the control of the equipment listed on the edit form. Depending on the control permissions and the time of day, machines can be switched off or on. Control commands are subject to the preset conditions. The following tests were conducted to confirm that each control mode functions according to the design.

Verification tests

There are two modes of control, namely, peak control and off-peak control. These modes refer to when the stop or start procedures are initiated. Within each mode is the option to use status control or pulse control. This refers to when a stop or start procedure is considered to be completed. Once a procedure is completed the relevant tags are reset to zero. Ramp functions were used to simulate the dam levels and temperature inputs that were used in the tests.

1. Status control test

The status control mode should discontinue a stop or start command when the relevant status tag value has changed according to the instruction. This means that the start tag should remain '1' until the status has changed to *On*. Vice versa, the stop tag should remain '1' until the status has changed to *Off*.

The first test was done by changing the status from *On* to *Off* three minutes after the stop tag was triggered. Figure 2.13 shows that the stop tag is reset to zero once the status value changed to zero. The second test was done by changing the status from *Off* to *On* five minutes after the start tag was triggered. Figure 2.14 shows that the start tag is reset to zero once the status value changed to one.

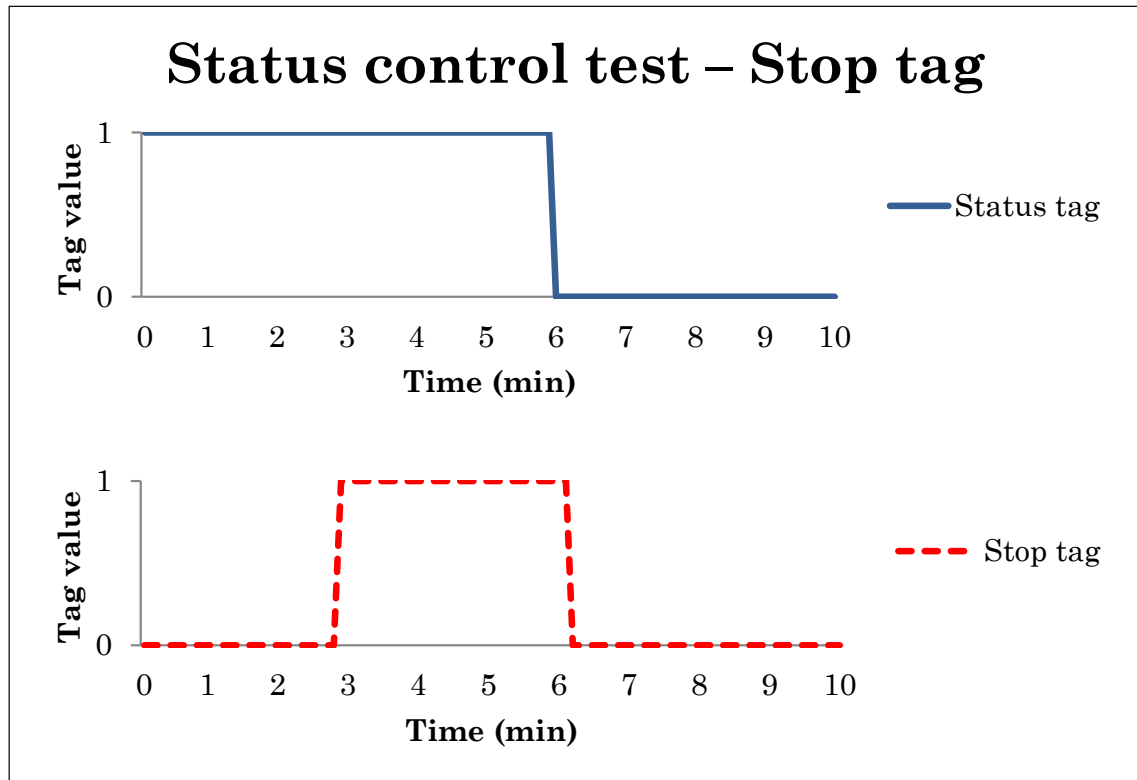


Figure 2.13: *Status control test with a stop tag*

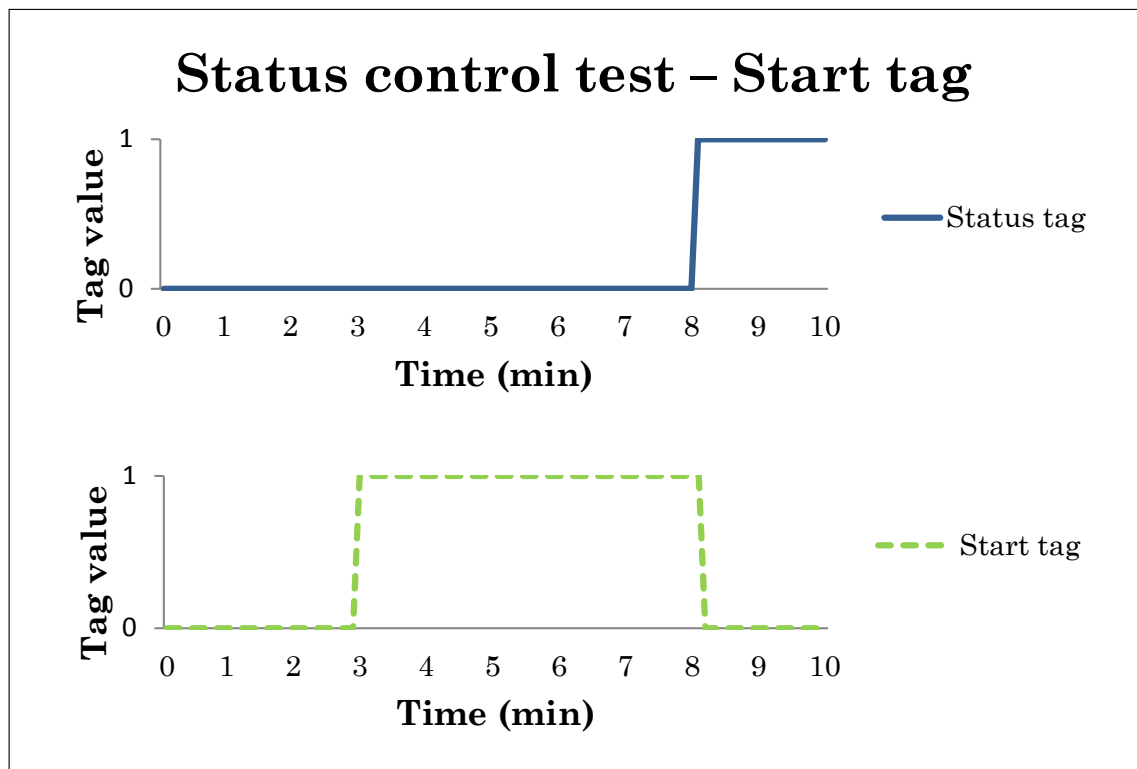


Figure 2.14: *Status control test with a start tag*

The results of the two status control tests show correct operation of this control option. In each case the BAC controller reset the tags to zero once the status changed according to the instruction. Status control is therefore verified.

2. Pulse control test

Unlike status control, the pulse control mode only takes the pulse period into account. Stop and start tags should therefore only be set for the given period, regardless of whether the status of the equipment has changed.

Both of the pulse control tests were performed by setting the pulse period to five minutes. The status was changed from *On* to *Off* two minutes after the stop tag was triggered. Figure 2.15 shows that the stop tag remained high for the remaining three minutes. In the next test, the status was changed from *Off* to *On* seven minutes after the start tag was triggered. Figure 2.16 shows that the start tag was reset to zero, even though the instruction had not been completed.

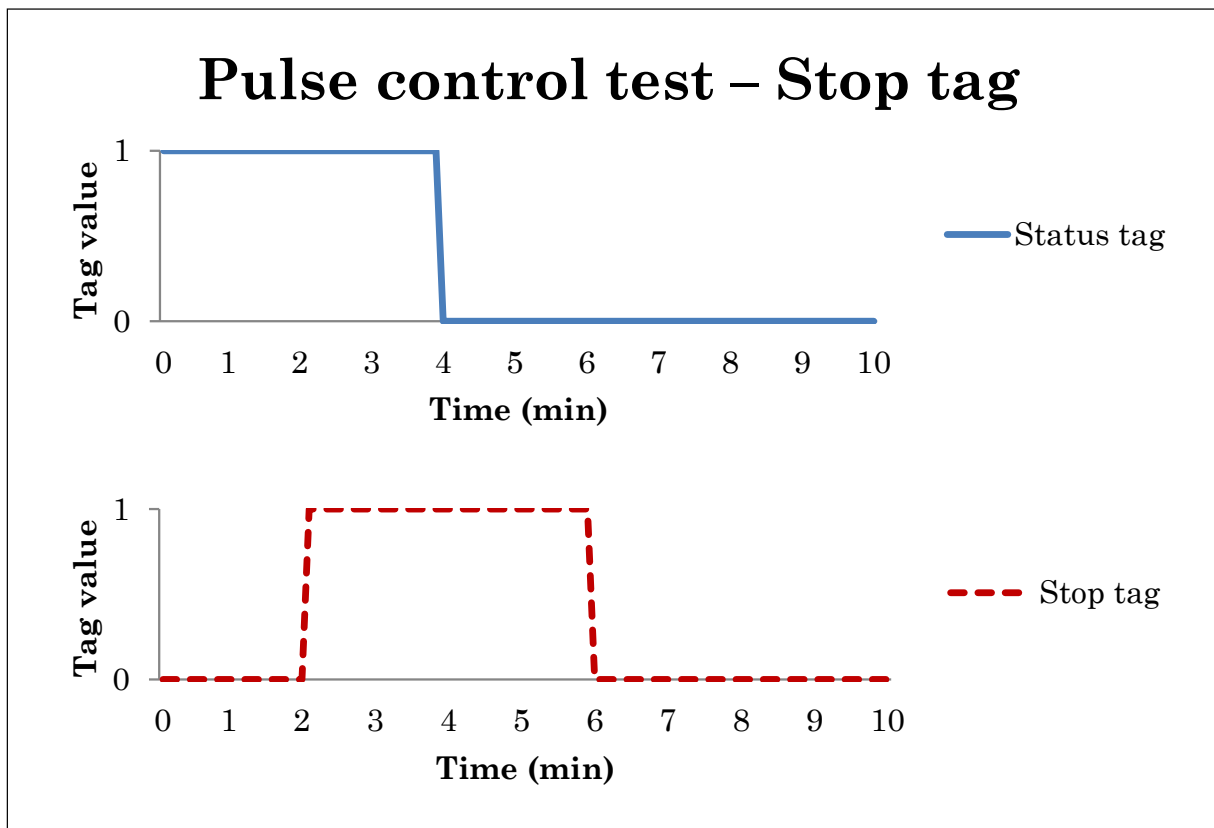


Figure 2.15: *Pulse control test with a stop tag*

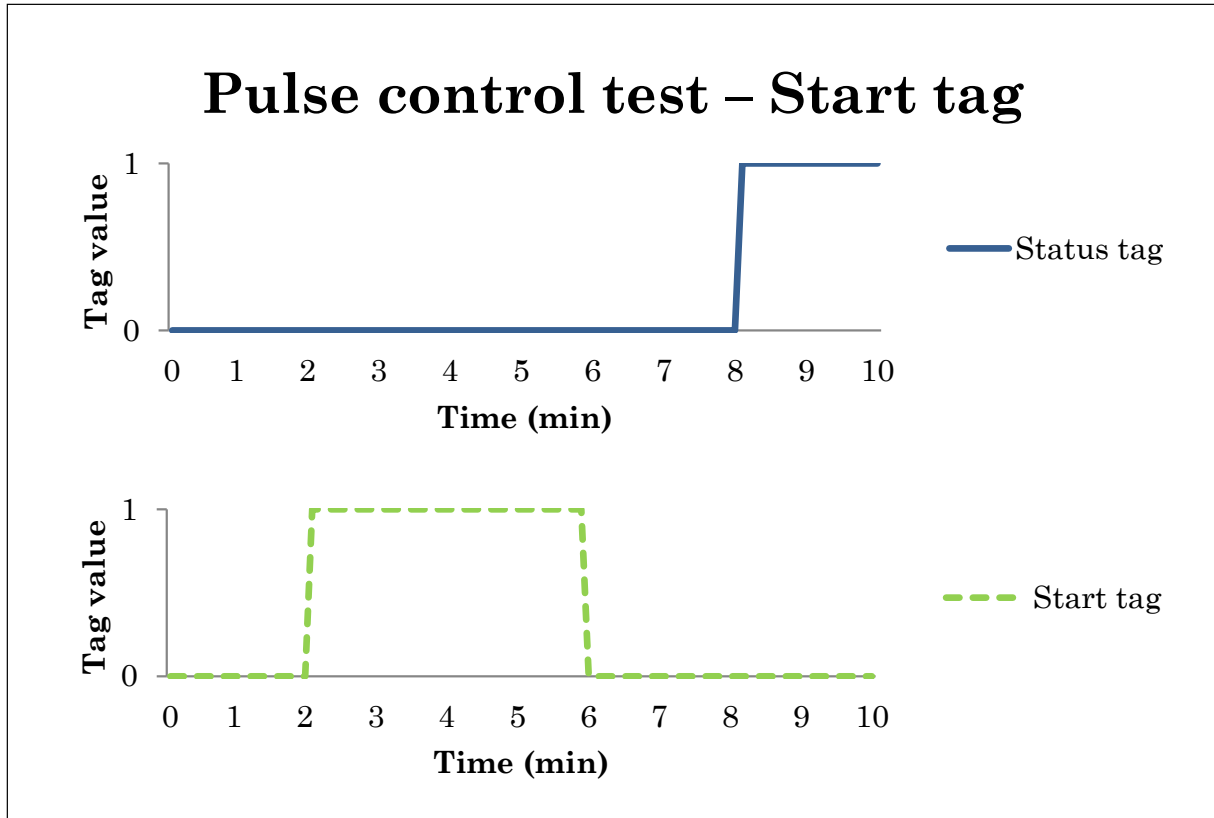


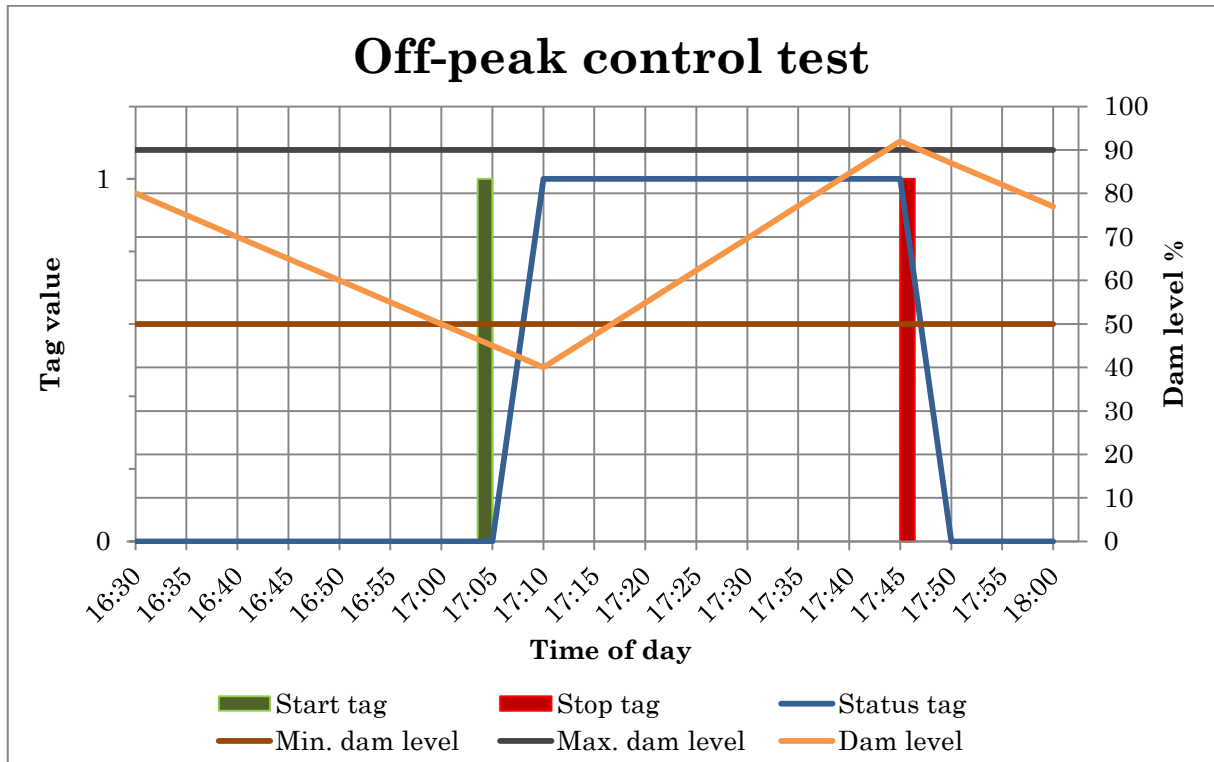
Figure 2.16: *Pulse control test with a start tag*

The results of the two pulse control tests show correct operation of this control option. In each case the BAC controller reset the tags to zero once the pulse time period was over. Pulse control is therefore verified.

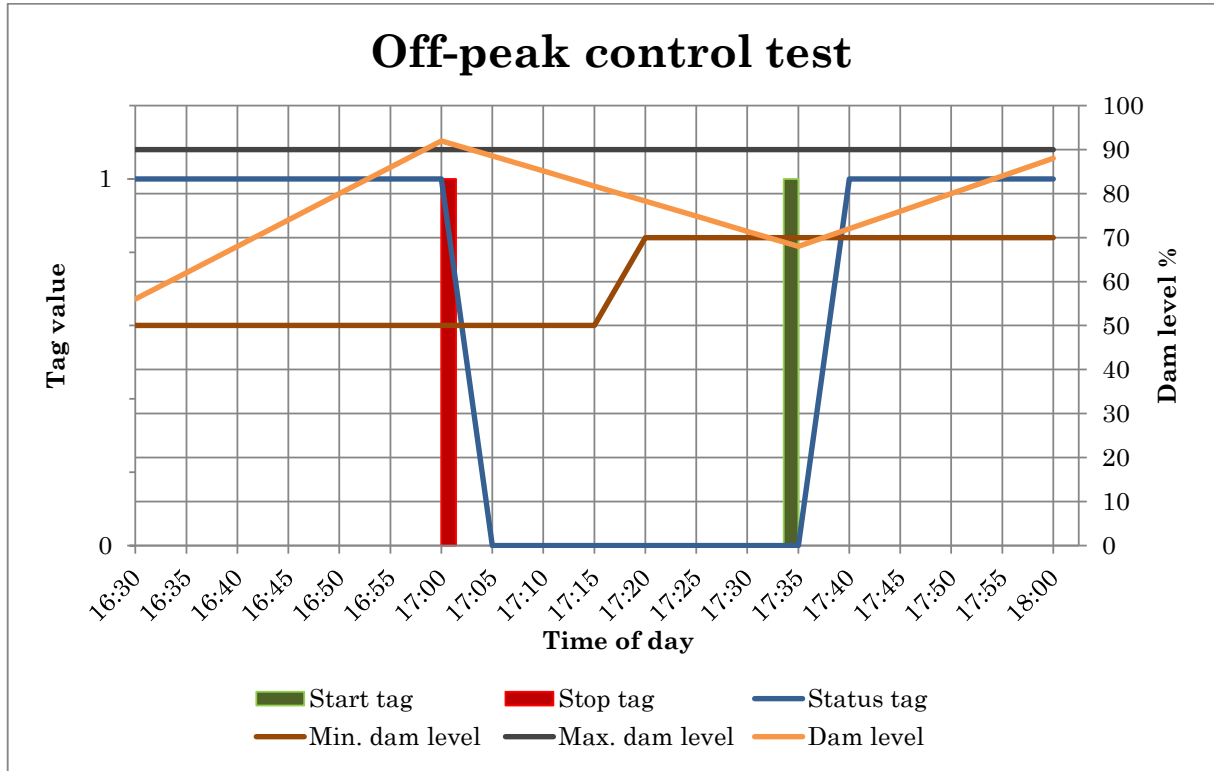
3. Off-peak control test

This control mode is used to prepare the refrigeration system for the peak period. Stop tags should be triggered when the dam level is high and start tags should be triggered when the dam level is low.

Figure 2.17 shows an off-peak control procedure with a simulated dam level input. The pump status changes to *On* when the start tag is triggered at 17:05. This was due to the dam level dropping below the specified minimum of 50%. At 17:45 the stop tag is triggered and the pump status changes to *Off*. This event occurred when the dam level exceeded the maximum value of 90%.


 Figure 2.17: *Off-peak control test – Scenario 1*

It is also possible to assign a time-dependent profile value to the allowable minimum or maximum dam levels. This enables the user to increase the minimum dam level value when the peak period is approaching. Figure 2.18 shows an off-peak control procedure where the allowable minimum is increased 40 minutes prior to the start of the peak period. The graph shows the pump's start tag was triggered at 17:35. A subsequent increase in the dam level is visible and at 18:00 the dam level reaches 88%.


 Figure 2.18: *Off-peak control test – Scenario 2*

The results show correct operation of the off-peak control procedure. This control procedure continuously compares the *Dam level* tag value to the specified minimum and maximum values. Control elements (only pumps and fridge plants) are switched on when the dam level drops below the minimum. The dam level will thus start to increase. As soon as the dam level exceeds the maximum, the control elements are switched off. Off-peak control is therefore verified.

4. Peak control test

This control procedure always starts with shutting down the listed control elements. Machines will not be switched off if the temperature and dam level measurements are not within the control range. Start tags should be triggered if any one of the start conditions are triggered.

The first condition that can trigger the BAC controller to end the peak control procedure is a high temperature measurement. A start command must be sent to all the control elements when the temperature exceeds the specified maximum. Figure 2.19 shows the execution of a peak control procedure with simulated underground air temperatures as input. The stop tag is triggered at 18:00 when the peak period starts. At 19:45 the temperature measurement is

above the allowable maximum. The start tag value therefore changed to '1', followed by the status which changed to 'On'.

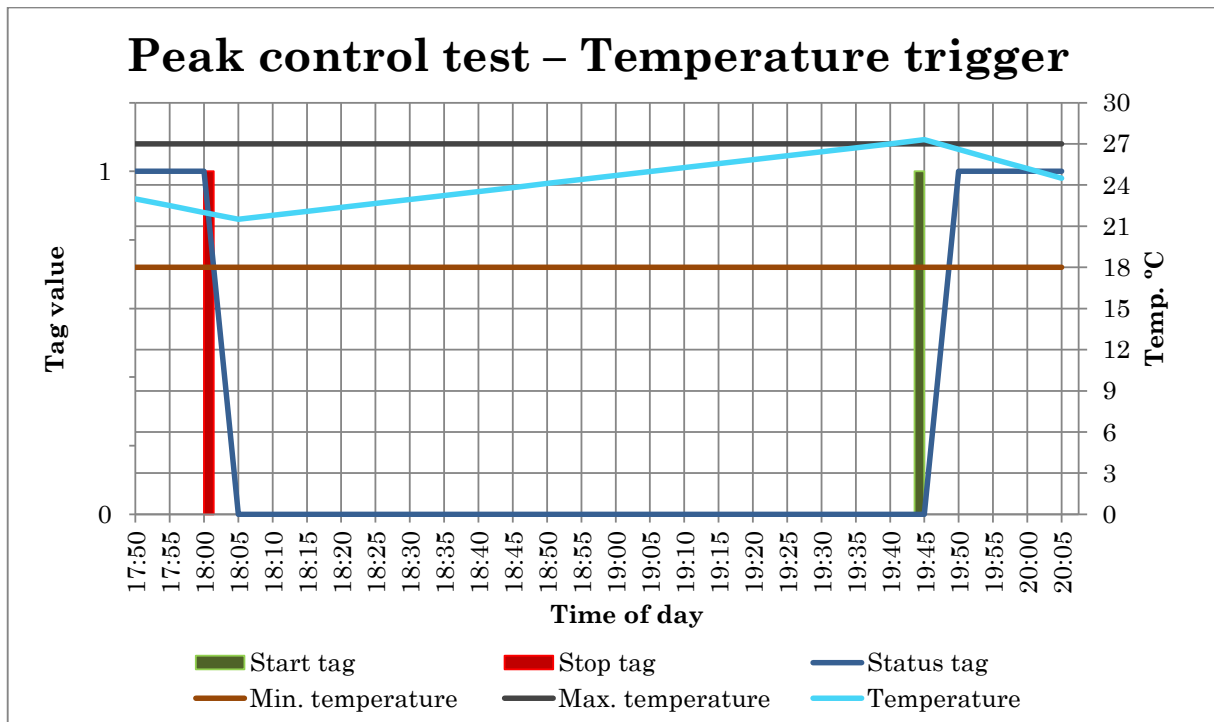
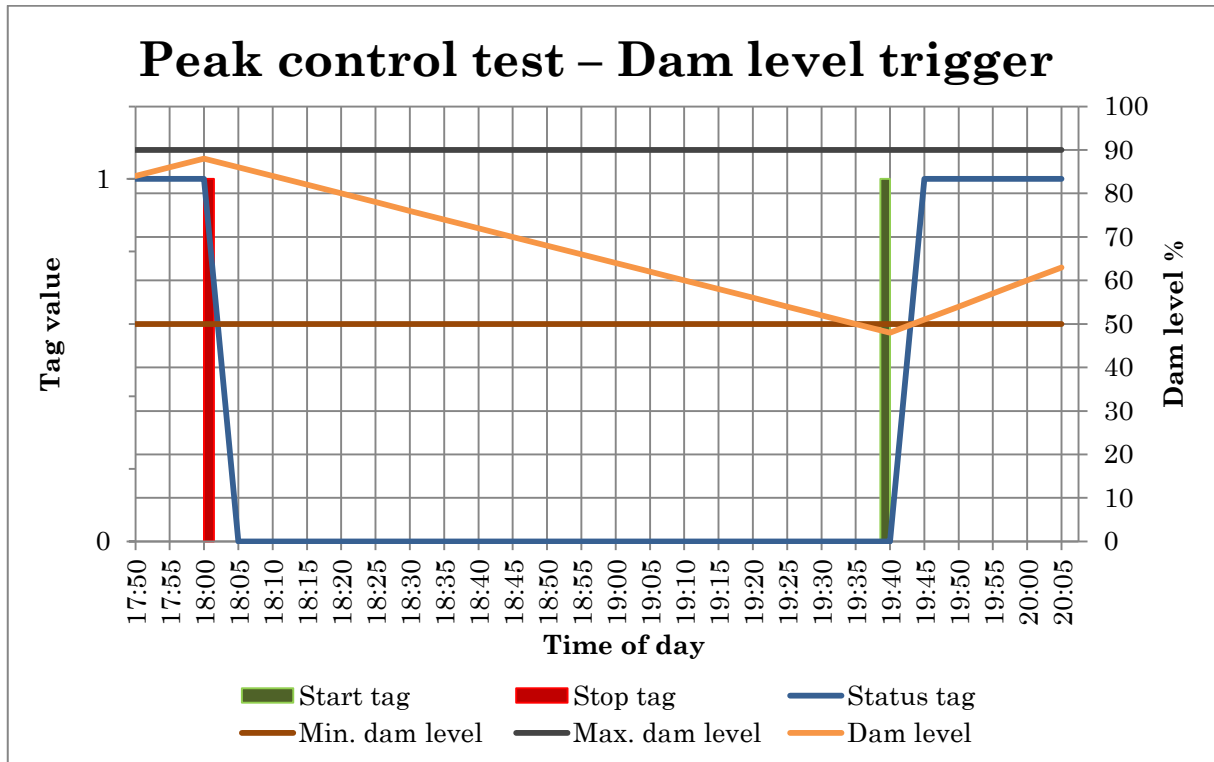
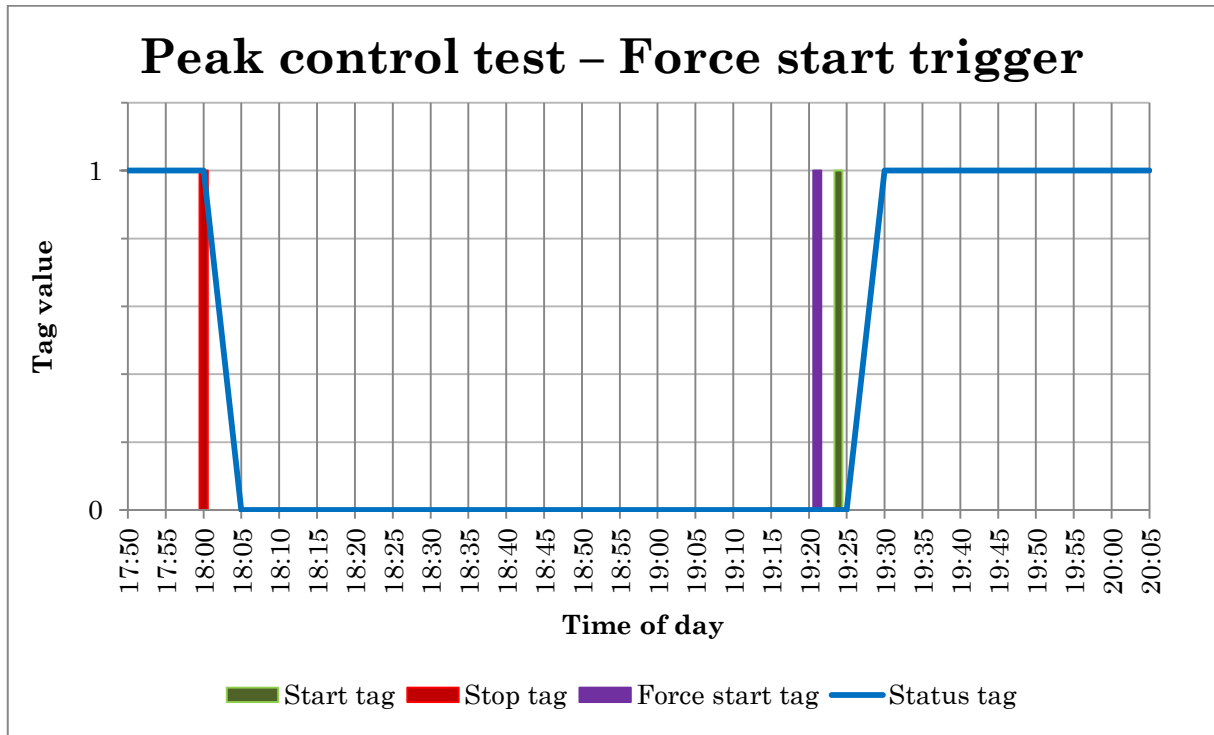


Figure 2.19: *Peak control test – Temperature trigger*

The second peak control test was performed using a simulated dam level as input. A low dam level should trigger the BAC controller to switch on the control elements. Figure 2.20 shows the result of the test where the peak control procedure was ended at 19:40. The dam level measurement at that point was 50%. It therefore triggered the start tags of all the control elements.


 Figure 2.20: *Peak control test – Dam level trigger*

Depending on the written agreement with the mine, it may be required to end the peak control procedure at 20:00. This means that the controller needs to start the components at the end of the peak period. Environmental conditions may still be within range, meaning that a time-dependent start-up trigger is needed. In a case like this, the *Force start tag* can be used. These tags can be given a 24-hour profile value, where a specific output is linked to a time interval during the day. Figure 2.21 demonstrates the effect of using a *Force start tag* programmed to return a value of '1' at 19:20.


 Figure 2.21: *Peak control test – Force start trigger*

The peak control test results correspond with the expected outcome. In each case the controller initiated a stop procedure by setting the stop tags at 18:00. The start tags remained zero until a start-up condition was triggered. Once a start-up event occurred, the start tags of the control elements were automatically set to '1'. Peak control is therefore verified.

2.6 Summary

A control system was developed specifically for mine bulk air coolers. The control system is able to switch off BACs during Eskom peak periods. In addition to the BACs, refrigeration equipment such as pumps and chillers can also be added to the control elements. The BAC controller is dynamic and will abandon the load shift procedure if any parameter does not comply with preset conditions.

The main objective was to realise cost savings by reducing the electricity usage during the Eskom peak period. Peak period electricity usage is much more expensive than the off-peak and standard periods. It therefore makes financial sense to shift the electricity usage to the off-peak period.

The BAC controller can be used to prepare the refrigeration system before the peak period by making use of the off-peak control procedure. This ensures that the system can sustain the demand while load shifting is implemented. The peak control procedure sends stop commands to the designated machines at the start of the peak period. If any start-up condition is triggered the controller sends start commands to the control elements.

CHAPTER 3

RESULTS

3.1 Foreword

This chapter contains relevant information regarding the validation of the BAC controller. Aspects that were considered during the implementation phase are discussed. These aspects are not site-specific and mostly refer to hardware and software integration in a general sense. The case studies provide detailed information relating to the individual implementations. In order to illustrate the effect of the intervention, each case study includes results pertaining to one day's measurements. Results are presented and compared with the theoretical results.

3.2 Implementation

The software control system was developed in a simulation environment. Variations in component values were incorporated via simulated SCADA tags. Control system commands were executed manually on the platform. Once the design verification was completed it was possible to start with the on-site implementation.

Site infrastructure considerations

The user determines how the control system would be used on the specific site. Firstly, the equipment that needed to be controlled was identified and assigned to BAC controllers as shown in Figure 3.1. A software platform was then created according to the site layout. The final step before the platform is complete is to assign the relevant tags to the corresponding input and output fields.

The following systems are the main elements on site that are controlled:

- Fridge plant evaporator water pumps;
- Fridge plant condensor water pumps;
- Condenser cooling tower fans;
- Fridge plant condenser water inlet valves;
- Fridge plant transfer pumps;
- Pre-cool tower fans;
- Pre-cool tower transfer pumps;
- Bulk air cooler fans; and
- Bulk air cooler water pumps.

As this is a new project, it was necessary to determine whether new on-site infrastructure was needed. Before implementing the BAC platform the following additions were made where necessary:

- Isolation of condenser inlet water line valves;
- Automation of condenser cooling tower fans;
- Automation of fridge plant water transfer pumps;
- Underground temperature and relative humidity loggers; and
- BAC temperature sensors.

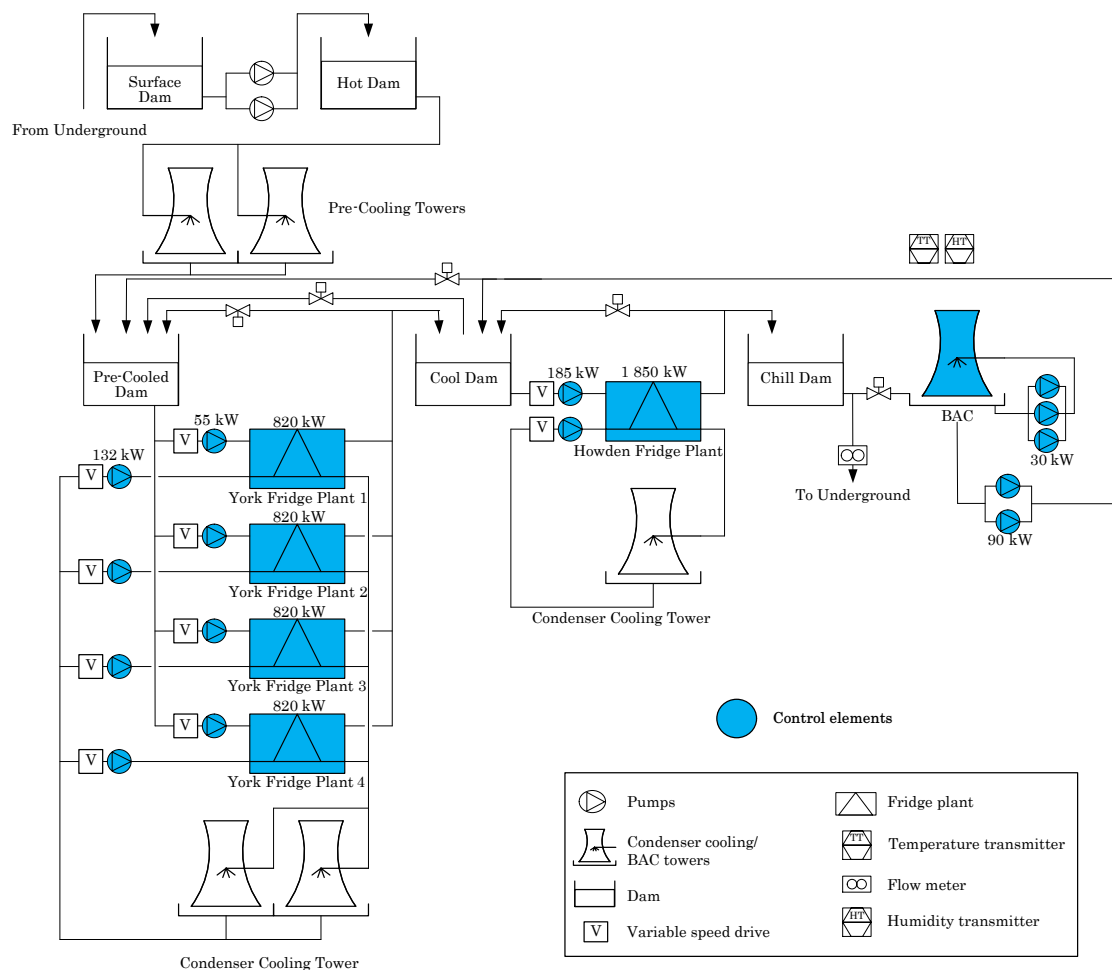


Figure 3.1: Control elements indicated on layout

Figure 3.2 shows a BAC on site. The temperature sensor that was installed on the BAC is shown in Figure 3.3. This sensor measures the BAC outlet temperature. Some sites do not have the infrastructure needed to enable communication between underground sensors and the control room on the surface. In these cases the control is based on the BAC

outlet temperature. The temperature sensors are connected to the weather station modules (Figure 3.4) which display temperature-related measurements.



Figure 3.2: *BAC on site*



Figure 3.3: *BAC outlet temperature sensor*



Figure 3.4: *Weather station module used on site*

The BAC platform contains new control elements and procedures. Provision for the elements and procedures were therefore made on the SCADA and the PLCs. Stop tags and start tags were added to the list of available tags. These tags are linked to a specific machine when they are created. Control procedures were also written in the PLC program to indicate how the tag values should be handled.

If the system is running in automatic mode, a stop tag value of '1' triggers the PLC to initiate the stop procedure. The stop procedure is site-specific and is written according to the installed equipment. Various stages are incorporated into these procedures. Time delays are built in between the shut-down commands of consecutive machines. This is to ensure that pressure levels are stable before moving on to the next command. Start procedures also work on the same principle.

The SCADA system controls the interface between the REMS BAC platform and the PLC. Depending on the status of the control system, different input and output values are sent to the PLC by the SCADA. Figure 3.5 demonstrates the communication logic between the relevant systems. The on-site SCADA computer is responsible for the following operations:

- Making system tags available to REMS BAC platform;
- Reading set point and control tags from REMS BAC and writing it to the PLC when REMS BAC is in Automatic mode; and

- Writing set point and control tags to the PLC when REMS BAC control is off or in Manual mode.

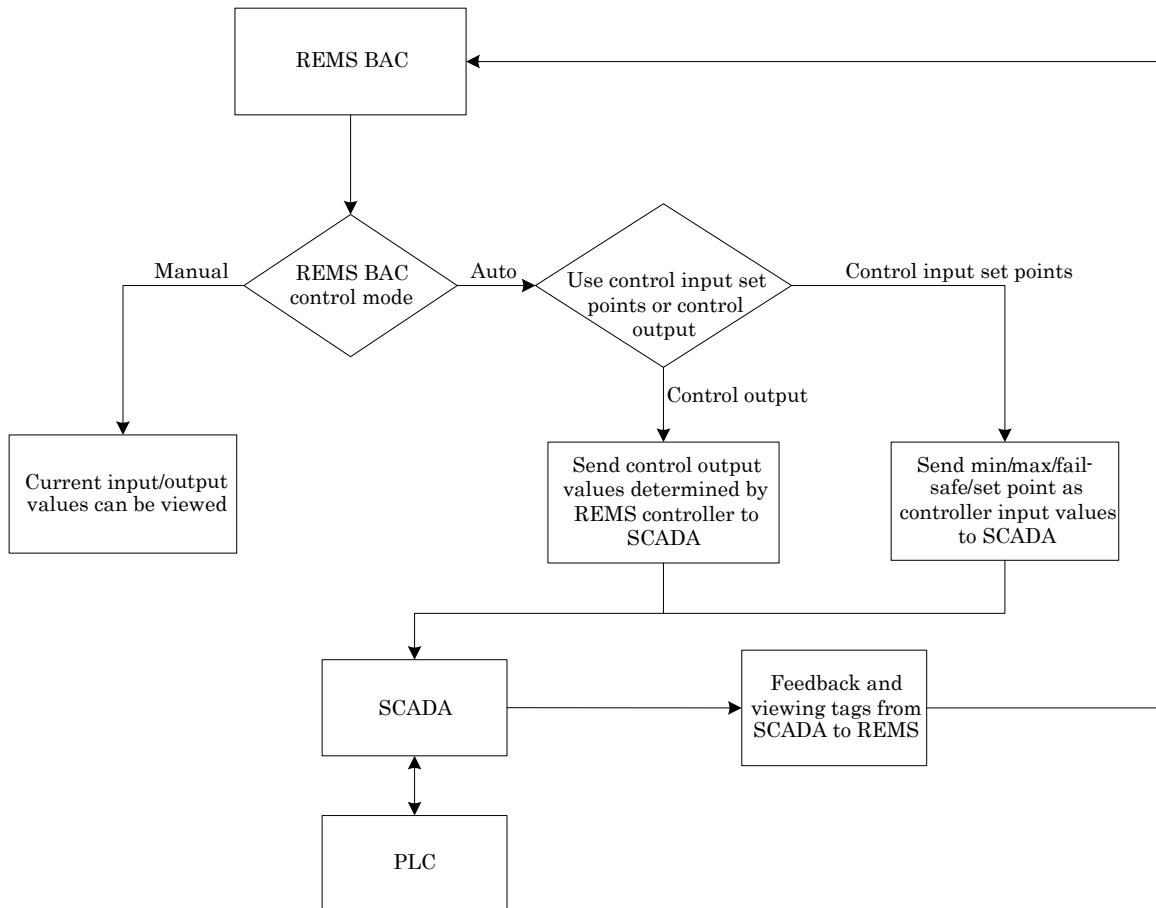


Figure 3.5: *REMS BAC communication control diagram*

Figure 3.6 shows the platform layout of a BAC project on a site with an open loop configuration, while Figure 3.7 shows the layout of a BAC project on a site with a closed loop configuration. Various refrigeration system elements have been added and connected to each other. This represents a system setup on site. Each component displays actual equipment readings. The platform is dynamic and component values are updated continuously.

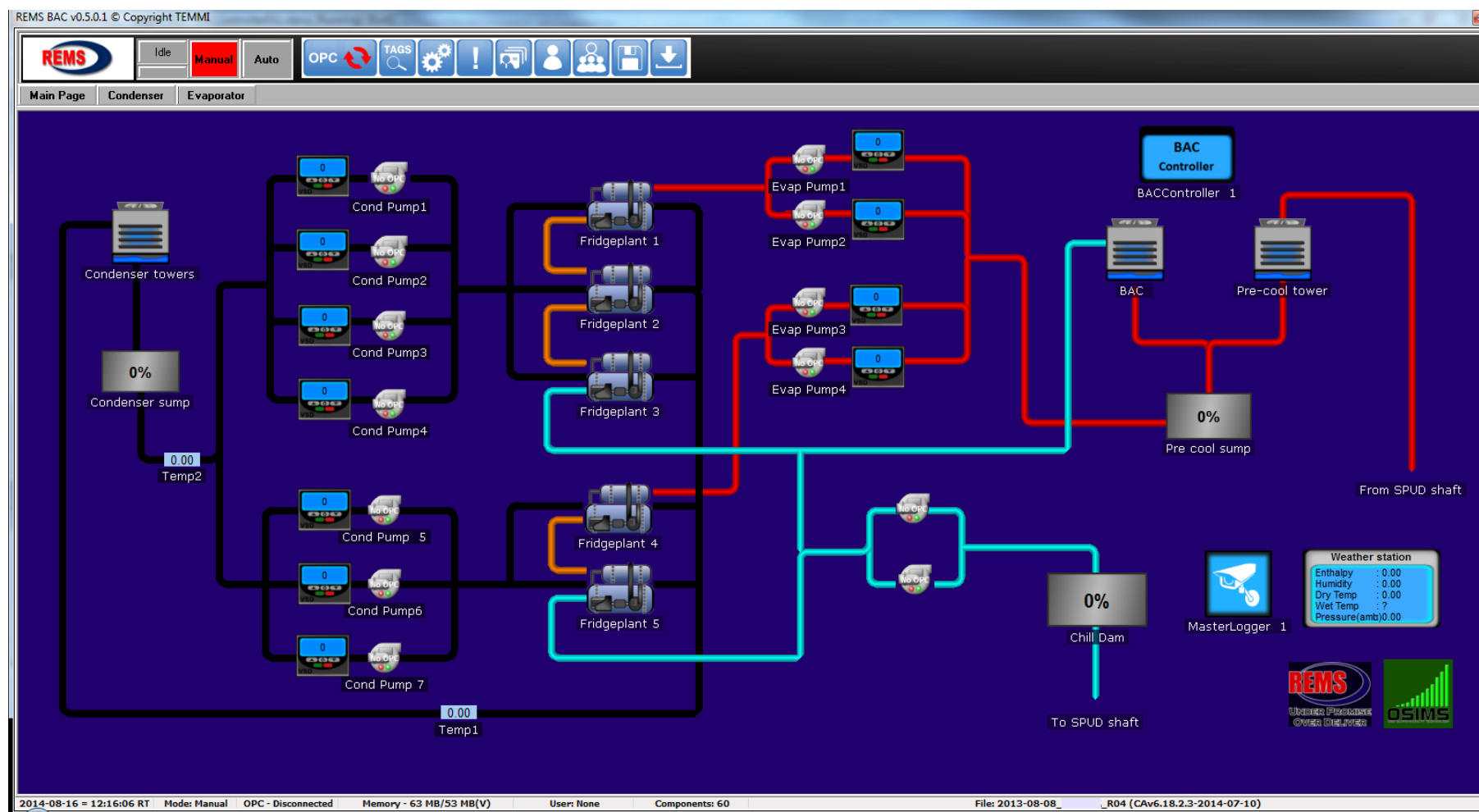


Figure 3.6: BAC platform – Open loop configuration

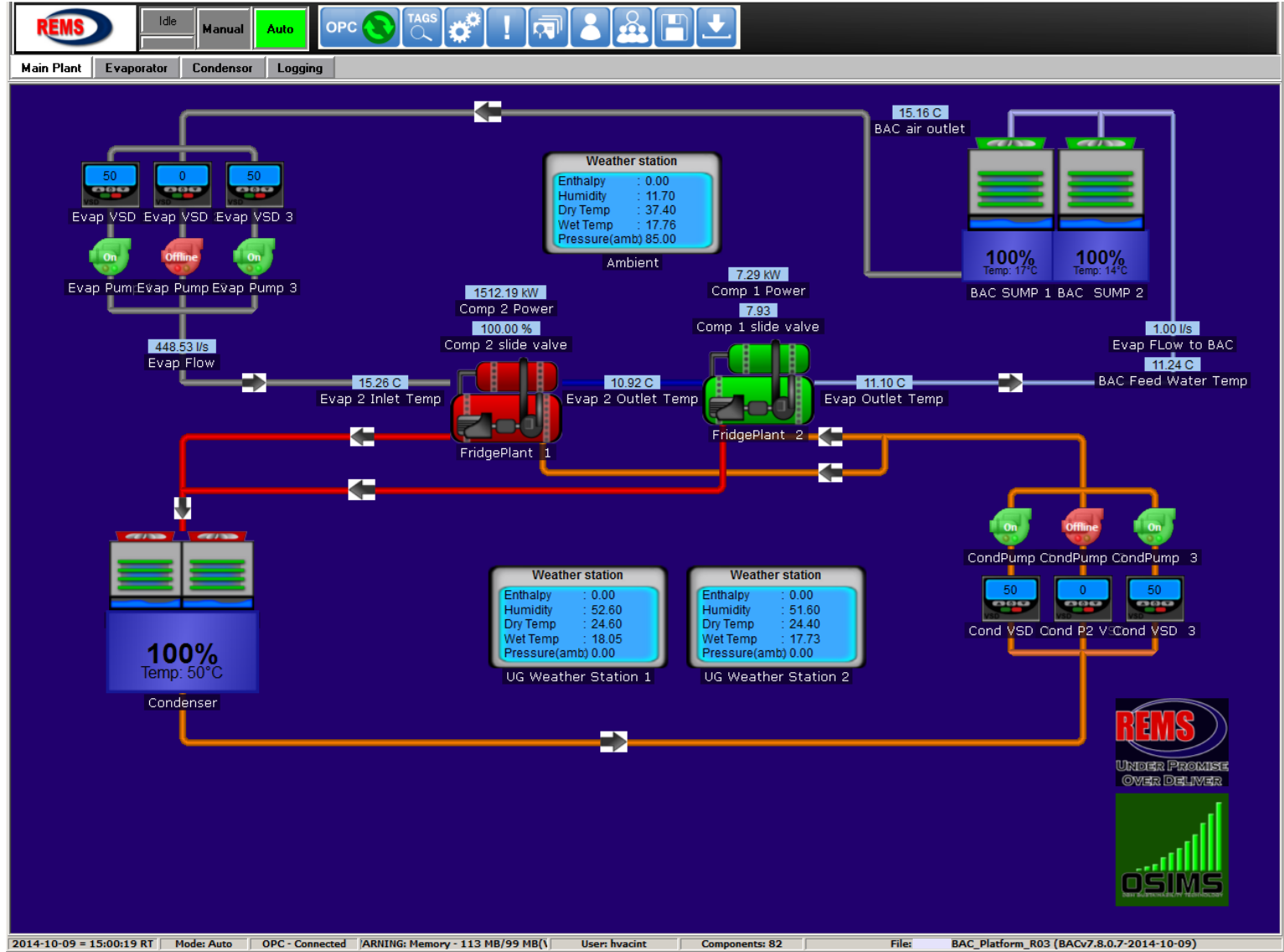


Figure 3.7: BAC platform – Closed loop configuration

The on-site equipment, SCADA computer, PLCs and REMS platform communicate with each other via the on-site control room. Everything is connected to the control room, which establishes the necessary connections. The communication medium most commonly used on site is PROFIBUS cables. PROFIBUS is short for Process Field Bus and it uses a protocol specifically developed for industrial plants where machines are automated [48].

3.3 Case study 1: Closed loop configuration

This section discusses the implementation of the BAC controller and the results that were achieved. The refrigeration system on this site consists of two fridge plants that supply cold water to one BAC. The cooling capacity of the fridge plants is 10 MW. Ambient air is cooled by the BACs to a wet-bulb temperature of 7°C. An underground temperature sensor was installed to measure the temperature and relative humidity. The underground temperature measurement was used by the BAC controller as a control parameter.

System specifications

Figure 3.8 shows the site configuration of this case study. The fridge plants and condenser cooling towers provide the BAC with cold water at a temperature of 3°C. The four BAC fans produce an airflow of 240 kg/s which is sent to the underground shafts. Table 3.1 displays the specifications of the BAC. Specifications of the two fridge plants are given in Table 3.2.

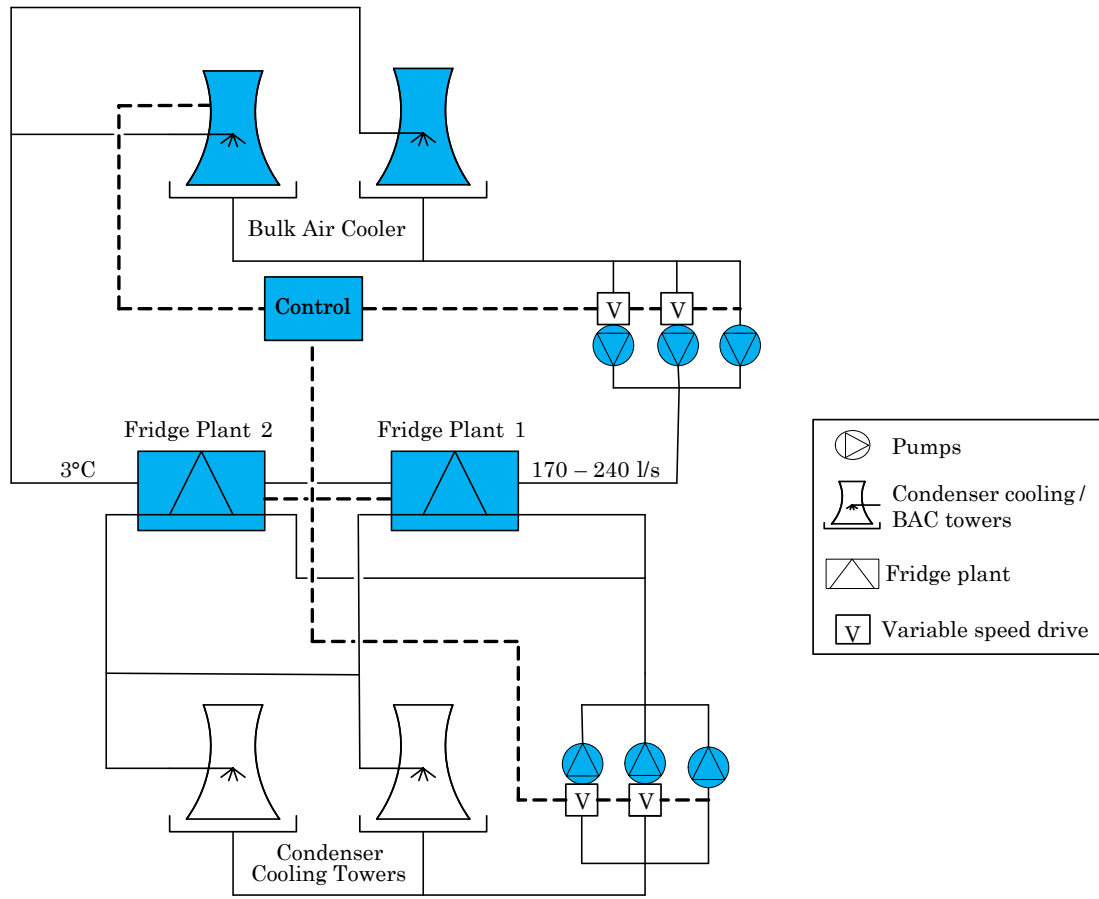


Figure 3.8: Case study 1 – Site configuration

Table 3.1: Case study 1 – BAC specification

Description	Value
Number of BACs	1
Water Inlet Temperature (°C)	3
Water Outlet Temperature (°C)	13
Water Flow (kg/s)	240
Airflow (kg/s)	240
Air Inlet Wet-bulb Temperature (°C)	22
Air Outlet Wet-bulb Temperature (°C)	7
Number of BAC cooling fans	4
BAC Cooling Fans (kW)	300

Table 3.2: *Case study 1 – Fridge plant specification*

Description	Value
Number of Refrigeration Plants	2
Make	Howden
Compressor Type	Screw
Refrigerant	Ammonia
Voltage (V)	11 000
Cooling Capacity (kW)	5 000
COP	3.6
Evaporator Outlet Temperature (°C)	7
Condenser Inlet Temperature (°C)	27
Evaporator Water Flow (kg/s)	240
Condenser Water Flow (kg/s)	450
Evaporator Pump Motor Rating (kW)	250
Number of Evaporator Pumps	3
Condenser Pump Motor Rating (kW)	275
Number of Condenser Pumps	3

Measured results

The measured results consist of start and stop commands, temperature measurements and the power profile. These results illustrate the effect of the intervention by the BAC controller. Refrigeration equipment was scheduled to switch off during the Eskom peak period. Measurements received from the underground temperature sensor and the total incoming power usage are presented here.

1. Start and stop commands

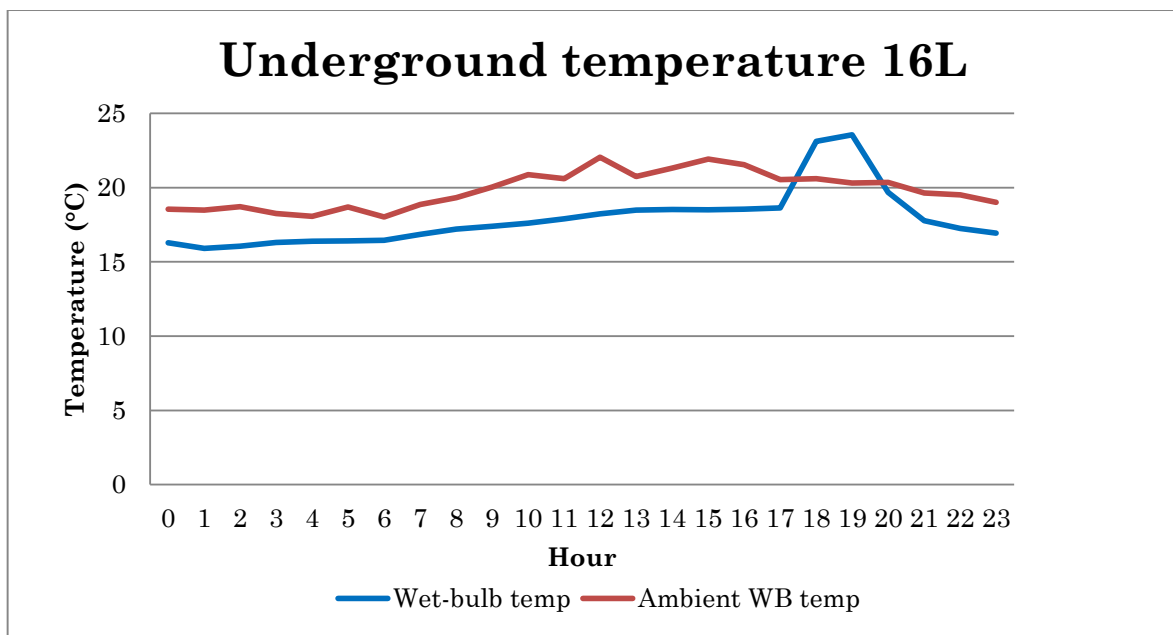
Table 3.3 lists the measurements of the control tags during the peak period. This site only uses a single stop tag and start tag to initiate the stop procedure and the start procedure respectively. The BAC controller set the stop tag value to ‘1’ at 18:00. The underground temperature did not exceed the maximum temperature set point during the peak control procedure. At 20:00 the force start tag value changes to ‘1’, which causes the BAC controller to set the start tag value to ‘1’. This initiates the start-up procedure and completes the peak control procedure.

Table 3.3: *Case study 1 – Stop and start commands*

<u>Hour</u>	<u>Stop tag</u>	<u>Start tag</u>	<u>Force start</u>	<u>Temp (°C)</u>	<u>Within range</u>
17:50	0	0	0	18.88	Yes
18:00	1	0	0	21.46	Yes
18:10	0	0	0	22.71	Yes
18:20	0	0	0	23.26	Yes
18:30	0	0	0	23.61	Yes
18:40	0	0	0	23.77	Yes
18:50	0	0	0	23.98	Yes
19:00	0	0	0	24.12	Yes
19:10	0	0	0	24.22	Yes
19:20	0	0	0	24.16	Yes
19:30	0	0	0	24.04	Yes
19:40	0	0	0	23.98	Yes
19:50	0	0	0	23.96	Yes
20:00	0	1	1	23.97	Yes
20:10	0	0	0	21.79	Yes

2. Temperature measurements

Only one underground temperature sensor was installed on 16L. Hourly averages were calculated and plotted against the ambient temperature measurement. Figure 3.9 shows the resulting temperature increase when the cold air supply was stopped. The temperature measurement does not exceed 24°C and quickly starts to drop once the machines start running again.

Figure 3.9: *Case study 1 – Underground temperature on 16L*

3. Power profile

The total incoming power for the corresponding 24-hour period is shown in Figure 3.10. Baseline information was obtained from historical data. The baseline usage for a typical weekday in the summer can also be seen. This result is a representation of a peak clipping procedure. The electricity usage is consistent with the baseline profile during the day, while the peak period usage is minimised. A 1.3 MW reduction was achieved.

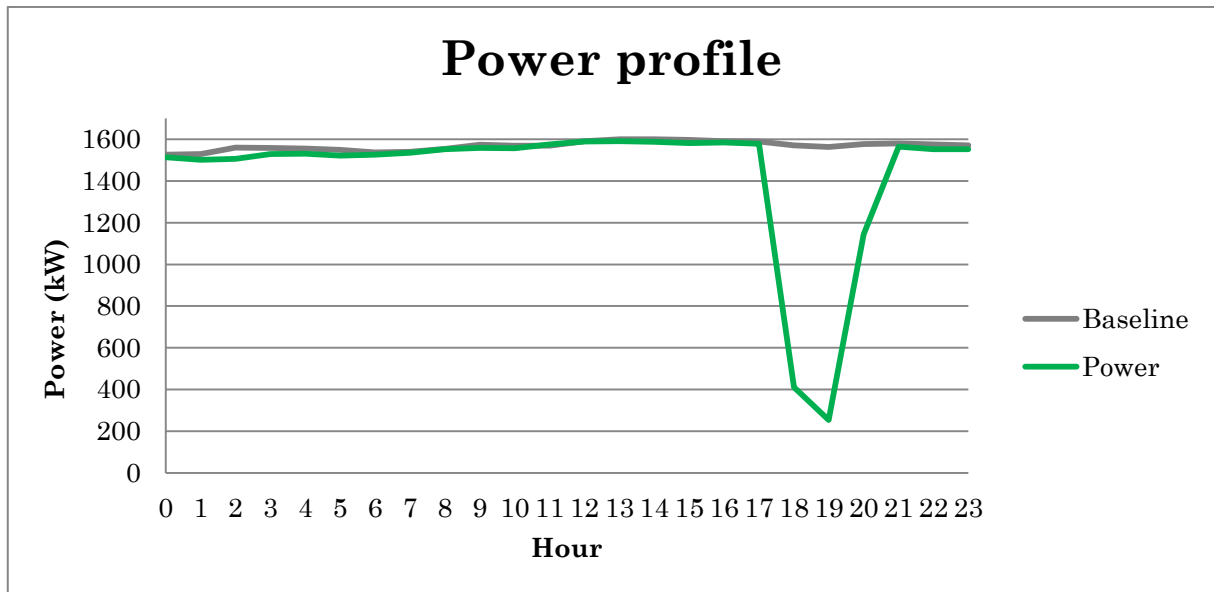


Figure 3.10: *Case study 1 – Power profile*

3.4 Case study 2: Closed loop configuration

This section discusses the on-site implementation of the BAC controller and the results that were achieved. The refrigeration system on this site consists of four fridge plants that supply cold water to two BACs. The cooling capacity of the fridge plants is 24 MW. Ambient air is cooled by the BACs to a wet-bulb temperature of 7°C. Three underground temperature sensors were installed to measure the temperature and relative humidity. The underground temperature measurement was used by the BAC controller as a control parameter.

System specifications

Figure 3.11 shows the site configuration of this case study. The fridge plants and condenser cooling towers provide the BAC with cold water at a temperature of 2.5°C. The BAC fans

produce an airflow of 728 kg/s which is sent to the underground shafts. Table 3.4 displays the specifications of the BAC. Specifications of the four fridge plants are given in Table 3.5.

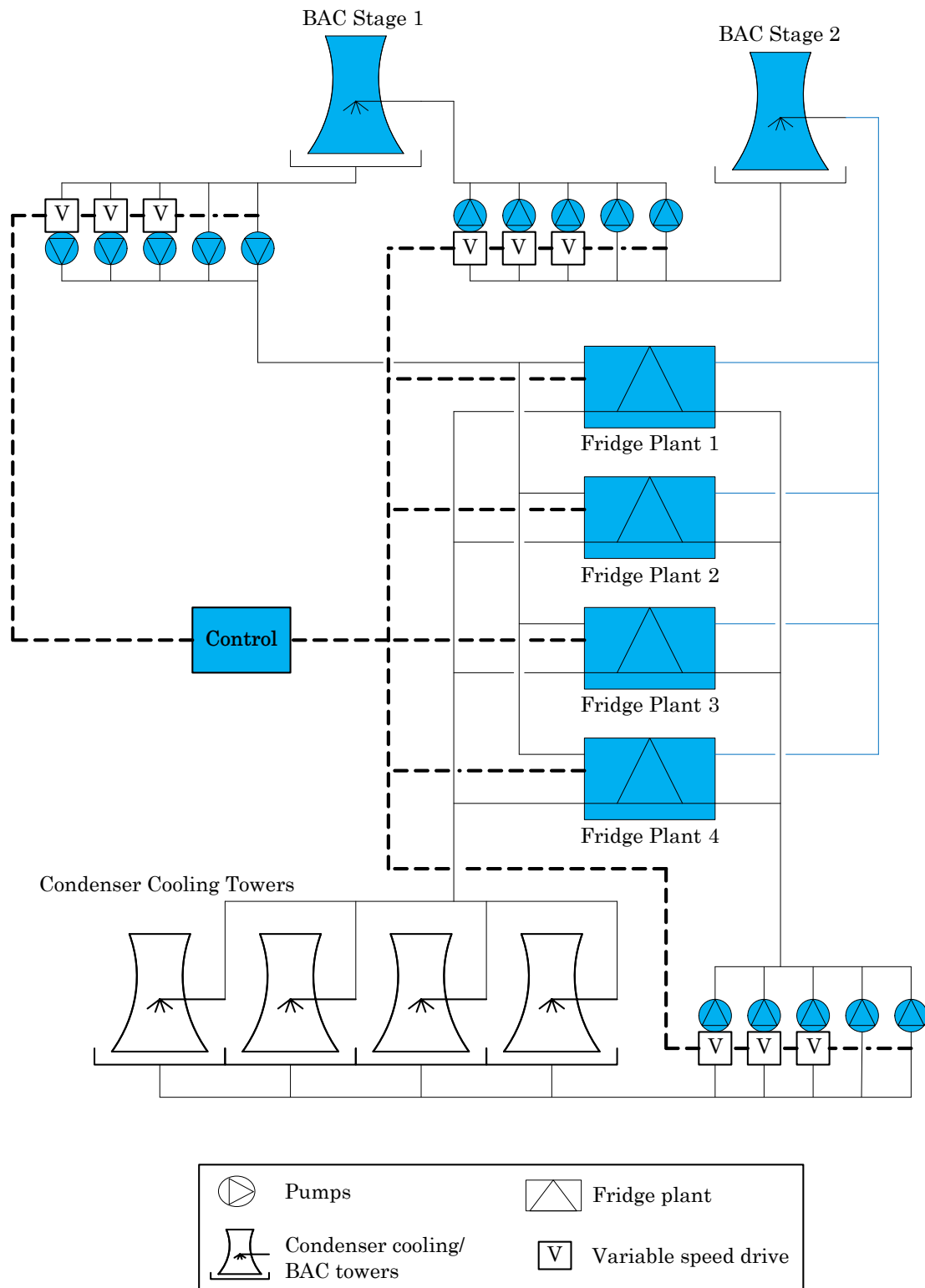


Figure 3.11: *Case study 2 – Site configuration*

Table 3.4: *Case study 2 – BAC specification*

Description	Value
Number of BACs	1
Water Inlet Temperature (°C)	3
Water Outlet Temperature (°C)	11
Water Flow (kg/s)	600
Airflow (kg/s)	728
Air Inlet Wet-bulb Temperature (°C)	17
Air Outlet Wet-bulb Temperature (°C)	7
Spray Pump Motor Rating (kW)	75
Number of Spray Pumps	5

Table 3.5: *Case study 2 – Fridge plant specification*

Description	Value
Number of Refrigeration Plants	4
Make	Howden
Compressor Type	Screw
Refrigerant	Ammonia
Voltage (V)	11 000
Cooling Capacity (kW)	6 000
COP	5.5
Evaporator Outlet Temperature (°C)	2
Condenser Inlet Temperature (°C)	21.44
Evaporator Water Flow (kg/s)	141
Condenser Water Flow (kg/s)	212
Evaporator Pump Motor Rating (kW)	132
Number of Evaporator pumps	5
Condenser Pump Motor Rating (kW)	110
Number of Condenser Pumps	5

Measured results

The measured results consist of start and stop commands, temperature measurements and the power profile. Due to the lack of cooling provided by the BACs and fridge plants, the underground temperature increased during the peak period. A consequent power usage reduction is therefore realised. Measurements received from the underground temperature sensors and the total incoming power usage are presented here.

1. Start and stop commands

Table 3.6 lists some of the platform measurements between 18:00 and 20:00. At the start of the peak period the BAC controller set the stop tag values to ‘1’. The underground temperature measurement remained within the specified limit for the duration of the peak period control procedure. It was therefore not necessary to switch on the equipment. The force start tag was preset to end the peak period control. Hence the value changed to ‘1’ at 20:00. This triggered the start tag values and the refrigeration equipment was switched back on.

Table 3.6: *Case study 2 – Stop and start commands*

<u>Hour</u>	<u>Stop tag</u>	<u>Start tag</u>	<u>Force start</u>	<u>Temp (°C)</u>	<u>Within range</u>
17:50	0	0	0	22.29	Yes
18:00	1	0	0	22.37	Yes
18:10	0	0	0	22.30	Yes
18:20	0	0	0	22.43	Yes
18:30	0	0	0	22.57	Yes
18:40	0	0	0	22.71	Yes
18:50	0	0	0	22.82	Yes
19:00	0	0	0	22.93	Yes
19:10	0	0	0	23.07	Yes
19:20	0	0	0	23.15	Yes
19:30	0	0	0	23.29	Yes
19:40	0	0	0	23.40	Yes
19:50	0	0	0	23.47	Yes
20:00	0	1	1	23.53	Yes
20:10	0	0	0	23.58	Yes

2. Temperature measurements

Three underground temperature sensors were installed on three different levels. These are three of the lowest levels namely 95L, 100L and 110L. There is a clear increase in temperature when the refrigeration equipment is switched off. A maximum temperature of 24.2 °C was measured on the bottom level (110L). This, however, is still within the acceptable temperature range. Once the machines are switched on, the temperature starts to drop immediately and finally returns to normal.

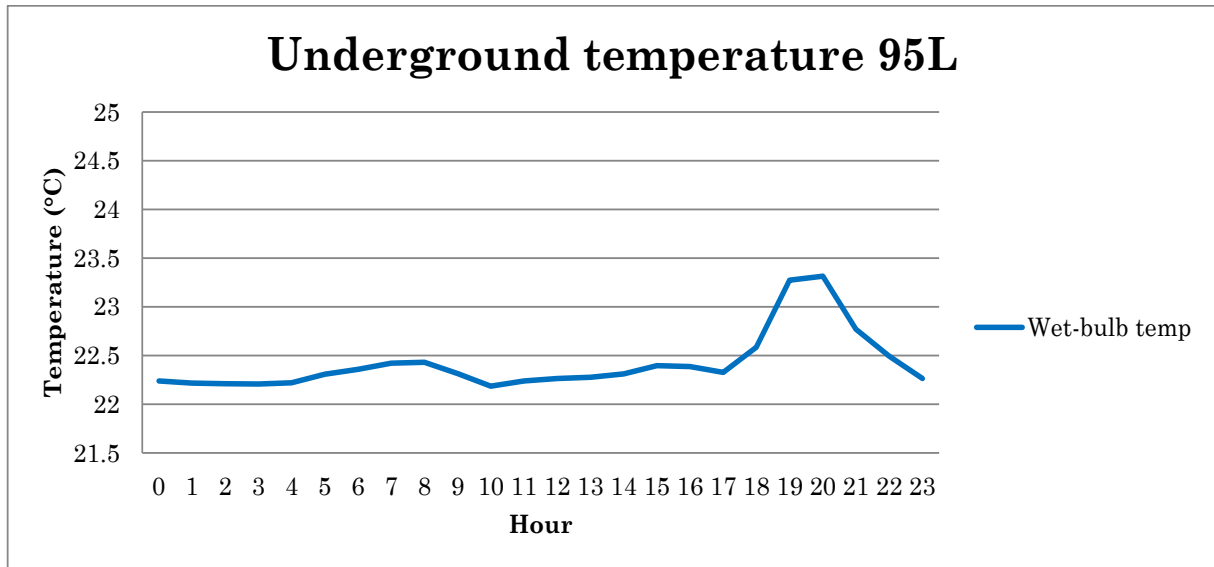


Figure 3.12: *Case study 2 – Underground temperature on 95L*

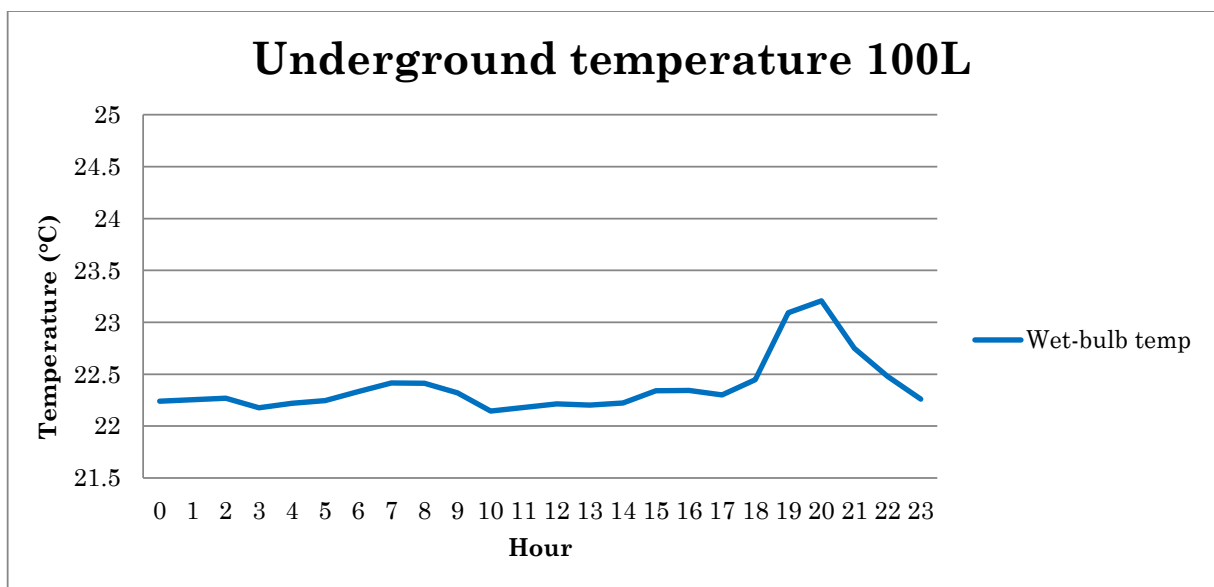


Figure 3.13: *Case study 2 – Underground temperature on 100L*

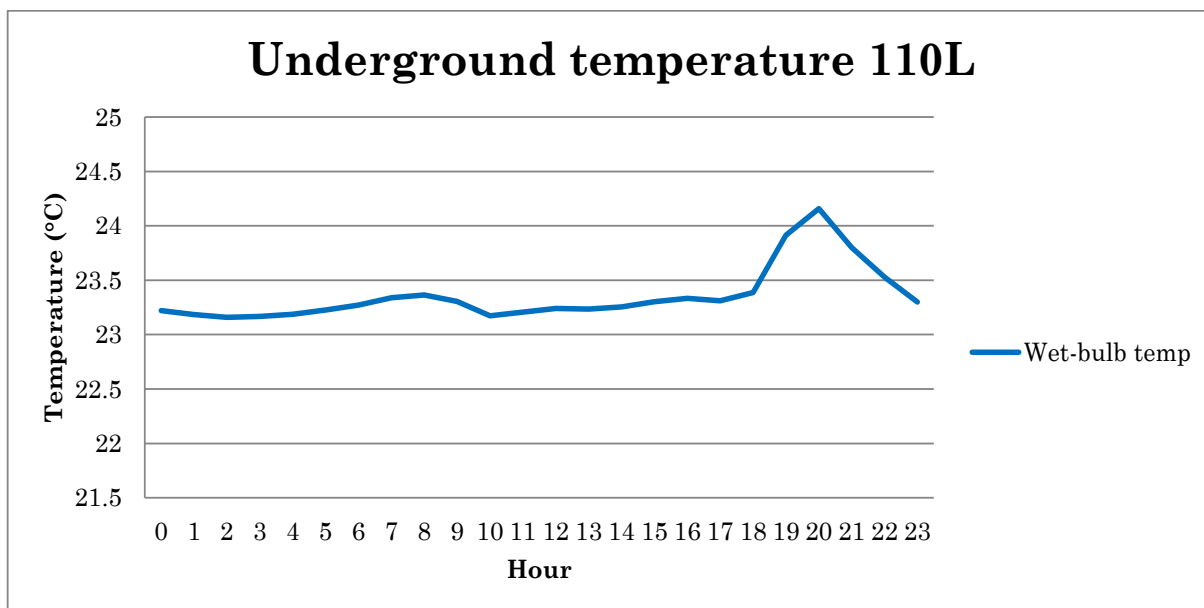


Figure 3.14: *Case study 2 – Underground temperature on 110L*

3. Power profile

Figure 3.15 shows the total incoming power of the plant. The baseline is a profile of a typical weekday in the summer. It is clear that the power usage during the peak period is well below the baseline. A maximum difference (saving) of 2.7 MW was measured. Power usage throughout the day is mostly above the baseline to ensure that the load shift procedure is possible and to maintain the targeted production quantities.

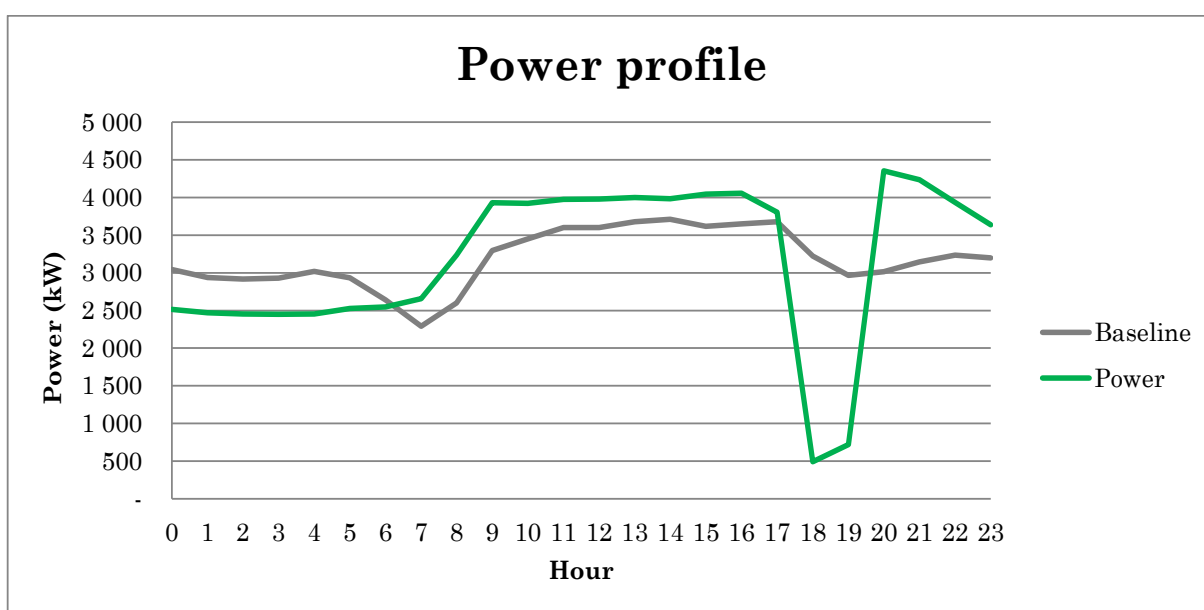


Figure 3.15: *Case study 2 – Power profile*

3.5 Case study 3: Open loop configuration

This section discusses the implementation of the BAC controller on a site with an open loop configuration. The refrigeration system on this site consists of five Howden chillers that supply cold water to one BAC. The cooling capacity of the plant is 27 MW. Ambient air is cooled by the BACs to a wet-bulb temperature of 7.7°C. The BAC controller uses the BAC outlet temperature and the chilled water dam level as control parameters. A logger was installed on an underground level to measure the effect on the underground temperature.

System specifications

Figure 3.16 shows the site configuration of this case study. Water is pumped into the chilled water dam at a temperature of 1.5°C. Table 3.7 lists the BAC specification. The BAC cools the air by means of an induced draught and therefore operates without any fans. The specifications of the fridge plants are given in Table 3.8.

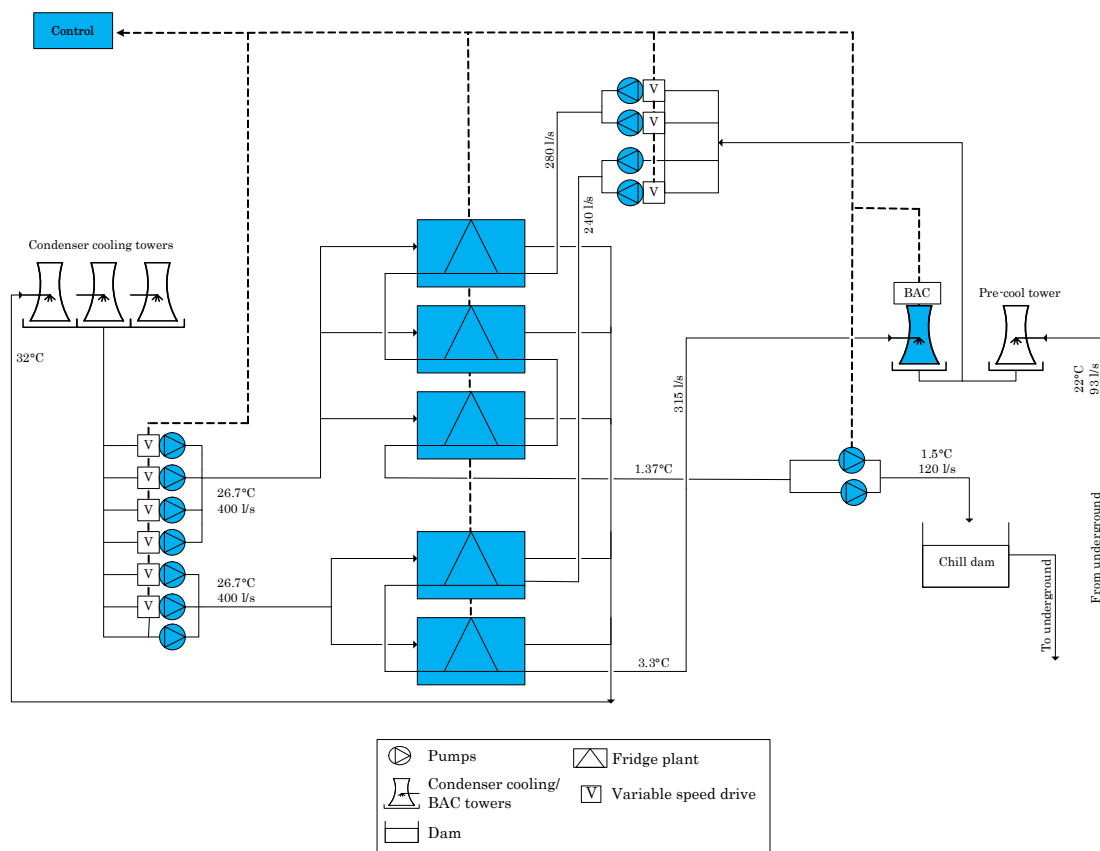


Figure 3.16: Case study 3 – Site configuration

Table 3.7: *Case study 3 – BAC specification*

Description	Value
Number of BACs	1
Water Inlet Temperature (°C)	2
Water Outlet Temperature (°C)	12
Water Flow (l/s)	425
Airflow (kg/s)	420
Air Inlet Wet-bulb Temperature (°C)	20
Air Outlet Wet-bulb Temperature (°C)	7.7

Table 3.8: *Case study 3 – Fridge plant specification*

Description	Value
Number of Refrigeration Plants	5
Make	Howden
Compressor Type	Screw
Refrigerant	Ammonia
Voltage (V)	6 600
Cooling Capacity (kW)	5 340
COP	5.75
Evaporator Outlet Temperature (°C)	5.6
Condenser Inlet Temperature (°C)	20
Evaporator Water Flow (kg/s)	280
Condenser Water Flow (kg/s)	400
Evaporator Pump Motor Rating (kW)	400
Number of Evaporator Pumps	4
Condenser Pump Motor Rating (kW)	250
Number of Condenser Pumps	6

Measured results

The measured results consist of start and stop commands, temperature measurements, dam level measurements and the power profile. Depending on the time of day and the environmental conditions, the BAC controller scheduled the control elements to stop or to start. Control commands have an effect on the BAC outlet temperature, the underground temperature as well as the power usage. The hourly averages of the temperature measurements and the total incoming power usage are presented here.

Various factors can influence the chill dam level. Depending on whether there are scheduled drilling or blasting operations, the rate of change can vary. As soon as the dam level drops below the minimum set point, fridge plants are scheduled to start. This causes the dam level to stabilise before it starts to increase.

1. Start and stop commands

Table 3.9 lists important platform measurements from 18:00 to 20:00. The BAC controller set the stop tag values to '1' at the start of the peak period. This initiated the peak control procedure. The BAC outlet temperature and the chill dam level was monitored during the control procedure. A start-up condition was triggered at 19:10 when the dam level dropped below 50%. The start tags were set to '1' and machines were therefore switched back on systematically.

Table 3.9: *Case study 3 – Stop and start commands*

<u>Hour</u>	<u>Stop tag</u>	<u>Start tag</u>	<u>Force start</u>	<u>Dam level(%)</u>	<u>Temp (°C)</u>	<u>Within range</u>
17:50	0	0	0	79	4.53	Yes
18:00	1	0	0	74	3.97	Yes
18:10	0	0	0	69	12.73	Yes
18:20	0	0	0	63	13.29	Yes
18:30	0	0	0	59	13.77	Yes
18:40	0	0	0	58	14.44	Yes
18:50	0	0	0	56	14.75	Yes
19:00	0	0	0	54	15.23	Yes
19:10	0	1	0	49	15.54	No
19:20	0	0	0	54	15.74	Yes
19:30	0	0	0	58	16.05	Yes
19:40	0	0	0	63	16.13	Yes
19:50	0	0	0	68	16.31	Yes
20:00	0	0	0	73	16.51	Yes
20:10	0	0	0	77	16.66	Yes

2. Temperature measurements

A temperature sensor, installed on the inside of the BAC, provided the measurements that were used as a control parameter. The BAC outlet temperature did not exceed the maximum set point of 20°C. Figure 3.17 shows the BAC temperature while Figure 3.18 shows the underground temperature. These figures display the hourly average of the measured temperature values.

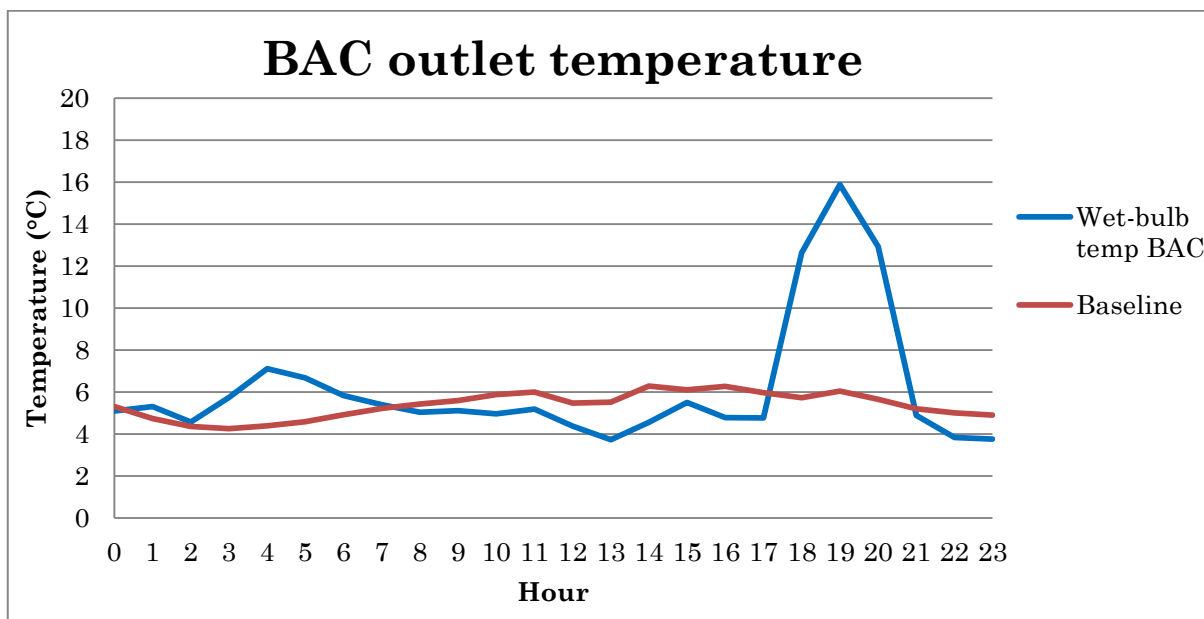


Figure 3.17: Case study 3 – BAC outlet temperature

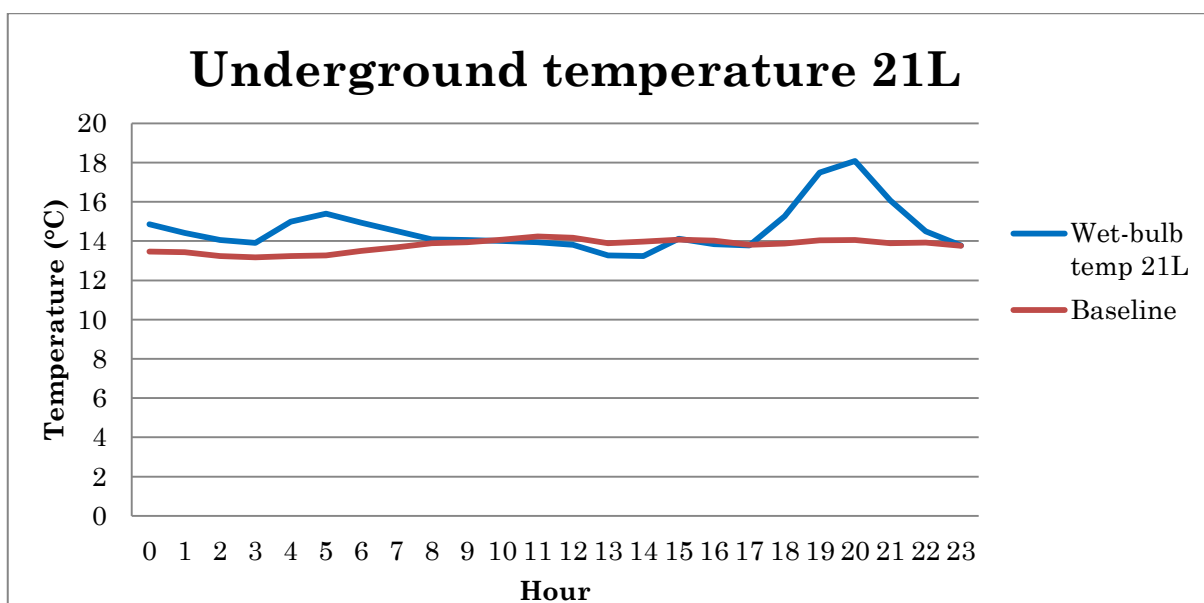


Figure 3.18: Case study 3 – Underground temperature on 21L

3. Dam level measurements

The chill dam provides the cold service water for the underground operations. It is very important that this supply of water is uninterrupted. The minimum set point is therefore set at 50% to ensure that cold water is always available. Figure 3.19 shows a 24-hour profile of the dam level measurements.

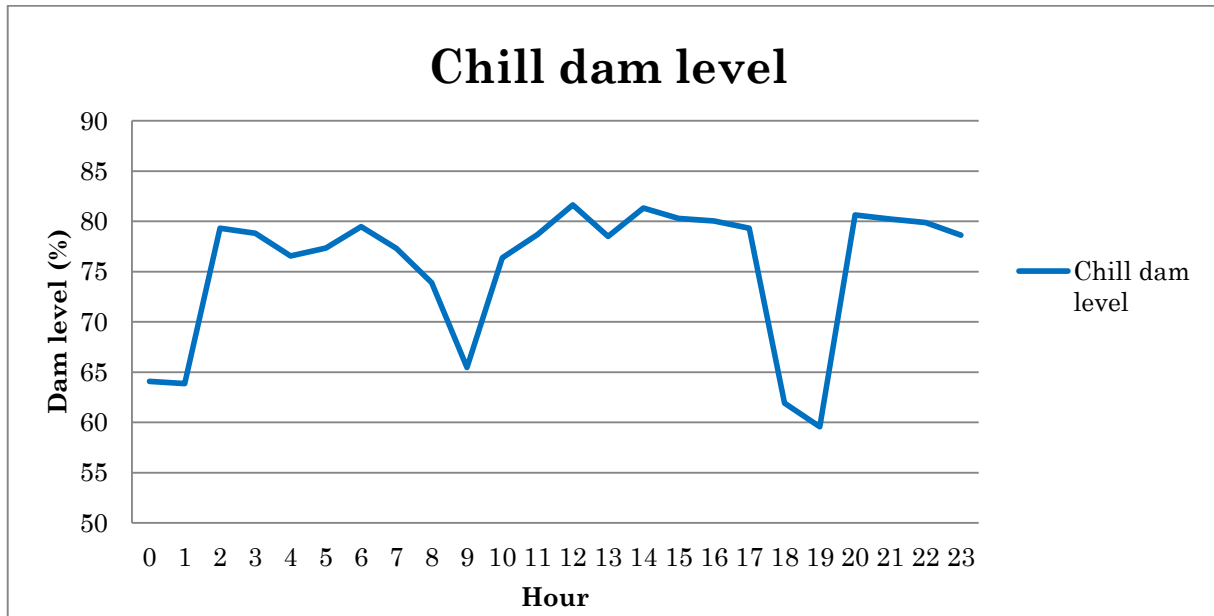


Figure 3.19: Case study 3 – Chill dam level

4. Power profile

The power usage of the day was used to compile an hourly average profile. This can be seen in Figure 3.20. Typical electricity usage during the summer months were used as a baseline. A maximum electricity usage reduction of 3 MW was realised during the peak period.

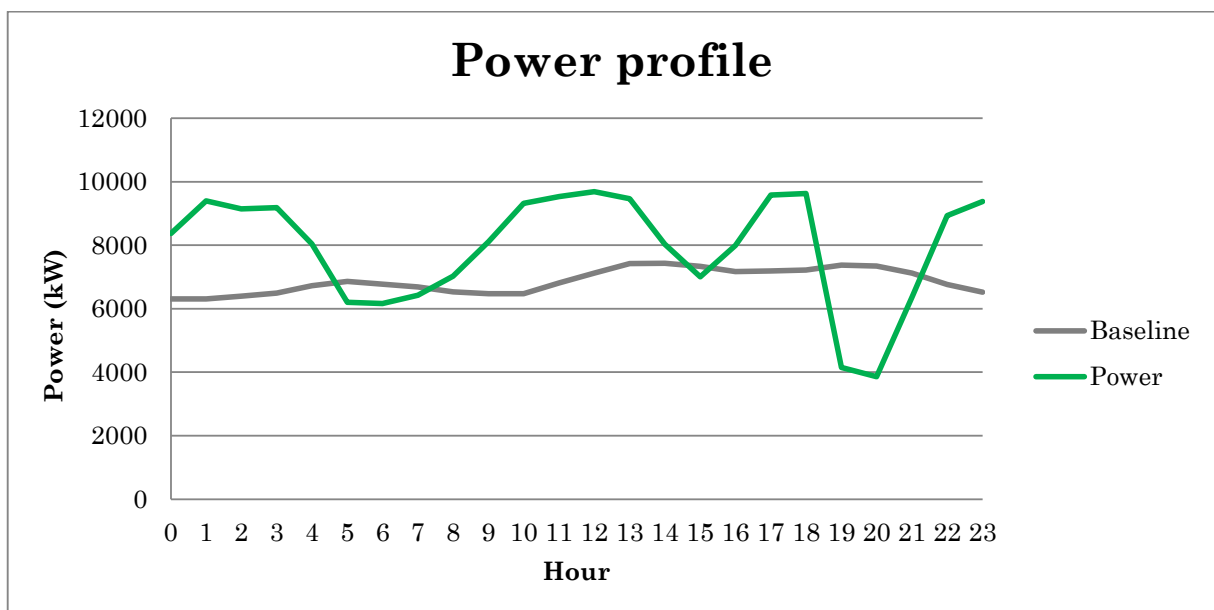


Figure 3.20: Case study 3 – Profile profile

3.6 Summary

The operation of the BAC controller was successfully validated. Three case studies have shown that the BAC controller can realise cost savings. This is made possible by minimizing the peak period usage. Control elements are switched back on if a start-up condition is triggered. Stop and start commands can be written directly to the SCADA tags, meaning control procedures will be executed automatically. It is also possible for a system operator to execute the schedule as determined by the BAC controller.

Daily cost savings were calculated for the three case studies. The calculations were made with an average daily electricity saving for each site. These cost savings were used to determine what the annual financial impact would be. The cost saving on Mine A was more than the other two even though the electricity saving was less. This is because peak clipping was used on Mine A, while load shifting was used on Mine B and Mine C. Figure 3.21 shows the possible annual savings for each site.

Refrigeration plant	Daily saving achieved	Possible annual saving
Case study 1: Mine A	R1 687.10	R472 297.02
Case study 2: Mine B	R1 207.79	R334 720.69
Case study 3: Mine C	R1 302.26	R359 676.70

Figure 3.21: *Possible annual savings*

CHAPTER 4

CONCLUSION

4.1 Summary

There is a clear need to reduce electricity usage during the Eskom peak period. Eskom's current capacity to provide power is under pressure to supply South Africa's growing demand. DSM initiatives such as load shifting and peak clipping projects can have a significant impact on the power grid. These initiatives also offer additional benefits in the form of cost savings for the client.

Eskom introduced the TOU tariff structures which work on a sliding rate scale. This means electricity is significantly more expensive during periods of high demand, compared with periods of low demand. Users are consequently encouraged to lower their electricity usage during these peak periods. Energy management projects incorporate the tariff structures into the control strategies that are implemented on the mines.

The focus of this study was to develop and implement a control system which could be used to operate BACs more efficiently. It was also important not to alter the production output of the mines. A BAC controller, capable of automatic operation, was therefore designed and developed.

The BAC controller was specifically designed to be used on refrigeration plants of deep mines. Refrigeration plants on deep mines make use of machines that are energy intensive. Due to the nature of mining operations, the ventilation and cooling equipment are constantly running. Automatic control enables the mine to limit their peak period electricity usage while adhering to all the safety regulations.

BACs, fridge plants (chillers) and pumps can be listed as control elements on the BAC controller's interface. Control elements can be switched on or off, depending on the specified input limits and the time of day. The objective is to switch off the machines at the start of the peak period. If a temperature measurement exceeds the upper boundary, the peak control procedure is ended and the control elements are switched on. A dam level measurement below the allowable minimum will also stop the peak control procedure.

Verification tests were done to assess the correct working of the controller. The status control test showed that the controller resets the start and stop tags when the status of the respective control element has changed accordingly. The pulse control test showed that the controller uses the specified tag pulse time to determine when start and stop tags need to be reset.

The off-peak control test was used to verify that the dam level measurement can trigger the start and stop tags during off-peak periods. Similarly, the peak control test demonstrated that the stop tags are set at the beginning of the peak period. The start tags were

automatically set when a start-up condition was triggered. Control commands are only given when the *Control enabled tag* value is true.

The correct operation of the control system was validated with three case studies. Implementation started with the evaluation of the site infrastructure. Hardware installations were done where necessary. The site-specific control philosophy was determined according to the mine's requirements. Once this was completed, it was possible to use the BAC controller. In some cases the mine did not allow automatic control. This meant that an operator had to execute the commands that were given by the controller.

Two case studies were done on sites with closed loop configurations. Temperature sensors were installed underground to enable the controller to use a temperature measurement as input parameter. Both case studies have shown that the increase in temperature during the peak control procedure is acceptable. The temperature measurements remained within the specified range.

One case study was done on a site with an open loop configuration. A temperature sensor was installed on the inside of the BAC to measure the BAC outlet temperature. Dam levels as well as temperature measurements were used as input parameters. Depending on the dam level at the start of the peak period and the amount of service water needed, a low dam level trigger may occur. This case study demonstrates a low dam level event where the measurement was below the specified minimum.

Despite the fact that successful operation of the controller can be demonstrated, certain obstacles delayed or impeded the progress that was made. In some cases the refrigeration plant experienced unforeseen interruptions due to malfunctioning equipment. One example is a VSD that had to be replaced following a mechanical failure. These drives are procured from international suppliers. The replacement process took eight weeks. Automatic control was very limited without the aforementioned drive.

Another hurdle was to enable the SCADA system to display the control commands of the BAC controller. Additional programming was needed to create a REMS BAC commands panel on the SCADA screen. The commands panel is a graphical representation of start and stop requests. Operators also needed to be trained to carry out the BAC controller instructions.

The BAC controller has therefore been designed, developed, tested and implemented. It has shown to be capable of following a schedule to realise electricity cost savings. It can monitor and control various refrigeration machines. Equipment can only be switched off if all the input parameters comply with the safety regulations. Energy intensive machines can

therefore remain off during the peak period, if it safe to do so. This will also assist Eskom with their campaign to reduce electricity usage during periods of high demand.

4.2 Future development

This study can be divided into two main categories. The first is research and development, while the second includes maintenance and control. Each of these categories leaves room for improvement and expansion.

The research and development process is a continuous cycle. A design scope gives an outline of what is needed. This is used to develop a prototype. A prototype is tested and the feedback is used to make modifications and improvements. The BAC controller has been tested, modified and improved a number of times.

Future work regarding research and development can be done once feedback is available on medium- to long-term use of the controller. Continuous use for several weeks or months will help to identify further problem areas. This may also generate valuable suggestions for new developments.

The next step with respect to the development of the controller should be better use of the prioritisation. Each control element must be given a priority level according to its efficiency. The controller can then start the most efficient machine. Priority values can also take into account whether a motor is driven by a VSD, and spread out machine running hours and maintenance.

There also exists an opportunity to improve the maintenance and control aspects. By analysing the results, it would be possible to change the control strategy. Regular tests of different operating methods should enable the user to maximise the potential of the different control procedures.

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