

Automated mine compressed air control for sustainable savings

J Jonker
22251626

Dissertation submitted in fulfilment of the requirements for the
degree **Magister in Mechanical Engineering** at the
Potchefstroom Campus of the North-West University

Supervisor: Prof M Kleingeld

November 2016



ABSTRACT

Title: Automated mine compressed air control for sustainable savings

Author: Jeandré Jonker

Supervisor: Prof. Marius Kleingeld

Degree: Master of Engineering (Mechanical)

Keywords: Compressed air controller, compressor network, inlet guide vane angle, compressor power consumption, compressor power savings, pressure set point

Compressed air generation consists of approximately 19% of a mine's total electricity consumption. It was found that manually operated compressed air networks are controlled inefficiently. The need exists to reduce the electricity cost of a mining complex by optimising the control of the compressed air network.

This was achieved by integrating the demand and supply sides of compressed air networks. In order to accomplish this, the demand and supply of compressed air networks were characterised. Additional investigation identified electrical cost saving strategies implemented on the demand and supply sides. An existing compressor controller was identified that is capable to automatically control the supply of compressed air according to the requirements of compressed air demand.

The Dynamic Compressor Selector (DCS) controller was identified as a suitable compressed air control system. The DCS controller simulates a virtual compressed air network in order to calculate the pressure set point for compressors. The DCS controller then schedules the compressors in order to maintain the required network pressure. Flow loss, pressure drop and future flow and pressure profiles are considered to calculate the required network pressure and compressor schedules.

The DCS controller was implemented at a gold mining complex in South Africa. The DCS controller was able to simulate compressor discharge pressure set points and was able to schedule the most effective compressor combination based on actual and future demand requirements.

However, when the simulation result was evaluated certain limitations and complications were encountered.

An improved control strategy was subsequently developed. Communication to different equipment and field instrumentation has already been established. Therefore, the improved control strategy uses the DCS controller as a backbone for the established communication links. The improved control strategy is able to calculate the pressure set points of compressors by considering auto compression, flow loss and pressure drops.

Certain conditions were identified in order to determine when a compressor should be started or stopped. To further optimise the compressed air network, the guide vane angles of each compressor was set to an optimal position when there are major disturbances in the system. This resulted in a more stable network pressure.

The improved control strategy was able to automatically control the supply of compressed air to accurately match the demand of compressed air. This resulted in an improvement in the energy efficiency of the compressed air network. With the implementation of the improved control strategy, an average evening peak clip in excess of 3 MW was realised for a period of three months. The improved control strategy should be rolled out to all major compressed air networks in the industry.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my Lord and Saviour for blessing me with the ability to complete this dissertation. Without His love and grace, I would not have been able to succeed in the challenges of life.

I would also like to thank the following people:

- Prof. E. H. Mathews and Prof. M. Kleingeld, thank you for affording me the opportunity to further my education.
- Dr Christiaan Kriel, Mr Wouter Ferreira and Mr Sydney Higgs for assisting with the development and implementation of the project.
- Dr Rudi Joubert and Mr Franco Jansen van Rensburg for proofreading my dissertation and giving suggestions where needed.
- A special thanks to my family and friends for their support and understanding during the write up of this dissertation. Without your continued support, I would not have been motivated to complete this study.

Finally, I would also like to thank TEMM International (Pty) Ltd and HVAC International (Pty) Ltd for the opportunity and financial assistance to complete this study.

TABLE OF CONTENTS

ABBREVIATIONS.....	V
LIST OF EQUATIONS	VI
LIST OF FIGURES.....	VII
LIST OF TABLES.....	X
CHAPTER 1. BACKGROUND	1
1.1 Introduction.....	1
1.2 Compressed air networks	3
1.3 Demand side management	7
1.4 Compressor control strategies	9
1.5 Problem statement and objectives.....	12
CHAPTER 2. LITERATURE STUDY	15
2.1 Introduction.....	15
2.2 Cost-saving strategies on the demand side.....	16
2.3 Cost-saving strategies on the supply side.....	28
2.4 Existing controllers	34
2.5 Conclusion	51
CHAPTER 3. IMPLEMENTING THE DCS CONTROLLER.....	52
3.1 Introduction.....	52
3.2 Implementing DCS	53
3.3 Developing an improved control strategy	70
3.4 Verification	104
3.5 Conclusion	110
CHAPTER 4. RESULTS AFTER IMPLEMENTATION	112
4.1 Introduction.....	112
4.2 Commissioning results.....	112
4.3 Control strategy impact after implementation.....	124
4.4 Study validation	126
4.5 Conclusion	129
CHAPTER 5. CONCLUSION	130
5.1 Summary	130
5.2 Recommendations for future work.....	133
CHAPTER 6. BIBLIOGRAPHY.....	135

ABBREVIATIONS

DCS	Dynamic Compressors Selector
GDP	Gross Domestic Product
DSM	Demand Side Management
TOU	Time of Use
ESCo	Energy Service Companies
DoE	South Africa's Department of Energy
SCADA	Supervisory Control and Data Acquisition
GUI	Graphics User Interface
IDE	Integrated Development Environment
DCC	Dynamic Compressor Controller

LIST OF EQUATIONS

Equation 1: Mass flow	24
Equation 2: Effect of auto compression	25
Equation 3: Compressor electrical power.....	30
Equation 4: Fluid density.....	35
Equation 5: Reynolds number	36
Equation 6: Darcy friction factor.....	36
Equation 7: Bernoulli’s principle	37
Equation 8: Adjusted demand flow	42
Equation 9: Calculating the desired upstream supply pressure at each shaft	76
Equation 10: Calculating the desired upstream supply pressure at Gold Plant B.....	76
Equation 11: Calculating the required supply flow	82
Equation 12: Quadratic equation	87
Equation 13: Required flow of the Sulzer B2 and Sulzers A1-3	98
Equation 14: Quadratic formula	100

LIST OF FIGURES

Figure 1: Mineworker drilling [1]	1
Figure 2: Gold mine electricity cost breakdown [10].....	2
Figure 3: Typical compressed air network on surface.....	3
Figure 4: Typical compressed air network	5
Figure 5: Compressed air requirements of a deep level gold mine	7
Figure 6: Literature study overview	15
Figure 7: Pneumatic rock drill [52]	17
Figure 8: Pneumatic loader [26]	17
Figure 9: Pneumatic actuator [50]	18
Figure 10: Pneumatic cylinder.....	18
Figure 11: Underground refuge bay [51].....	19
Figure 12: Mining shaft operation schedule	21
Figure 13: Control valve assembly	23
Figure 14 Multi-stage centrifugal compressors [71]	29
Figure 15: Compressor characteristics curve [72].....	32
Figure 16: Smoothed real time data.....	40
Figure 17: Simulation network example	43
Figure 18: Compressor component	45
Figure 19: Simulated compressor combination	47
Figure 20: Flow diagram	49
Figure 21: Google Earth surface layout of Mining Complex A	54
Figure 22: The DCS controller, SCADA and PLC communication link	55
Figure 23: Mining Complex A surface layout.....	59
Figure 24: Average compressor running status	60
Figure 25: Pressure requirements	61
Figure 26: Virtual network of Mining Complex A.....	63
Figure 27: Test phase pressure conditions.....	65
Figure 28: Actual compressors schedule and flow conditions during test day.....	66
Figure 29: Simulated compressors schedule and flow conditions during test day	67
Figure 30: Systematic approach to develop control strategy.....	70
Figure 31: Control valve components	72
Figure 32 Parameters to calculate the desired surface pressure supply at each shaft	75

Figure 33: Calculating each consumer’s pressure requirement including pressure drop	77
Figure 34: Compressors start priority allocation	80
Figure 35: Estimation of flow loss in system	81
Figure 36: 30 minute predicted demand flow adjustment	83
Figure 37: Minimum guide vane angle regression model	84
Figure 38: Characteristics curve of Sulzer A1	86
Figure 39: Conditions evaluated for compressor start procedure	89
Figure 40: Conditions evaluated for compressor stop procedure	90
Figure 41: Compressors combinations flow range	92
Figure 42: Compressor guide vane control – Stop procedure	94
Figure 43: Compressor efficiency at different guide vane angles	97
Figure 44: Determining the required supply flow for each compressor	99
Figure 45: Compressor guide vane control – Stability control	101
Figure 46: Compressors’ blow-off curve	103
Figure 47: PLC compressors blow-off avoidance control strategy	103
Figure 48: Simulation results for compressors pressure set point	105
Figure 49: Actual supply and demand flow	106
Figure 50: Simulation results for required supply flow	107
Figure 51: Simulation results for compressors scheduling	108
Figure 52: Simulation result for power profile	109
Figure 53: Results for pressure requirements	113
Figure 54: Results for required supply flow and demand flow	114
Figure 55: Results for start conditions	115
Figure 56: Results for stop conditions	115
Figure 57: Results for compressor scheduling	116
Figure 58: Results for supply and demand flow	117
Figure 59: Pressure stability control	119
Figure 60: Results for guide vane angle stability control – Condition 1	120
Figure 61: Results for guide vane angle stability control – Condition 2	121
Figure 62: Ring pressure vs. Ring pressure set point	122
Figure 63: Sulzer B2 trip	123
Figure 64: Electrical cost impact after implementation	125
Figure 65: Simulated and post-implementation power profile	126
Figure 66: Regression model flow vs. actual flow for Sulzer A1-3	127
Figure 67: Regression model flow vs. actual flow for VK100 B1	128

Figure 68: Regression model flow vs. actual flow for Sulzer B2.....128
Figure 69: Mineworker on the job [76]130

LIST OF TABLES

Table 1: Pneumatic equipment requirements	17
Table 2: Process parameters required.....	53
Table 3: Mining Complex A - Installed compressors.....	58
Table 4: Compressor’s minimum inlet guide vane angles.....	85
Table 5: Compressors regression models	87
Table 6: Power savings achieved	125
Table 7: Regression model accuracy	129

CHAPTER 1. BACKGROUND



Figure 1: Mineworker drilling [1]

1.1 Introduction

Mining companies have been facing challenges to stay profitable since the commodity price of the mining sector dropped to record low levels in 2016 [2]. While the price index was high, mining companies invested large amounts of money to increase production. Producing more minerals at a higher trading price has resulted in increased profits [3].

However, with the price decrease supply has not changed significantly. Investments made to increase production, are now losing money [4]. Increased electricity rates and endless negotiations with trade unions over wages make it challenging for mining companies in South Africa to stay profitable [5] [6].

It is estimated that 20-30% of a typical gold mine's total operation cost can be contributed to energy cost [7]. Eskom is the main supplier of electricity to industries in South Africa [8]. This includes the mining sector. In South Africa, gold mining is ranked as the third highest electrical consumer, contributing up to 15% of total consumption [9].

With mining companies under pressure to stay profitable, it is an indisputable fact that measures to reduce the electricity cost of a mine should be investigated. Figure 2 illustrates a typical South African gold mine's electricity cost breakdown.

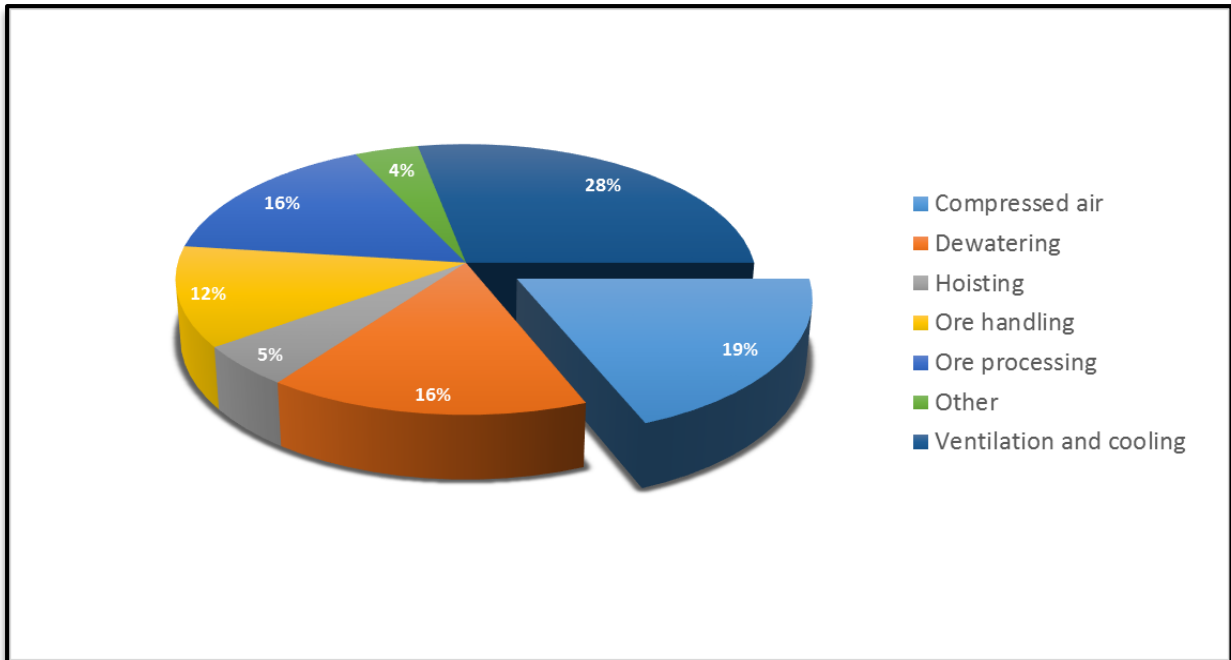


Figure 2: Gold mine electricity cost breakdown [10]

Figure 2 shows the major energy consumers on a typical gold mine, which include compressed air, dewatering and ventilation and cooling [10]. Compressed air consumption is high because the mining industry makes use of compressed air equipment for mining due to the equipment's reliability and ease of use.

A typical mine's compressed air system consists of one or more compressors on the surface. Compressed air is distributed to various consumers by means of steel pipe networks to surface and underground operations [11]. Due to the extreme depths of South African gold mines compressed air systems are found to be inefficient and expensive to operate [12].

It is estimated that 10 – 20 % of energy used to generate compressed air is effectively used by equipment at different locations underground [13]. Improving the efficiency of the compressed air systems at South African gold mines could achieve significant electrical cost-savings. This dissertation will consequently focus on improving the typical compressed air networks of South African gold mines.

1.2 Compressed air networks

A typical mining complex in South Africa consists of several interconnected shafts, processing plants and workshops. There are generally more than one compressors located at each shaft that produce the required compressed air for that specific shaft and other users. When more than one compressor are supplying air from one location, it is normally referred to as a compressor house [14].

In order to deliver compressed air to all consumers, a steel pipe network connects the compressor houses and consumers [15]. Figure 3 displays a typical layout of the steel pipe compressed air distribution network on surface. The compressed air pipe network is normally referred to as a compressed air ring.

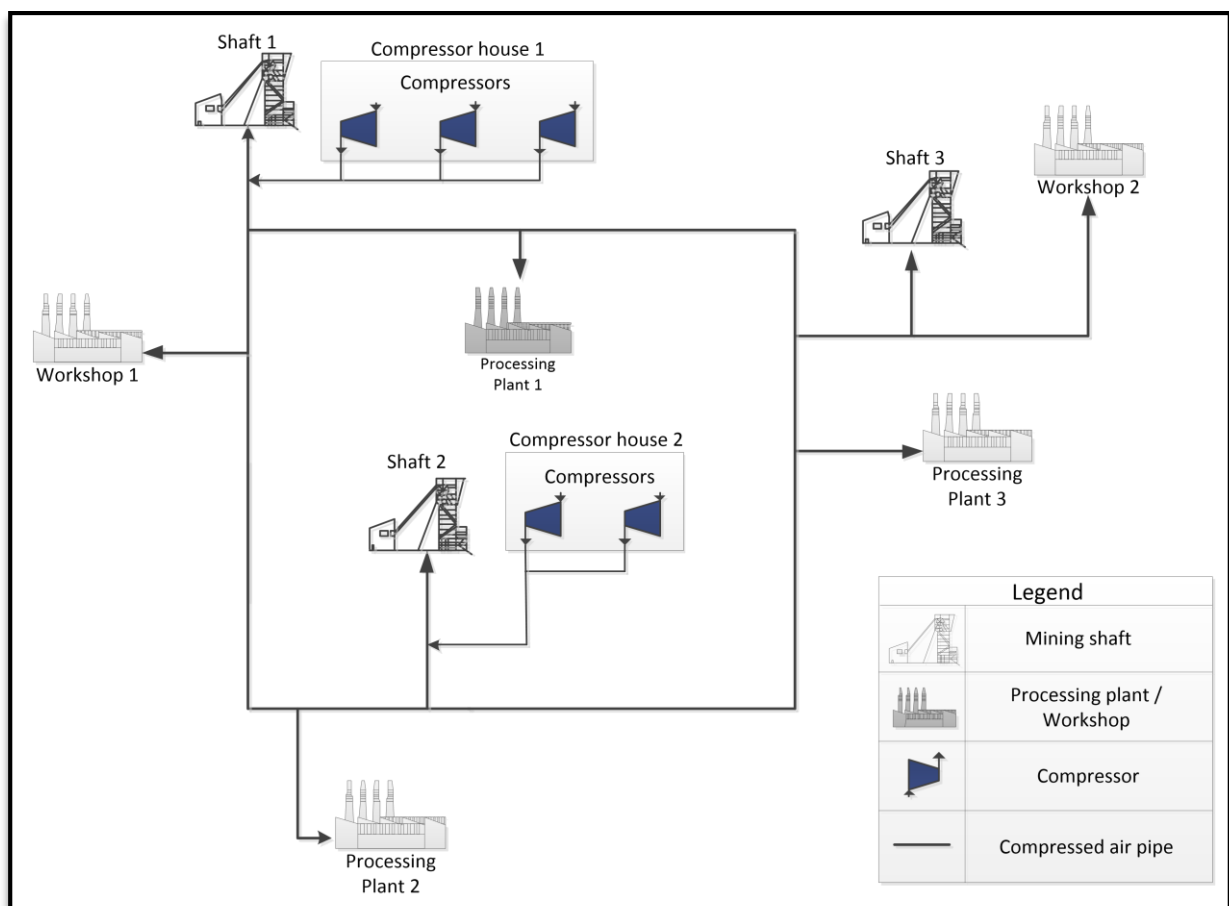


Figure 3: Typical compressed air network on surface

These compressed air rings can reach lengths of up to 75 km in total [16]. The compressed air ring adds benefits to the compressed air system over a point to point delivery system. Benefits such as scheduled maintenance on the ring can be accomplished by isolating sections of the ring. By isolating sections, production is not affected because the supply of compressed air is not influenced [15].

Other benefits include availability of compressors. When a compressor is scheduled for maintenance or is unable to operate due to a breakage, another compressor can be used to supply the compressed ring according to the requirements of the consumers [14]. Production will not be affected and maintenance on compressors can be scheduled with ease.

Compressed air is a vital component for production in deep level mines. The largest compressed air consumer is the rock drills [17]. Although compressed air is used by various types of equipment on surface and underground. During a typical drilling shift on a mining shaft, compressed air consumption can reach up to 50 kg/s, which is on average 70% more than off-peak periods [18]. The main reasons for using pneumatic equipment is for the reliability pneumatic equipment offer.

South African gold mines can reach depths of up to four kilometres [19]. At these depths, the rock surface temperatures can reach 50°C. Compressed air equipment has the advantage of generating a cooling effect caused by the air depressurising. This ensures that pneumatic equipment, like rock drills, will not overheat and as a result reduce delays in production. As an added advantage, the drill operator also benefits from the cool air released into the atmosphere in the workspace [20].

Mining underground discharges high levels of natural methane gas. Igniting the methane gas can result in an explosion. Electrical equipment operating in these high levels of methane gas increases the risk of igniting the methane gas. This safety concern is consequently reduced by using pneumatic equipment rather than electrical equipment [21].

1.2.1 Compressed air supply and demand

Figure 4 shows a simplified compressed air network configuration found at a mining complex. The mining complex consists of a compressor house (housing two compressors), supplying compressed air through a steel pipe to a mining shaft and processing plant on surface. The different types of pneumatic equipment used at a typical mining complex are illustrated in Figure 3.

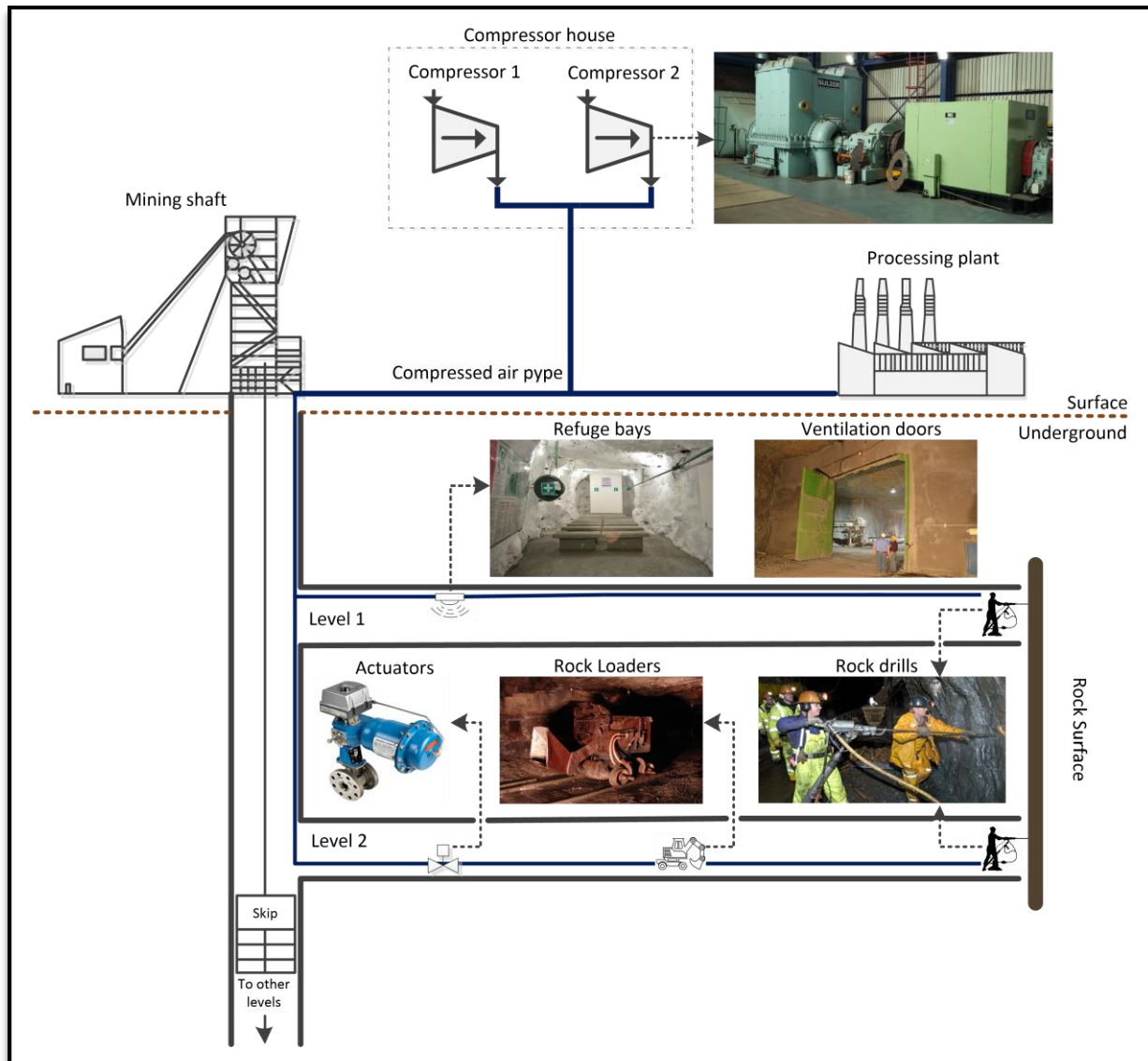


Figure 4: Typical compressed air network

At South African mines, multi-stage centrifugal compressors are commonly used to supply compressed air. Multi-stage centrifugal compressors are used due to their reliability and supply capacity. The compressors are able to deliver a large quantity of compressed air at a stable discharge pressure [22]. Investigations have revealed that compressors of a total installed capacity of up to 85 MW are found at mines in South Africa [23].

Compressed air consumers on surface include not only the processing plants, but also workshops and other pneumatic control equipment. From Figure 4 it can be seen that compressed air is supplied to a processing plant and a deep level mining shaft. The processing plant uses compressed air for various processes like agitation, leaching and flotation [24].

Figure 4 illustrates that compressed air is further distributed through pipe networks from the shaft to pneumatic equipment on mining levels underground. Typical compressed consumers underground include pneumatic control equipment, loaders, refuge bays, ventilation doors and rock drills [25] [26]. Compressed air is also used for ventilation [20].

Blacksmiths and mechanical workshops can be found at a typical mining complex that uses compressed air for equipment [16]. Pneumatic actuators and cylinders are also commonly used on surface for different control applications.

There are other types of pneumatic equipment not mentioned in this section that also use compressed air to operate. However, the equipment discussed consume the most of the compressed air supplied. By focusing on the requirements of these end users, a methodical approach can be followed to optimise the supply of compressed air.

1.2.2 Demand requirements

Pneumatic equipment is designed to use compressed air at certain requirements. These requirements must be met in order for the equipment to operate optimally. The primary requirements are the flow and the pressure of compressed air supply. Each compressed air consumer has different requirements to ensure the pneumatic equipment operates optimally [15]. It is therefore important that the compressors supply an efficient amount of compressed air to meet the requirements of all the consumers on the ring.

On deep level mines, underground mining operations change during a typical production day. The requirements of a mining shaft change according to the different operation schedules. The daily operation schedule during a production day consists of a drilling shift, blasting shift and a cleaning shift [27]. Figure 4 shows the pressure requirements and flow consumption of a typical production day on a gold mine.

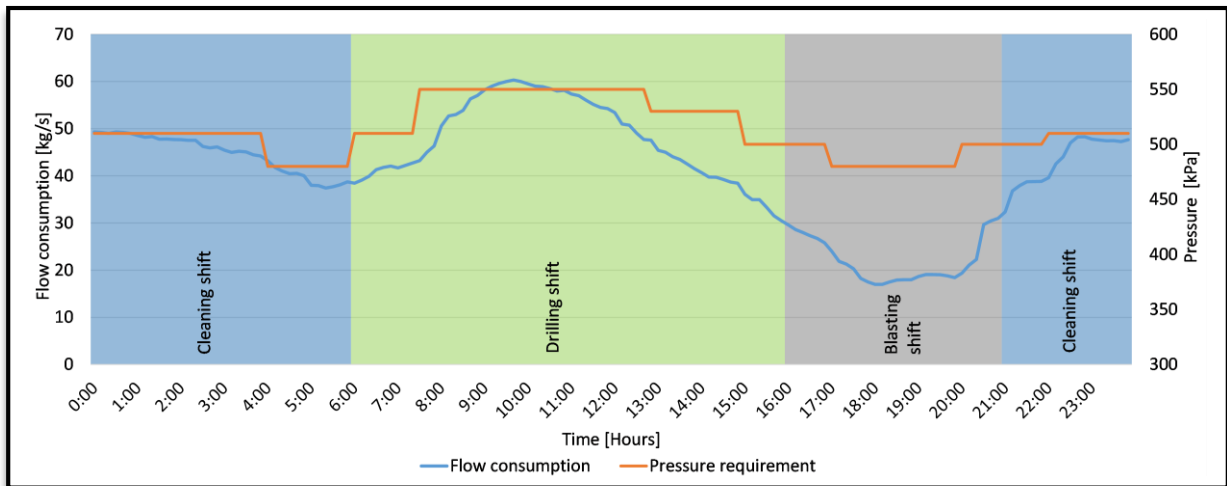


Figure 5: Compressed air requirements of a deep level gold mine

When focusing on the pressure requirement and flow consumption presented in Figure 4, it is evident that the compressed air requirements of a gold mine change throughout a typical production day. The pneumatic equipment operated during certain shifts uses compressed air according to different requirements. The equipment used during different shifts will be further discussed in Chapter 2.

Processing plants operate non-stop during the entire week to ensure that continuous agitation occurs. Therefore, processing plants require constant pressure and flow throughout the day to operate optimally [22]. Although the equipment used in workshops requires relatively high pressures, they are primarily operated in conjunction with the drilling shifts where high pressures are usually available [18].

A substantial number of pneumatic equipment are encountered at a typical mining complex. The requirements of the various equipment mentioned will be specified and further discussed in the Literature study to adequately identify areas where energy efficient improvements can be made.

1.3 Demand side management

Eskom introduced methods to reduce the overall demand for electricity in South Africa after the demand exceeded the supply on the national power grid in 2005 [28]. One of these methods is Demand Side Management (DSM) projects. The main goal of DSM projects is to decrease energy usage of industrial electricity consumers by upgrading equipment and improving energy efficiency. This must be achieved without affecting production levels [29].

Eskom bills their high electrical demand consumers according to a Time-of-Use (ToU) billing schedule. The most expensive electrical periods are on weekdays between 07:00 and 10:00 and between 18:00 and 20:00. These periods are respectively referred to as Eskom's morning and evening peak tariff periods. Energy Service Companies (ESCO) are contracted by Eskom to implement DSM projects to achieve a predetermined energy saving during Eskom's peak tariff periods [30].

The ESCo is responsible for on-site investigations in order to develop an engineering concept that could achieve energy saving. With approval from Eskom, the ESCo will implement a DSM project. Implementation is followed by a performance assessment phase. This involves an independent third party who evaluates the project's performance and determines if the proposed electrical saving target has been achieved. The achieved savings are then reported back to Eskom.

South Africa's Department of Energy (DoE) realised that DSM projects are a good alternative to increasing South Africa's electricity generation capacity [31]. An incentive programme to support ESCOs was therefore developed by the DoE. The incentive programme that was developed allows the ESCOs to sell energy that has been saved by the DSM projects implemented back to Eskom at a predetermined rate. The price rate (R/kWh or R/kW) is determined by considering the cost of supplying electricity.

The offer stipulates that the ESCo or project supplier will receive payment in three-month periods over three years. If for some reason the project does not obtain the agreed target, adjustments are made to the payments. Therefore, it is of the utmost importance to sustain the project's energy performance for three years to receive the full project funding. This responsibility is attributed to the ESCo [31].

The DSM programme has the added benefit of financial support from Eskom to implement projects. This consequently adds to the feasibility of energy projects for the ESCo because the return on investment is significantly reduced for DSM projects [27].

Various DSM projects have been implemented on the demand side of a compressed air network at mines in South Africa. These projects consist of installing control valves to regulate the supply pressure according to the requirements of the specific consumer. The control valves are installed on the surface at mining shafts, processing plants and workshops. Underground mining levels'

compressed air consumption can also be regulated by installing control valves to regulate the supply pressure on the air line feeding each level.

Electrical savings have been achieved by installing control valves [18]. Other initiatives to reduce the demand, involves maintenance strategies on the compressed air distribution in order to maintain air leaks. DSM projects implemented on the demand side of compressed air networks will be further discussed in Chapter 2.

1.3.1 Integration between demand and supply

As mentioned in the previous section the demand flow varies throughout a production day. It is important that the compressors supply sufficient compressed air to meet the changing demand throughout the day. By matching the demand flow with adequate supply flow, significant electrical savings can be achieved. This concept has been proved to be successful. Energy savings of approximately 10 % have been achieved on compressed air networks using this strategy [32].

However, pneumatic equipment will not operate optimally if the compressors do not meet the demand. This will directly affect the production of the entire mining complex. Production at the processing plants is entirely dependent on what is produced (rock ore) by the mining shafts. If drilling is unable to commence as a result of insufficient compressed air supply, no ore will be provided to the processing plant. Consequently, production on the entire mining complex will come to a standstill [33]. However, if the compressors oversupply compressed air to the consumers, energy is unnecessarily wasted.

Before the energy shortage in 2005, electricity cost in South Africa was inexpensive when compared to costs in other countries [34]. This meant compressed air could be widely used in the mining sector to distribute energy to the various end users on surface and underground. Compressor capacity has been greatly increased to maintain the growing demand.

It is evident that the best practical solution to improve a compressed air network is to adjust the supply in order to match the demand. Otherwise, no electrical saving will be realised for DSM projects because there will be no adjustments made to the supply. Capacity control on compressors is therefore of significant importance when optimising a compressed air network.

Capacity control entails controlling the delivery flow of a compressor in terms of kilograms per second. Capacity control is used to match the compressed air supply with the required demand at a specific point in time. The compressor supply flow can be controlled to match the demand by use of the following methods:

- Compressor combination [35];
- Loading and off-loading compressors;
- Suction and/or discharge throttling [36];
- Inlet guide vane control [37]; and
- Blow-off valve control [38].

These capacity control methods will be discussed in more detail in Chapter 2.

1.4 Compressor control strategies

It has been found that compressors run unnecessarily throughout the day at South African mines in the past. Compressors are abundantly available and due to negligible electricity cost compressors operate continuously throughout the day. Mine personnel believe that maintenance cost on compressors will escalate with compressors starting and stopping frequently [39]. Safety features such as blow-off control is used when the system pressure increases to dangerous levels [40].

However, with the electricity prices increasing over the years the mining sector has realised that measures to reduce the electricity cost of compressors must be considered. In order to achieve energy savings, the supply must be adjusted according to the reduced demand. Therefore, various DSM projects have been implemented on the supply side of compressed air networks. These projects include the following:

- Centralising compressor control;
- Automating compressor operation;
- Operator training; and
- Implementing compressor controllers.

In order to improve the compressor electricity usage, mines have upgraded control instrumentation. Supervisory Control and Data Acquisition (SCADA) systems have been installed. The SCADA system is primarily used for remote monitoring and control purposes. The control from the SCADA was achieved through controlling Programmable Logic Controllers (PLC). PLCs can communicate directly with field equipment. PLCs have the ability to control the field equipment to a certain set point and receive readings from instruments [41].

This SCADA to PLC control enables operators to remotely monitor and control the entire compressed air network from a centralised control room. The delivery pressure set point of compressors can be changed and compressors can be stopped and started remotely. This has significantly improved the efficiency of a system. Operators can change compressor combinations and delivery set points according to the changing demand. With an improvement made to the monitoring of compressed air usage, the supply can be controlled to match the demand requirements more accurately.

Moore Industries International has further improved the efficiency of compressed air networks. The company has developed a controller that is able to automatically control the operation of compressors. The Moore controller communicates specific commands directly to the compressor's PLCs. A massive benefit was surge protection; the Moore controller is able to automatically control the blow-off valve. Therefore, when a compressor reaches surge conditions the Moore controller will send a signal to open the blow-off valve in order to avoid surge [42]. Another benefit of the Moore controller is the automatic control of a compressor's inlet guide vane angles. The controller adjusts the inlet guide vane angle to regulate the delivery pressure of the compressor according to the pressure set point [43].

Other features of the Moore controller include advanced monitoring systems. The monitoring systems are able to send feedback from different compressor components to the SCADA system. Feedback from different positioners installed on the guide vanes and blow-off valve is available for the operator to observe. The Moore controller also improves condition monitoring. Process data such as bearing temperature and vibrations are analysed to detect deviations. These deviations trigger alerts to maintenance personnel who can then assess the severity of the deviation [44].

DSM projects implemented on the supply side also involve training operators to control the compressors according to predetermined schedules [45]. The schedules are set up by characterising the compressed air network requirements throughout a typical day. By evaluating the flow and pressure requirements for the different operating schedules of the shaft, processing and workshops, a master pressure schedule can be determined.

The master schedule is used to control the compressors' delivery pressure according to requirements of the consumers. Compressors are stopped and started in order to maintain the network pressure according to predetermined schedules. For example, this resulted in compressors being stopped after the drilling shift when less air flow is required.

Other control systems include implementing the dynamic compressor selector (DCS). The DCS controller is able to determine the required network pressure and has the ability to determine the most effective compressor combination [46] [47].

The abilities and limitations of these strategies and control systems will be further investigated in order to develop a control strategy to improve the energy efficiency of a compressed air network. The control strategy must address the limitations encountered in order to achieve sustainable electrical cost-savings.

1.5 Problem statement and objectives

The supply of compressed air is directly connected to the demand of consumers on compressed air networks. Due to the ever-changing demand requirements, using predetermined schedules to control the supply result in an inefficient compressed air network. Various methods and strategies have been implemented to achieve electrical savings on the demand side and supply side of compressed air networks. However, investigation into a mine compressed air network presents the possibility of achieving significant energy savings.

It has been found that compressed air network on most South African mines is monitored and controlled by control room operators. Although compressors operate automatically, the responsibility of determining when the compressor should run lies with an operator. The operator is also responsible for changing the compressor's discharge pressure set points according to

predetermined schedules. The problems associated with the mentioned control strategy is as follows:

- Network pressure is higher than required;
- Inefficient compressors are selected;
- Compressor guide vanes are not utilised; and
- Excessive compressor blow-off and/or unloading occur.

The demand requirement of consumers is therefore not efficiently matched by the compressed air supply flow. In order to achieve the potential energy savings the supply and demand of compressed air need to be integrated and controlled as a single system. The objective of this study is therefore as follows:

- Characterise the demand and supply sides;
- Identify cost-saving strategies on the demand and supply sides;
- Investigate existing compressed air control strategies and controllers; and
- Develop an improved compressed air control strategy.

The main objective of this study is to develop a control strategy that will control the air supply in order to accurately match the demand requirements. A compressed air control strategy will therefore be developed to improve the compressed air system, without negatively influencing production.

This will be achieved by determining an optimal compressor discharge set point by continuously evaluating the requirements of major consumers. The compressors will then be scheduled in order to maintain the network pressure according to the optimal required pressure set point.

1.5.1 Overview of dissertation

Chapter 2: Literature study

Chapter 2 offers a discussion of the supply and demand sides of compressed air networks. A detailed study was conducted in order to identify relevant supply and demand side cost-saving strategies. The DCS controller has been identified as a controller, which is able to integrate the demand and supply sides dynamically. The chapter concludes by describing the inner workings of the DCS controller.

Chapter 3: Development and verification

The DCS controller has been identified as a suitable controller that is able to automatically control a compressed air network. The DCS controller was implemented at a mining complex. Limitations were encountered with the existing control system.

Limitations are addressed by developing a new improved control strategy by using the DCS controller as a backbone for communication links. The design of the new control strategy will be fully discussed. A validation of the new control system is determined in order to show the feasibility of the proposed control.

Chapter 4: Implementation and results

The results obtained from implementing the new control strategy is discussed in detail. Verification of the control strategy is also discussed and this proves the validation of this dissertation.

Chapter 5: Conclusion and recommendations

The findings and control strategy are concluded in this chapter. Further recommendations for improvements and research on the improved control strategy are given.

CHAPTER 2. LITERATURE STUDY

2.1 Introduction

Figure 6 presents the overview and topics that are investigated in this chapter. A systematic approach will be followed in this chapter in order to identify strategies that will improve the energy efficiency of a compressed air network.

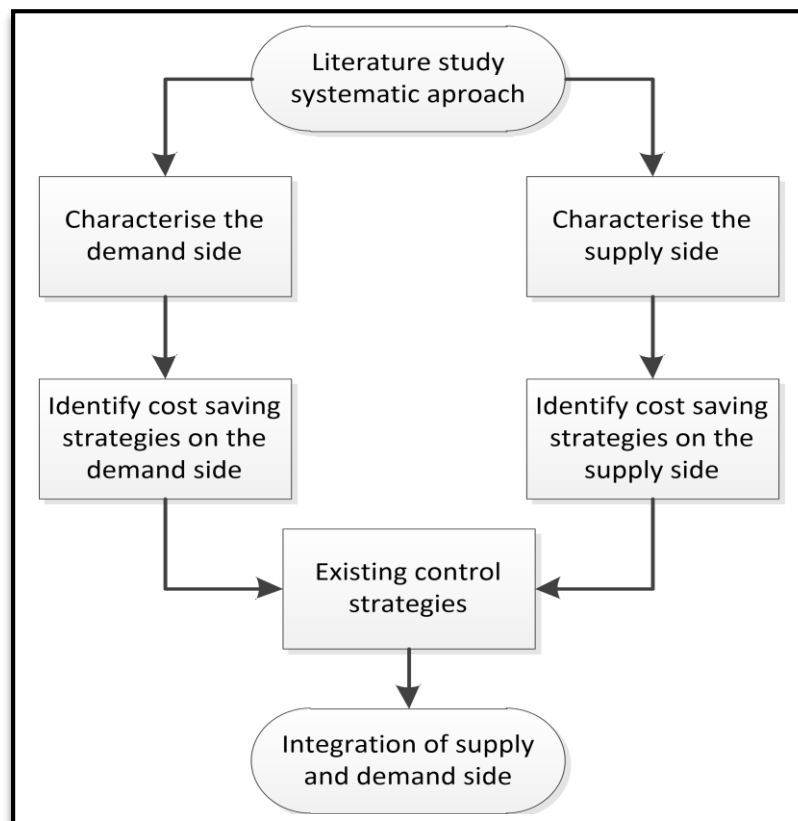


Figure 6: Literature study overview

A detailed investigation will be conducted to develop a broad understanding of the demand and supply sides of a compressed air network. Further investigation will identify existing electrical cost-saving strategies implemented on the demand and supply sides.

Existing controllers will be researched that can automatically control the supply of compressed air according to the requirements of the demand. This will be critical to identify a control strategy that is able to integrate the demand- and supply requirements of compressed air. This will consequently improve the energy efficiency of a compressed air network to achieve potential energy savings.

2.2 Cost-saving strategies on the demand side

2.2.1 Preamble

Various cost-saving strategies have been implemented on the demand side of compressed air networks. The DSM projects that will be investigated in this section include the following:

- Installation of control valves;
- Compressed air leak management; and
- Reducing network pressure.

Before these cost-saving strategies are discussed, the requirements of the typical pneumatic equipment mentioned in section 1.2.1 must be quantified. A better understanding is therefore attained on the entire demand side of a compressed air network.

2.2.2 Characterising the demand side

As discussed in section 1.2.2, pneumatic equipment is designed to use compressed air at certain flow and pressure requirements. Each mining shaft, processing plant and workshop uses different pneumatic equipment that requires compressed air at certain requirements [15]. The equipment will not operate optimally if insufficient air is supplied, therefore the compressors must supply the compressed air ring to meet the requirements of all consumers [48].

Pressure is the most important requirement for pneumatic equipment. Pressure can be defined as the driver for pneumatic equipment's counterparts [49]. If the pressure is too high, the equipment can be damaged or may operate inefficiently. If the pressure is not high enough, the equipment will not operate correctly or may not operate at all [25].

The pressure requirements of the compressed air consumers will be specified to ensure equipment operates optimally. Table 1 lists the compressed air requirements for pneumatic equipment used at a typical mining shaft:

Table 1: Pneumatic equipment requirements

Pneumatic Equipment	Pressure Requirements [kPa]
Rock drills [23]	500-600
Rock loaders [26]	400-500
Actuators on valves [50]	400
Cylinders on ventilation doors[26]	400
Refuge bays [51]	200-300

2.2.2.1 *Pneumatic rock drills*

The pneumatic rock drills are used to drill holes in the rock face of the gold reef underground [25]. The holes are filled with explosives and detonated in order to blast away the rock. Figure 7 illustrates a pneumatic hand-held rock drill.



Figure 7: Pneumatic rock drill [52]

2.2.2.2 *Pneumatic loaders*

After detonating the explosives, the loose rocks from the blast are moved by pneumatic loaders. The loader is usually track-bound and is used to lift rock from the ground into the loader's hull. The rock is then transported to surface by other material-handling equipment.



Figure 8: Pneumatic loader [26]

2.2.2.3 *Pneumatic actuators*

Compressed air and water are controlled and regulated underground and on surface by valves. Pneumatic actuators are installed on these valves to add remote controllability to the valves. The pressure upstream of the valve should be sufficient to operate optimally. To manage the risk of accidental open or closing when the air pressure drops due to unforeseen circumstances, the pneumatic actuators are equipped with the manual open or close function.



Figure 9: Pneumatic actuator [50]

2.2.2.4 *Pneumatic cylinders*

On the ore transportation system, pneumatic cylinders are used to automatically open chute doors and loading boxes. Figure 10 illustrates a pneumatic cylinder used to open a chute door.



Figure 10: Pneumatic cylinder

2.2.2.5 *Refuge bays*

Refuge bays are safety shelters used underground for use in emergencies. In emergencies, miners can shelter in refuge bays until it is safe or until they are rescued. Inside refuge bays, utilities such as water and first aid kits are stored. Compressed air is used to keep the atmospheric pressure of a refuge bay at a higher pressure than the surrounding atmosphere.

This will ensure that no smoke or dangerous gases can enter the refuge bay due to the positive pressure. The required volume flow rate of air that needs to be supplied to refuge bays is estimated at 85 l/min for every person in the refuge bay [53]. The ideal supply pressure required to prevent toxic gases from entering a refuge bay must be maintained at 200 – 300 kPa [54].

South African mining regulations state that a positive pressure is required at all times underground. This means that even if there is no personnel underground the refuge bays must still be supplied with compressed air. Figure 11 illustrates an underground refuge bay.



Figure 11: Underground refuge bay [51]

2.2.2.6 *Other underground consumers*

Air hoists [55] and winches [56] are other non-critical consumers that operate at a pressure range of 400 – 600 kPa. Although it is considered as bad practice, compressed air is also used for cooling and ventilation purposes in underground working areas. Other equipment includes pneumatic pumps and pneumatic tools [16].

2.2.2.7 *Process plants*

On surface, various processes and equipment at the plants require compressed air to operate. Processes such as agitation and aeration are important operations in the gold-leaching process – a process used for gold extraction. These processes require relatively high flow at a reduced pressure. The operating pressure range of these processes is 380 – 500 kPa [24]. Processing plants operate with minimal stoppages to ensure uniform extraction. Therefore, constant pressure and flow are required throughout a typical workday.

2.2.2.8 *Workshops*

At the workshops, different pneumatic equipment can be found. Mechanical workshops use pneumatic tools such as air jacks, tyre inflators and other low-flow, high-pressure tools. Pneumatic equipment such as air presses and hammers are typically used at blacksmith workshops.

These users require pressures in excess of 480 kPa [24]. Although the equipment used in workshops require relatively high pressures, they are primarily operated in conjunction with the drilling shifts where high pressures are usually available.

2.2.2.9 *Compressed air pipe network*

Compressor houses can be several kilometres away from the point where the end users are located. Another indeterminate consumer is compressed air that is lost through leaks in the distribution network. This consequently wastes electricity. The complexity and size of compressed air networks result in a number of leaks. It is estimated that 20 – 30 % of compressed air is lost through leaks [42]. Pressure drops and frictional losses are also present in compressed air networks [57]. Leaks, improper section bends, inadequate sized pipelines and instrumentation such as valves all contribute to frictional losses and pressure drops.

As mentioned in section 1.2.1, there are other pneumatic equipment not mentioned in this study. However, if the pressure requirements of the pneumatic equipment discussed in this section is matched by compressed air supply, it can be assumed that the other equipment will operate optimally.

Operation of a typical mining complex changes during a production day. Different types of pneumatic equipment are used during different operating shifts. Consequently, the pressure and flow requirements of consumers change throughout the day. The typical operation schedules of a mining complex will be discussed in the following section.

2.2.3 Operating schedule

Figure 12 illustrates the different operating schedules of a typical gold mine during a production day. Also illustrated in Figure 12 is an approximate daily flow consumption and pressure profile required during the different production schedules.

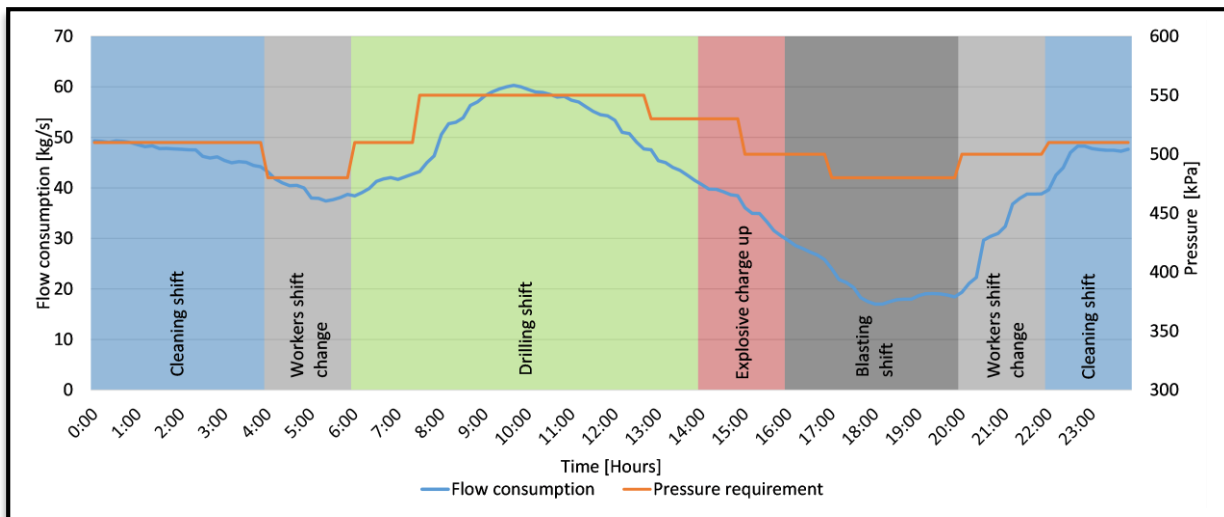


Figure 12: Mining shaft operation schedule

The daily operation schedule during a production day consists of a drilling shift, explosive charge shift, blasting shift and a cleaning shift [27]. A typical production day will start at 4:00 AM when workers start travelling from surface to underground working stations. Working stations underground are up to four kilometres away from where the workers leave the skip.

The skip is the enclosed cage mines use to vertically hoist workers underground or to surface. Workers can take up to two hours to reach their working areas. This is due to the distance they have to travel and the number of workers travelling underground. Travelling time is strict because skip availability is limited.

When the workers reach their working stations the drilling shift begins. The pneumatic drills are used to drill holes in the rock surface where the explosives will be placed. The demand flow and

pressure requirements will be the highest during the drilling shift as a result of all the drills in operation [41]. Once the workers are finished with the drilling, they travel back to the skip area where they are hoisted to surface.

The explosives are then placed in the designated drilling holes and wired to a centralised blasting panel. Responsible mine personnel will manually activate the panel to charge the explosives and evacuate to surface. Once all the mine personnel are on surface, the explosives are detonated.

During the blasting shift no mine personnel is allowed underground due to the danger involved with detonating explosives in a confined space like the underground working areas. During the blasting shift, only the refuge bays are supplied with compressed air. Therefore, the compressed air requirements of the shaft during this period are at the lowest point.

After the blasting shift, mineworkers travel back to the working areas to officially begin with the cleaning shift. Pneumatic loaders are used to clean the debris and loose ore from the ground. The ore is then transported from underground to the processing plants on surface by other material handling equipment.

These schedules are fixed-shift cycles and most mining complexes perform blasting in the same period. This means that during the blasting shift, the requirements of the compressed air network is at its lowest point because less air is required from all the interconnected shafts.

As mentioned in section 1.2.2, the processing plants operate non-stop during a typical working weekday and therefore require constant pressure and flow throughout the day to operate optimally [22]. It is therefore important to keep in mind that during the blasting shift, adequate compressed air must still be supplied to ensure the operation of the process plants is not affected. Nonetheless, the required ring pressure is more easily obtained with fewer compressors in operation because less air is required from the shafts during the blasting shift.

With Eskom introducing the DSM initiative, various projects have been implemented to optimise the demand of consumers in order to achieve electrical cost-saving. DSM projects and strategies that have been implemented on the demand side will be discussed in the following section.

2.2.4 Installing control valves

As discussed in the previous section, the requirements of critical consumers differ from one another. Mining shafts use compressed air at different requirements that are dependent on the specific operation shift. On the other hand, processing plants use compressed air at a lower constant pressure during a production day.

The network pressure of the compressed air ring must be maintained according to the highest consumer's requirement at a specific time to ensure equipment operates optimally. This results in a higher network pressure that is required by other low-compressed air consumers. This cause inefficiencies in the compressed air network because some consumers are supplied with compressed air at a higher pressure than required.

In order to optimise the consumption of compressed air, control valves are installed at critical consumers. The control valves regulate the supply of each consumer according to the consumer's requirement. A control valve consists of a controllable valve (actuator installed on valve), PLC, measuring instrumentation and communication links to a centralised control room. Figure 13 presents a typical layout of a control valve.

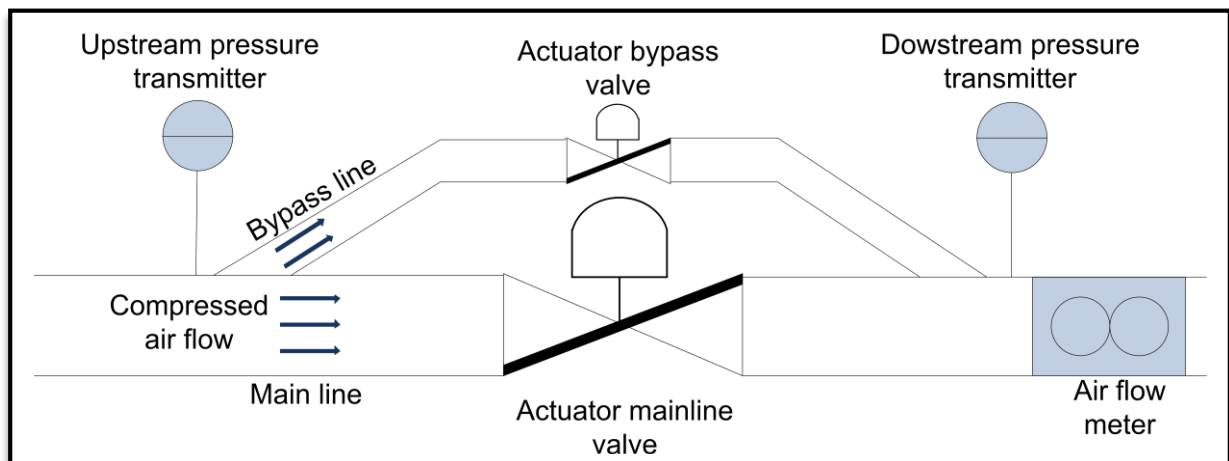


Figure 13: Control valve assembly

As displayed in Figure 13, the mainline is connected to the compressed air ring and supplies the compressed air to each consumer. The compressed air requirements of the specific consumer is maintained by installing an actuated valve on the mainline [58]. The actuator is a mechanism that

opens and closes the valve automatically according to P&ID control loops, which are programmed on the valve's PLC.

The actuator will open and close the valve in order to regulate the flow to control the downstream pressure according to a pressure set point. The actuator can either be controlled by electricity or compressed air. Pneumatic actuators are cheaper than electrical actuators. This can be ascribed to pneumatic actuators that are less reliable than electrical actuators. If the system pressure is not high enough the pneumatic actuator will not be able to control the valve [16].

Figure 13 illustrates a bypass line installed on the mainline. The bypass line will have a smaller pipe diameter than the pipe diameter of the mainline. The bypass line is used to regulate the downstream pressure during the blasting shift. As discussed in section 2.2.2, the flow consumption during this period is usually very low when compared to the flow consumption during the drilling shift. In fluid dynamics, mass flow is defined as the mass of a fluid which passes per unit of time. The formula for mass flow through a pipe can be expressed as defined in Equation 1 [59]:

Equation 1: Mass flow

$m = \rho Q = \rho v A = \rho v \left(\frac{\pi d}{4}\right)^2$	
$m =$ Mass flow	[kg/s]
$\rho =$ Fluid density	[kg/m ³]
$v =$ Fluid velocity	[m/s]
$A =$ Cross section area	[m ²]
$d =$ Diameter	[m]
$Q =$ Volume flow	[m ³ /s]

From Equation 1 it is evident that the mass flow of air is dependent on the pipe diameter. In order to control the downstream pressure accurately in the low air flow periods, the mainline valve will close completely and air will be regulated through the smaller bypass line valve. The actuator valve on the bypass line regulates the flow according to the same principle as described for the mainline actuator valve.

Because the diameter of the bypass line is relatively smaller, a smaller valve is installed. The smaller bypass valve will therefore regulate the air flow in the blasting shift more accurately than the mainline valve is able to.

The compressed air consumption at each shaft is further managed at all critical underground mining levels. Control valves are installed on the levels to regulate the downstream pressure according to a predetermined pressure set point schedule for each level. These pressure set points are superimposed to determine the surface control valve pressure set point of the specific control point.

It is important to consider auto compression when the surface valve pressure set point is determined. Auto compression is the rise in pressure as a result of air being compressed because of its own weight due to gravity. The pressure of compressed air underground at a mining level could differ from the pressure of the compressed air at surface due to the effect of auto compression. The added pressure gained from a certain vertical distance can be calculated using Equation 2 [60]:

Equation 2: Effect of auto compression

$\Delta P = \rho gh$	
$\Delta P =$ Pressure gained	[kPa]
$\rho =$ Fluid density	[kg/m ³]
$g =$ Gravitational acceleration	[m/s ²]
$h =$ Vertical distance	[m]

For processing plants, the pressure set point will be a fixed value in order to supply compressed air at a constant required pressure. The pressure set point is determined by evaluating the requirements of the pneumatic equipment in operation.

Pressure transmitters and flow meters are installed at the control valves. The upstream pressure, downstream pressure and flow consumption are usually measured for each consumer. However, only the downstream pressure is necessary. The control valve and instrumentations installed at the consumer are typically referred to as air stations. According to previous studies, a 6.5 MW

demand reduction was achieved in the Eskom evening peak period on a gold mine by installing control valves on surface and underground [18].

2.2.5 Compressed air leak management

Compressed air distribution networks can reach lengths of up to 75 km. From the point of supply to the point where the compressed air is used can therefore be several kilometres away. The complexity of compressed air networks results in pipelines often containing leaks [61]. Compressed air leaks result in unnecessary compressor power consumption [62].

Compressed air is leaked at bends, valves, section joints, weak spots in the distribution network and locations where pneumatic equipment is connected to the distribution network [63]. A study conducted on an old South African gold mine, showed a single leak resulted in an increase of 1 MW in power consumption. This resulted in an increase of approximately 13% in total compressor power consumption [63]. The following main attributions cause leaks in a compressed air system:

- Improper compressed air use; and
- Poor maintenance on the distribution network.

Data from actual underground investigation show that in some working areas temperatures reach up to 40 °C. The working areas reach these temperatures due to inadequate cooling and ventilation. The workers therefore use open-ended compressed air pipes for cooling purposes in these areas. Doing so, compressed air is wastefully used for non-production activities. The electrical costs linked with using open-ended pipes for cooling purposes can justify installing alternative cooling solutions. This will result in less waste of compressed air and a reduction in power consumption.

The compressed air distribution network covers vast distances and is exposed to various damaging elements. These elements include rust, accidental damage and/or vandalism [39]. Rust occurs in the steel pipes that are used to distribute compressed air [12]. Rust is the main reason for weak spots in the distribution network. Rust will be reduced by installing stainless steel pipes. However, stainless steel pipes are more expensive than steel pipes and because of the size of the distribution network; infrastructure cost will be more expensive.

Vehicles and other large machinery travel over or near the distribution network that can cause accidental damage to the network resulting in air leaks. If the accidental damage is not reported, the air leak can be left unrepaired for numerous days.

Leaks in the system contribute to pressure drops that could cause equipment to operate inefficiently. This can consequently lead to a decrease in production levels [64]. Leak management is therefore an important cost-saving strategy to implement on the compressed air distribution networks.

2.2.6 Reducing network pressure

It has been found that the network pressure of manually operated compressed air networks is maintained at a higher pressure that is actually required by the consumers [65]. This is to ensure sufficient compressed air is supplied to the consumers for optimal production to occur. Investigations have proven that compressor power consumption can be reduced up to 20 % by lowering the discharge pressure [66]. There are multiple ways the network pressure can be reduced.

For instance, the network pressure can be reduced by considering electric rock drills rather than pneumatic rock drills. As discussed in section 2.2.2, the flow and pressure requirements are at a peak during the drilling shift when pneumatic drills are extensively used. Therefore, if electric drills are used on mining shafts the compressed air requirements of the entire mining complex will be reduced.

Electrical rock drills are more efficient than pneumatic drills [67]. However, most South African mines are relatively old and have the required infrastructure for pneumatic drills already installed. The infrastructure cost could therefore implicate the feasibility of replacing pneumatic rock drills with electrical drills. Other pneumatic equipment used for transport and ventilation doors should rather be replaced with electrical equipment in order to reduce the network pressure.

When small consumers such as processing plants or workshops have their own stand-alone compressors, the network pressure can be lowered. Stand-alone compressors are used to supply compressed air specifically for the requirements for small consumers. The network pressure can therefore be reduced during the off-peak times.

Another method of reducing the network pressure is by dividing the compressed air ring into a high- and low-pressure section [41]. This can be achieved by installing a control valve at strategic locations on the compressed air network. The high-pressure section can supply compressed air to the shaft and the low-pressure section can supply the processing plants.

Lowering the system pressure can reduce the amount of air lost due to leaks. The amount of air lost through a leak is a function of the network pressure. The higher the network pressure, the more compressed air is lost through leaks [68]. If the network pressure is too high, pneumatic equipment wears down more easily and could be damaged. Therefore, by lowering the network pressure, less air will be lost through leaks and wear on equipment will be reduced.

When the DSM strategies mentioned in this section are successfully implemented on compressed air network, the demand requirements of compressed air can be maintained throughout the day and be significantly reduced. However, if the supply is not adjusted to match the reduced demand, no electrical savings will be achieved.

It is therefore important to integrate the supply and demand requirements of compressed air, to ensure the supply accurately matches the demand. This can be achieved by characterising the compressors to adequately control the supply of compressed air. There are various strategies implemented on compressors to achieve this and these are discussed in the following section.

2.3 Cost-saving strategies on the supply side

2.3.1 Preamble

Multi-stage centrifugal compressors are commonly used to supply compressed air. As mentioned in section 1.2.1, multi-stage centrifugal compressors are enabled to deliver a large quantity of compressed air at a stable discharge pressure [22]. Single stage centrifugal compressors are made up of five main components, namely an impeller, guide vanes, a shaft, a volute casing and a diffuser [69]. The uncomplicated design of centrifugal compressors makes operating and maintenance simple.

Multi-stage centrifugal compressors consist of several impellers in series to form different compression stages. The air is compressed in each stage resulting in a high discharge pressure in order to meet the high requirements of a mining complex. Multi-stage compressors make use of

intercoolers between each compression stage to obtain a polytrophic compression exponent as close to one as possible [49].

Most compressor's rotation is generated by an electric motor. In one case, it was found that a steam turbine was used to supply the rotating force to a compressor in a petroleum processing plant [70]. Electrical motors are however more efficient for the size of most compressors found at mines [34]. Figure 13 illustrates an example of a multi-stage centrifugal compressor.

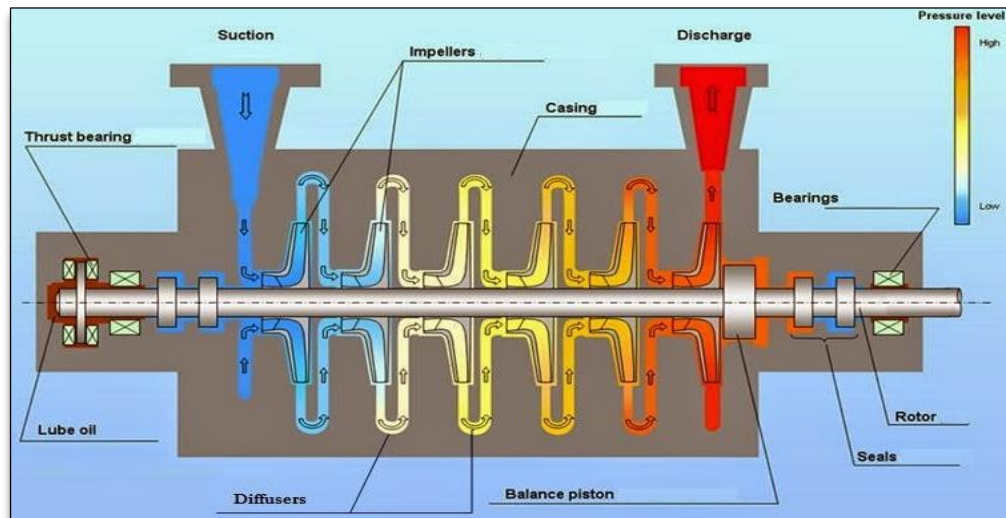


Figure 14 Multi-stage centrifugal compressors [71]

2.3.2 Characterising the supply side

The inner workings of a typical compressor consist of several intricate components and operation systems to produce compressed air at the highest efficiency. There is much literature available on the proper operation of these systems. In order to characterise the supply side, the mechanics of a compressor will not be investigated.

However, the parameters that influence compressor power and flow capacity will be discussed further. The electrical power used by a compressor to produce a certain amount of air at a certain discharge pressure can be calculated with Equation 3 [34]:

Equation 3: Compressor electrical power

$$P = \frac{\dot{m} C_p T_{in} \left(\left(\frac{p_{out}}{p_{in}} \right)^{\frac{k-1}{k}} - 1 \right)}{\eta_{comp}}$$

P = Electrical compressor power [kW]

\dot{m} = Mass flow [kg/s]

C_p = Molar specific heat of air [J/kg • K]

T_{in} = Inlet air temperature [K]

p_{out} = Discharge pressure [kPa]

p_{in} = Atmospheric pressure [kPa]

k = Specific heat ratio of air [-]

η_{comp} = Compressor efficiency [-]

Equation 3 shows that the parameters such as mass flow, inlet temperature, discharge pressure and compressor efficiency are in direct relation to compressor power. This study will focus on measures to reduce the discharge pressure and delivery flow of compressors. This will result in a reduction in power consumption.

These parameters are determined according to the demand of compressed air. The demand for compressed air is determined by the consumers on the compressed air ring and leaks in the distribution network. As mentioned in section 2.2 various DSM projects have been implemented on mining complexes to reduce the compressed air demand. However, in order to achieve energy savings the discharge pressure and delivery flow of compressors must also be adjusted to match the reduced demand.

This is done by capacity control methods. The following section will discuss these methods in detail. It is important to keep in mind that when these practices are implemented, the supply of compressed air should always match the demand. This will ensure the production of the mining complex is not affected.

2.3.3 Capacity control methods

Capacity control regarding compressor delivery entails controlling the supply flow to adequately match the requirement of the demand flow. If the compressors do not meet the demand, production will be affected. If the compressors supply more compressed air than is needed, energy is unnecessarily wasted. Capacity control is of significant importance when it comes to optimising a compressed air network. A compressor's discharge flow can be controlled by the following methods:

- Compressor combination [35];
- Loading and off-loading compressors [36];
- Suction and/or discharge throttling [36];
- Inlet guide vane control [37];
- Blow-off valve control [38]; and
- Speed control [68].

Stopping and starting compressors to supply the demand at certain times is the simplest method of capacity control. When a compressor has been stopped, there is a certain time delay before the compressor can be started. Therefore, a compressor should only be stopped once the compressed air requirements no longer justify an extra compressor. This time delay differs for each compressor.

Another way to control the capacity of a compressor is by unloading and loading of compressors. Unloading and loading entails isolating compressors from the compressed air system. A blow-off valve is opened and the compressed air is blown into the atmosphere. By opening the compressor's blow-off valve the compressor can be powered without the load needed for compression. In this unloaded state, the electrical motor supplies power to overcome only basic friction and therefore power consumption is significantly reduced.

Suction throttling involves limiting the air intake of a compressor by using a control valve. The control valve reduces the suction pressure of a compressor, which reduces the discharge flow. Discharge throttling is nearly the same as suction throttling; the difference is that the delivery flow

is limited by using a control valve on the output side of a compressor. The pressure drops over the valve used for suction and discharge throttling, result in a significant reduction in efficiency and discharge flow.

By controlling the inlet guide vanes of a compressor, the swirl pattern of the inlet air is altered by changing the angle of the intake air. The compressed air delivery capacity changes according to changes in the swirl pattern of the inlet air [15]. In other words, the guide vanes are used to adjust the angle of air into the compressor that will result in a reduction in supply flow.

Inlet guide vane control on a fixed speed compressor increases the operating range of the compressor and drastically improves the performance of the compressor by reducing the relative velocity to acceptable levels at different pressure levels. The delivery flow range at different pressures is defined by a compressor characteristics curve. A typical performance characteristics curve is graphically presented in Figure 15.

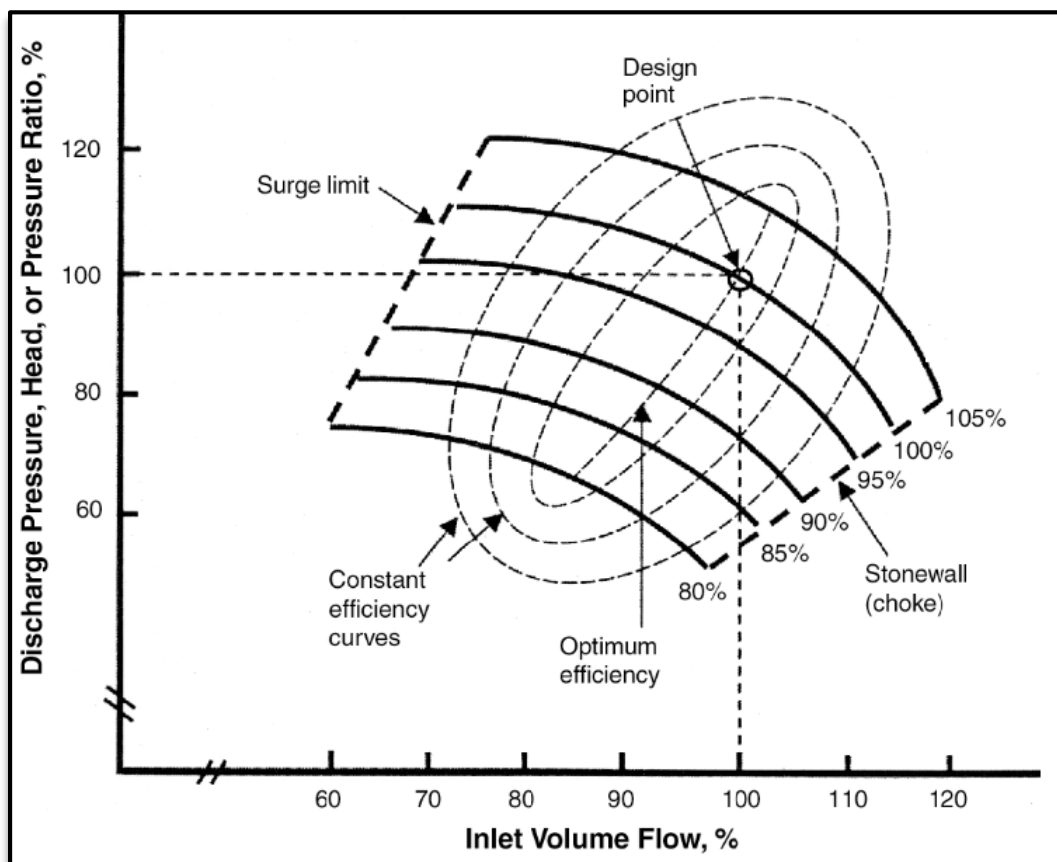


Figure 15: Compressor characteristics curve [72]

In Figure 15 the inlet volume flow ratio is plotted on the x-axis and the pressure ratio on the y-axis. The surge limit is along the upper left side of the graph and the choke limit on the lower right side. The curve shows a compressor's operating range, which is the area between the surge limit and choke limit. The design point indicates the compressor flow capacity at different pressures with the inlet guide vanes fully open, i.e. 100%.

The stonewall or choke limit defines the flow at which the air velocity at one of the impellers approaches sonic conditions (velocity through the compressor reaches Mach 1) [73]. At these conditions, the compressors are unable to develop pressure at an increased flow. The efficiency of the compressor is reduced beyond the choke limit.

Surge occurs when the compressor cannot overcome the outlet system pressure resistance (backpressure). The flow inside the compressor reverses, which causes a sudden change in axial thrust. Surge can damage various components of a compressor. Blow-off control is used to protect and avoid a compressor from surging.

This involves a fast-reacting blow-off valve opening that results in an increase in flow through the compressor that prevents surge from occurring. The compressor will go into blow-off conditions to protect itself from surging. The blow-off valve can also be used as capacity control method. However, the air is lost in the atmosphere and this is therefore considered as bad practice.

Compressors have an energy efficient line on the characteristics curve. The compressor will deliver the highest amount of air at the least amount of electrical power at any point on the line. The energy efficient line is slightly to the right of the surge limit.

Various studies on compressor capacity have been researched and speed control on the electrical motor as a compressor capacity control method was mentioned in a few. Installation of VSDs on the motor of compressors is a method typically discussed in terms of compressors' speed control. The cost of installing VSDs on compressor motors was analysed to evaluate the feasibility.

The study has concluded that it would need a substantial financial investment [18]. From practical experience, VSD installation on compressor motors are uncommon and will therefore not be further considered for this study.

In order to develop a control strategy these capacity control methods discussed must be considered. The most effective combination is by combining the inlet guide vane control with a proper surge avoidance control strategy. This will result in the compressor operating much closer to the surge line and therefore improve the efficiency of the compressors.

2.4 Existing controllers

Van Heerden [46] [47] has developed a controller that is able to dynamically determine compressors' discharge pressure set points and is able to simulate the most efficient compressor combination based on actual and predicted demand requirements. The following section describes the functionality of the DCS controller.

2.4.1 The DCS controller

The DCS controller is able to dynamically determine control outputs by simulating the entire compressed air network. The controller also compares predicted future demand requirements against actual demand requirements in order to determine more accurate control outputs. The compressor controller is therefore enabled to steadily control an ever-changing compressed air network.

The control was based on simulating the entire compressed air network. The results of the simulation are used to determine the output control commands. The calculations for the simulation was divided into two sections. Section simulations are done to determine the compressor discharge pressure set points and optimal required supply flow. Then other section simulations are done to determine the most energy efficient compressor combination that will deliver the optimal required supply flow. The simulation considered pressure drops and frictional loss in the compressed air network calculations, which adds accuracy to the results. Although these simulations are done separately, the outcomes influence each other.

For example, the optimal required network pressure is determined by evaluating the pressure requirements of the consumers. The compressor discharge pressure set points are set to deliver air at the optimal required network pressure. As the demand changes, the controller re-evaluates the compressed air network and adjusts the discharge pressure set points, if required. The discharge pressure is maintained by the automatic inlet guide vane angle control of the compressors.

The controller will also simulate the optimal required supply flow. The optimal required supply flow is then determined by evaluating the measured demand and supply flow. If it is required, the controller will send a command to the compressor houses to either stop or start a compressor to ensure the compressors match the optimal supply flow. This will ensure that the compressors supply sufficient air to maintain the required network pressure.

The simulations used by the DCS controller was based on work done by Venter [45]. Venter has made the following assumptions for his compressed air network calculations:

- The compressed air network will continuously be in steady state;
- Airflow is one-dimensional, incompressible and isothermal;
- Pipe sections have the same roughness throughout;
- Flow losses due to air leaks are negligible;
- The entire compressed air ring is at the same height; and
- The viscosity of air at 316 K is constant at 3.0134×10^{-5} kg /m•s.

In order to simulate the entire compressed air network the following thermodynamic equations are required to calculate theoretical results for the compressed air network controller.

Fluid density (ρ)

Fluid density is the mass of a fluid per volume, it is expressed as kilogram per cubic meter. The density of air is a function of temperature and pressure. The formula for density is [74]:

Equation 4: Fluid density

$\rho = \frac{P}{RT}$	
$\rho =$ Fluid density	[kg/m ³]
$R =$ Pressure	[kPa]
$R =$ Gas constant	[J • K ⁻¹ kg ⁻¹]
$T =$ Temperature	[K]

Reynolds number

The Reynolds number is used to determine whether flow is turbulent or laminar. The formula to determine the Reynolds number is [75]:

Equation 5: Reynolds number

$$Re = \frac{\rho v D}{\mu}$$

$Re =$ Reynolds number	[-]
$\rho =$ Fluid density	[kg/s]
$v =$ Fluid velocity	[m/s]
$D =$ Pipe diameter	[m]
$\mu =$ Viscosity	[kg/s · m]

Darcy friction factor

The Darcy friction factor is a dimensionless number used to describe the frictional losses in a pipe [75]. Using the Swamee–Jain approximation, the Darcy friction factor can be expressed as follows:

Equation 6: Darcy friction factor

$$f = \frac{0.25}{[\log(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}})]^2}$$

$f =$ Darcy friction factor	[kg/s]
$\varepsilon =$ Pipe roughness	[μ m]
$D =$ Pipe diameter	[m]
$Re =$ Reynolds number	[-]

Bernoulli's principle

Bernoulli's principle is a fluid dynamics principle that states that for an inviscid flow of a non-conducting fluid, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy. Bernoulli's principle can be expressed as follows [75]:

Equation 7: Bernoulli's principle

$$\frac{\rho v^2}{2} + \rho g z + P = \text{constant}$$

$\rho =$ Fluid density [kg/s]

$v =$ Fluid velocity [m/s]

$G =$ Gravitational acceleration [m/s²]

$z =$ Height [m]

$P =$ Pressure [kPa]

When this formula is applied to a pipe with two ends, the formula can be expressed as:

$$\frac{\rho_1 v_1^2}{2} + \rho_1 g_1 z_1 + P_1 = \frac{\rho_2 v_2^2}{2} + \rho_2 g_2 z_2 + P_2$$

With the assumptions made by Venter the following is true:

$$\rho_1 g_1 z_1 = \rho_2 g_2 z_2$$

Therefore Bernoulli's principle can be simplified to:

$$\frac{\rho_1 v_1^2}{2} + P_1 = \frac{\rho_2 v_2^2}{2} + P_2$$

If the pressure loss and pressure drop (P_{loss}) in the pipe is included, the Bernoulli's principle can be expressed as:

$$\frac{\rho_1 v_1^2}{2} + P_1 = \frac{\rho_2 v_2^2}{2} + P_2 + P_{loss}$$

These equations were used to design a theoretical compressor controller by incorporating mathematic modelling into a control system to simulate the air flow in a compressed air network dynamically. The actual system pressure and flow for each consumer were used as inputs to obtain the simulation results. The results were used to determine the flow needed from each compressor house at present and for future conditions. The simulation results were verified by using other simulation software tools.

The theoretical compressor controller was programmed in Visual Basic .NET. Visual Basic .NET does not have graphics user interface (GUI) functionality, which means that the controller is impracticable for the use of mine personnel.

Van Heerden used the approach of the theoretical compressor controller and integrated the method into a user-friendly interface platform. Delphi 6 Integrated Development Environment (IDE) has been used to develop the DCS controller. With the GUI functionality, a more practical controller with regard to the mine personnel has been developed.

The DCS controller has the functionality to automatically control the following components of a compressed air network:

- Receive real time process data;
- Simulate an optimal compressed air network by evaluating future conditions;
- Dynamically determine individual compressor discharge pressure set point;
- Prioritise compressor according to predicted requirements;
- Communicate discharge pressure set points and start, stop, load and unload commands to compressors;
- Send control pressure set points to surface control valves for the various consumers;
- Enable to split the compressed air network into a high pressure and low pressure network;
- Include compressor location into the simulation; and
- Consider compressed air leakage in the system and pressure losses.

Van Heerden has made improvements to the original DCS controller he developed. He has designed a dynamic compressor controller (DCC) [47] that addressed shortcomings with implementation on different mining complexes that the original DCS [46] had encountered. The shortcomings and improvements made on the original DCS will not be discussed in this section. However, the newest version of the developed controller will be discussed in detail and will be referred to as the DCS controller throughout this document.

As discussed in section 1.3.1, various equipment on surface and underground are remotely controlled by PLCs. Control output commands are sent to the PLC through the SCADA. Various instrumentation such as pressure transmitters and flow meters are installed on field equipment in a compressed air network. The measured readings are continuously communicated to the SCADA.

The DCS controller is able to communicate in real time with the SCADA via an OPC. OPC is an industry standard method that allows different devices by different manufacturers to communicate with each other. Therefore the DCS controller is enabled to send control outputs to the relevant equipment through the SCADA – PLC communication links. The DCS controller also receives process data from instrumentation in real time from the SCADA.

In order to optimally control the compressed air network in terms of the availability of real time data is a crucial aspect. The DCS controller uses filtered data to simulate the optimal network. Filtering the process data is necessary to ensure that calculations remain accurate. Figure 16 compares the real time data of a flow meter against the smoothed and filtered profile used for the calculations.

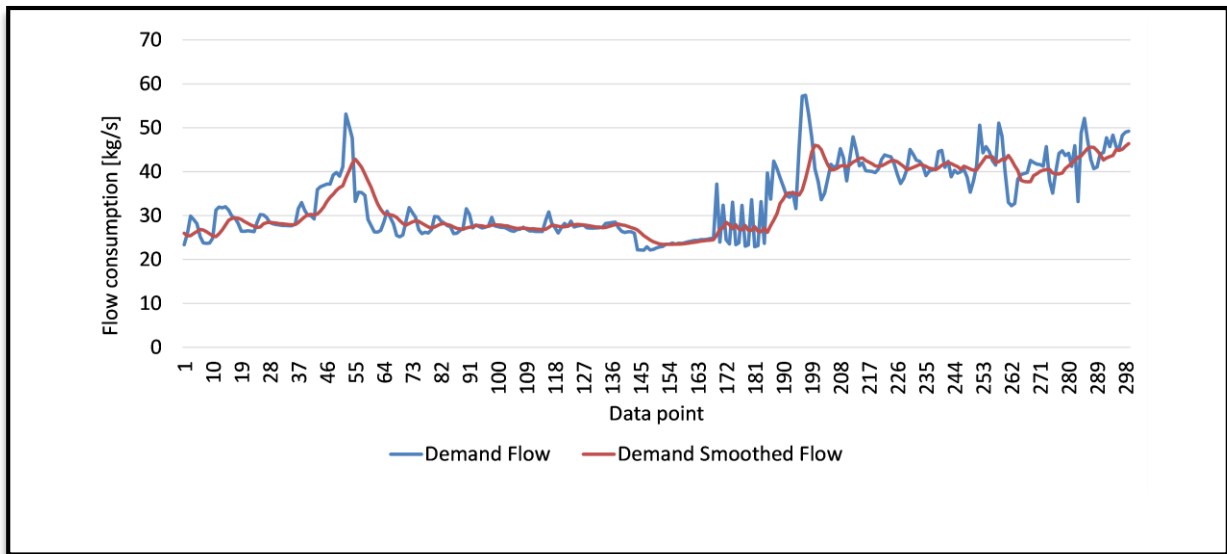


Figure 16: Smoothed real time data

The DCS controller is a component-based program, therefore the user is able to build virtual compressed air network by linking different components to represent the actual network. The DCS controller consists of the following components:

- Air node component;
- Air pipe component;
- Node feedback component;
- Air solver component;
- Compressor component;
- Compressor prioritiser component; and
- Compressor controller component.

The air node system is used for simulation purposes that represent the actual compressed air networks. This system was split into air nodes and air pipes. The air nodes represent the consumers, compressor houses and the different junctions encountered at a typical mining complex. The consumer node represents the control valve for a specific user and is referred to as a demand node. The nodes representing a compressor are referred to as a supply node. The user is able to edit the node type accordingly.

Input OPC tags are required for the supply and demand nodes. The tags required are the actual readings from instrumentation obtained through the OPC in real time. The required tags are listed below:

- Pressure tag - For demand nodes the pressure upstream and downstream of the control valve is required.
- Pressure set point tag - The pressure set point for each consumer and compressor is required. The compressor pressure set point will be used as a starting pressure when the network is simulated. The demand node's pressure set point is used as input for the calculations.
- Flow tag – The flow tag for supply nodes and demand nodes are necessary.
- Node variance – A fixed pressure adjustment can be made to the pressure set point value. The adjusted pressure set point will be used in the simulation.
- Future flow tag – The future calculated flow can be used in internal tags for displaying purposes.

The air nodes store input OPC tags in two minute intervals for reporting purposes. The air pipes represent the compressed air distribution network. Air pipes are used to connect different nodes together to form the compressed air network. The air pipe component does not require any process tags via OPC. Where two or more pipes connect, a junction node is used to represent the actual network. For each pipe the user specifies which two nodes are connected to the specific pipe. The user must also specify the properties of each pipe section. The required pipe properties include diameter (m), length (m), K loss coefficient and roughness (μm). By using the pipe/node system most compressed air networks can be build.

The simulation process is based on calculating the most ideal network and not the current network state. The simulation use Bernoulli's theorem to calculate each node's pressure and flow conditions in the virtual compressed air network. The flow loss through leaks is taken into account by adjusting each consumer's measured demand flow for the simulation. The Node Feedback component is responsible for adjusting the demand flow for each consumer. Equation 8 is used to calculate the adjusted demand flow for each consumer.

Equation 8: Adjusted demand flow

$$m_{Adjusted} = m_{Measured} * \left(1 + \frac{m_{Total_supply}}{m_{Total_demand}}\right)$$

$m_{Adjusted}$ = Scaled mass flow for specific consumer [kg/s]
 $m_{Measured}$ = Measured mass flow for specific consumer [kg/s]
 m_{Total_supply} = Total measured supply flow [kg/s]
 m_{Total_demand} = Total measured demand flow [kg/s]

By adding a factor of total supply and demand for each specific consumer's measured flow consumption, the flow loss in the network is considered. The adjusted demand flow is further compared to the calculated future demand flow of a specific consumer. The future demand flow is average values in half hourly logged intervals obtained for a specific day. These future demand profiles are then used to indicate what the required flow will be in 30 minutes or 60 minutes. Whichever one is higher will be used as the predicted flow in 30 to 60 minutes.

The predicted flow is then compared to the adjusted flow, determined by Equation 8. The highest demand flow between the two will be used as the required flow for that specific consumer. This is done to ensure that when the total required supply flow is calculated, the demand flow for each consumer and the total flow loss in the distribution network will be matched. The required demand flow for each consumer is then used by the air solver to simulate the virtual network.

The air solver is responsible to simulate the entire compressed air network by using mathematical modeling. The air solver uses all the process data from the air nodes and pipes for the calculations. Figure 17 illustrate a typical node system that will be used to explain the Air Solver.

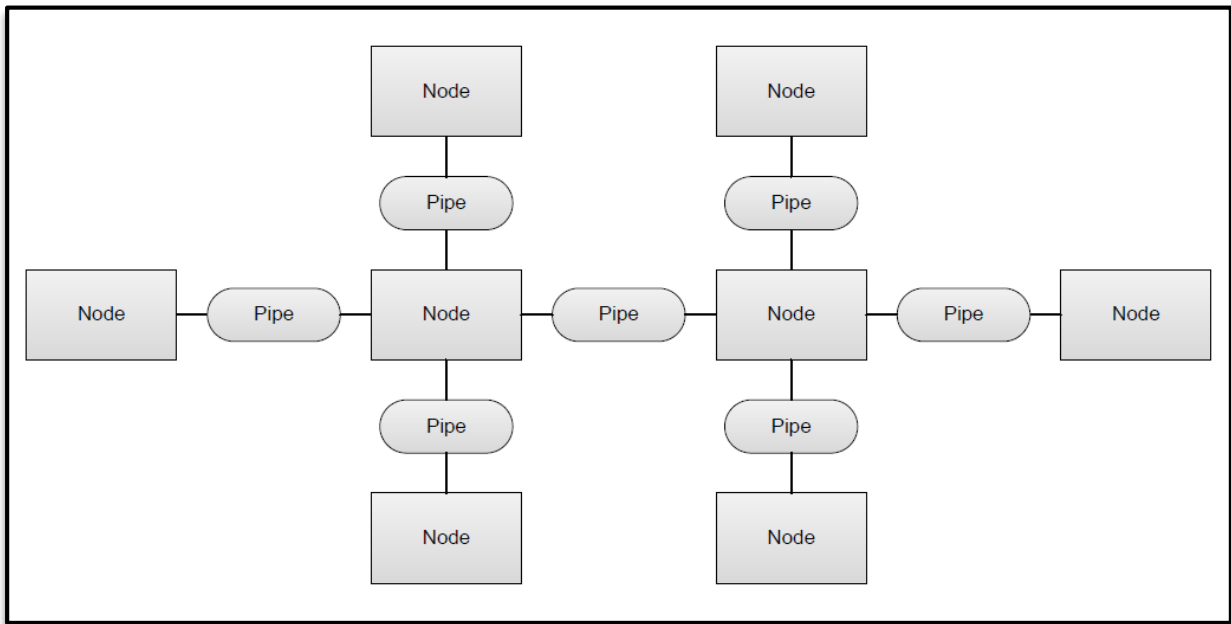


Figure 17: Simulation network example

In Figure 17, the nodes on the outer part of the example network represent the compressor houses and different consumers. For the simulation to work, the flow and pressure are required for the supply and demand nodes. The nodes in the middle represent the different junctions in the network. The air solver will estimate the flow and pressure of these junction nodes.

The air solver simulation begins by balancing the mass airflow through the entire network. This means that the total mass airflow into one node equals the mass flowing out of the node. This is done by dividing the network into smaller sections. The balancing of mass airflow for each individual node is simulated. By using Bernoulli's principle the mass flow through the pipes is then calculated. For the junction nodes it is assumed that the flow out of the nodes are negative and the flow into the nodes are positive. The sum of the flow in and out of all junction nodes is continuously calculated.

After the balance of air flow is completed throughout the entire network, the pressures of the junction nodes will be calculated. This is achieved by iterating different pressures for the specific junction node in order to get the sum of the mass flow as close to zero as possible. This is done to ensure that the total calculated supply flow equals the adjusted demand flow. The process will be repeated until the pressure of all the junction nodes is established. The accuracy of this simulation technique was proved by comparing the results with other commercial simulation software tools.

The required upstream pressure for each consumer is then evaluated against the specific consumers' pressure set point. If the calculated pressure requirement is not higher or equal to the consumer's pressure set point, the simulation starts over. This is repeated until all consumers' calculated required pressure is higher or equal to the pressure set point. After the simulation, all pressure and flow requirements are known, and the pressure set point and supply flow for each compressor are determined.

The simulation yields the following results:

- Mass flow balance through the pipes;
- Required upstream pressure for each consumer;
- Adjusted/predicted demand flow for each consumer; and
- Required supply flow.

The discharge pressure set point for each individual compressor is then calculated. To determine each compressor's discharge pressure set point, the pressure of a driven node is used. The driven node is taken as the consumer with the highest upstream pressure requirement.

This will ensure that if the network pressure is maintained at an adequate pressure determined by the driven node, all the other consumers' pressure requirements will be sufficiently supplied. A backup set point can be specified as a safety measure. The backup set point is a fixed pressure value that will be sent to the compressors if the air solver cannot calculate a suitable solution, or if input/output boundaries are exceeded.

The compressor component is used to visually represent each individual compressor. Figure 18 illustrates the compressor component that indicates if a compressor is currently running (on), in an unloaded state or completely shut down (off).

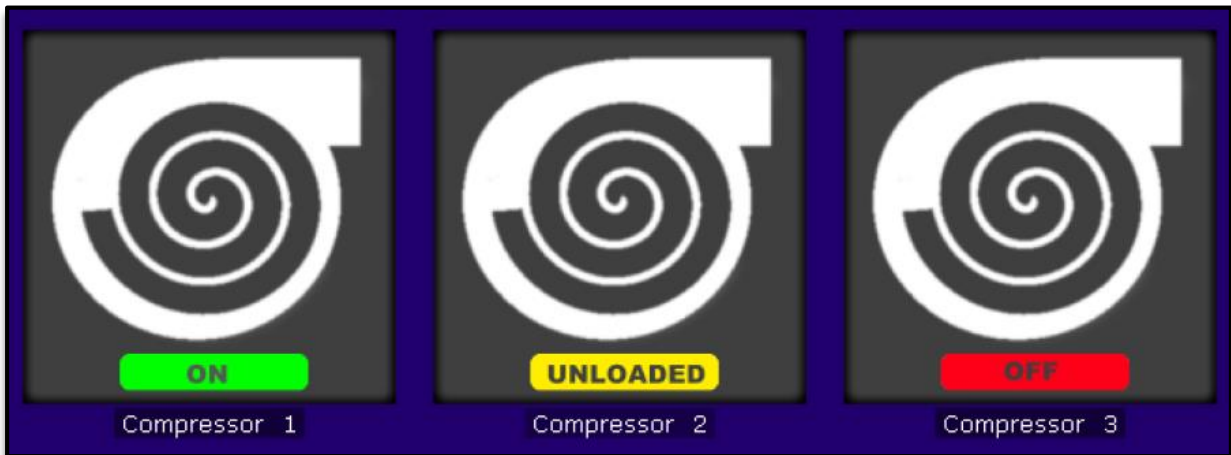


Figure 18: Compressor component

The user is able to select which compressors will be used as baseload and trimming compressors. The DCS controller will use this input requirement to simulate different compressor combinations. The baseload compressors will be given the highest priority when the compressor combination is simulated. The priorities of the trimming compressors will follow the baseload compressors and are determined according to the demand requirements. This is achieved by the compressor prioritiser component.

The user can also specify reserve compressors. The baseload and reserve classification can be determined by OPC tags, therefore the operator is able to switch baseload and reserve compressors according to maintenance schedule or other factors influencing compressor availability as required. The compressors process data required through OPC tags in the compressor controller is as follows:

- Discharge pressure tag;
- Discharge pressure set point tag;
- Delivery flow tag;
- Power consumption;
- Guide vane angle position in terms of percentage; and
- Blow-off valve position in terms of percentage.

Compressor status tags are also required through OPC for each compressor, this includes the following:

- Running tag – Indicates if a compressor is currently running.
- Loaded tag – Indicates whether the compressor is loaded or unloaded.
- Availability tag – Indicates if the compressor is available to control.
- Ready to start tag – Indicates if the compressor is in a condition to accept a start command.
- Alarm tag – Indication if any alarms are active for the compressor.
- Trip tag – Indicates if the compressor has tripped.
- Startup tag – Indicates that the compressor is in a startup phase.
- Shutdown tag - Indicates that the compressor is in a shutdown phase.

Most Moore controllers implemented on compressors are able to relay these required status tags to the SCADA which is then communicated to the DCS controller. These process variables and status tags are also stored in two-minute daily intervals that can be used for condition monitoring or reporting.

In order to simulate an optimal compressor combination, the compressor component determines the characteristics of each compressor in terms of performance and power efficiency. The performance is estimated by logging the flow range of each compressor at 20 kPa pressure intervals. The minimum and maximum guide vane angle is specified in each compressor component. The minimum and maximum discharge flow of the compressors are then registered between these guide vane angles at different pressures.

The power efficiency is determined by logging the compressor's power consumption to produce flow at these ranges for a certain pressure. These characteristics are continuously updated, however if errors occur the user is able to edit or delete logged values. The characteristics are used in the simulation to determine the most effective compressor combination.

The compressor controller component will translate and transmit all output commands. Each supply node is connected to a compressor controller. The compressor controller represents a

compressor house. The compressor controller will communicate output commands to each individual compressor at each compressor house. These output commands include the following:

- Discharge pressure set point;
- Stop/start command; and
- Unload/load command.

These commands are determined by the second simulation phase that simulates the best suitable compressor combination. This is achieved by evaluating the pressure requirements and adjusted demand flow that has been calculated by simulating the compressed air network and determining the most effective compressor combination that will meet these requirements. The air solver is also responsible for calculating the second phase simulation.

When the air solver simulates an optimal compressed air network state, multiple solutions are simulated afterwards. The solutions represent a specific combination of compressors. Each of these solutions differs in the selection of compressor to establish the most efficient combination to provide the required supply flow.

The simulation starts by adding or removing different compressors from the actual running compressors. The method of simulating these solutions are illustrated in Figure 19. A one represents a running compressor and a zero represents a compressor that is shutdown.

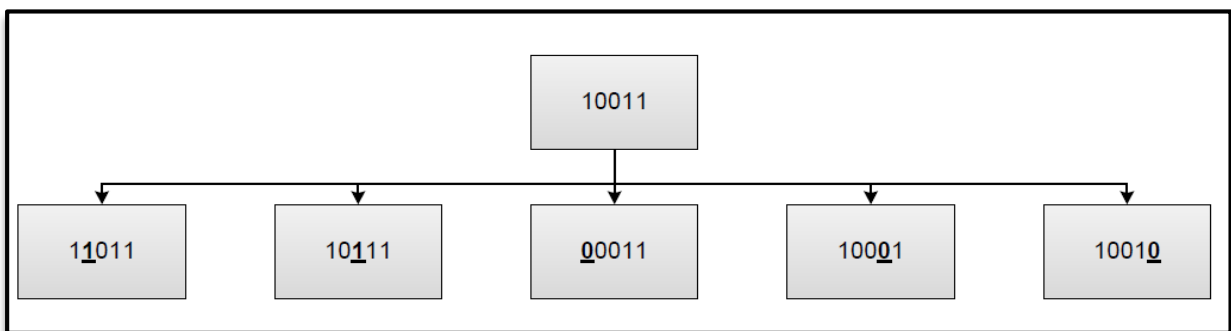


Figure 19: Simulated compressor combination

Figure 19 represents a compressed air network with five compressors. The simulation starts by adding or removing compressors from the actual running compressor combination to obtain the new compressor combinations. Optimally only one change will be made to the actual running compressor.

However, if the required supply flow is not matched, the simulation will further calculate another set of solutions for each solution initially obtained. Each solution will then have two changes to the actual running compressors, which is undesirable.

Each solution or in other terms compressor combination, is evaluated by a filtering process. The simulated compressor combinations will be eliminated if the solution does not meet the following filtering criteria:

- All compressors assigned as baseload compressors must be running;
- The minimum supply flow must be less than the required supply flow;
- The maximum supply flow must be more than the required supply flow; and
- All the proposed compressors must be available and ready to start.

The minimum and maximum flow for each compressor is determined by the characteristics logged in the compressor component. If any of these criteria is not true, the solution is eliminated. After the simulation, the total delivery flow and pressure required from the compressors are known for the optimal compressed air network. In order to determine the delivery flow of each individual compressor the method illustrated in Figure 20 is used.

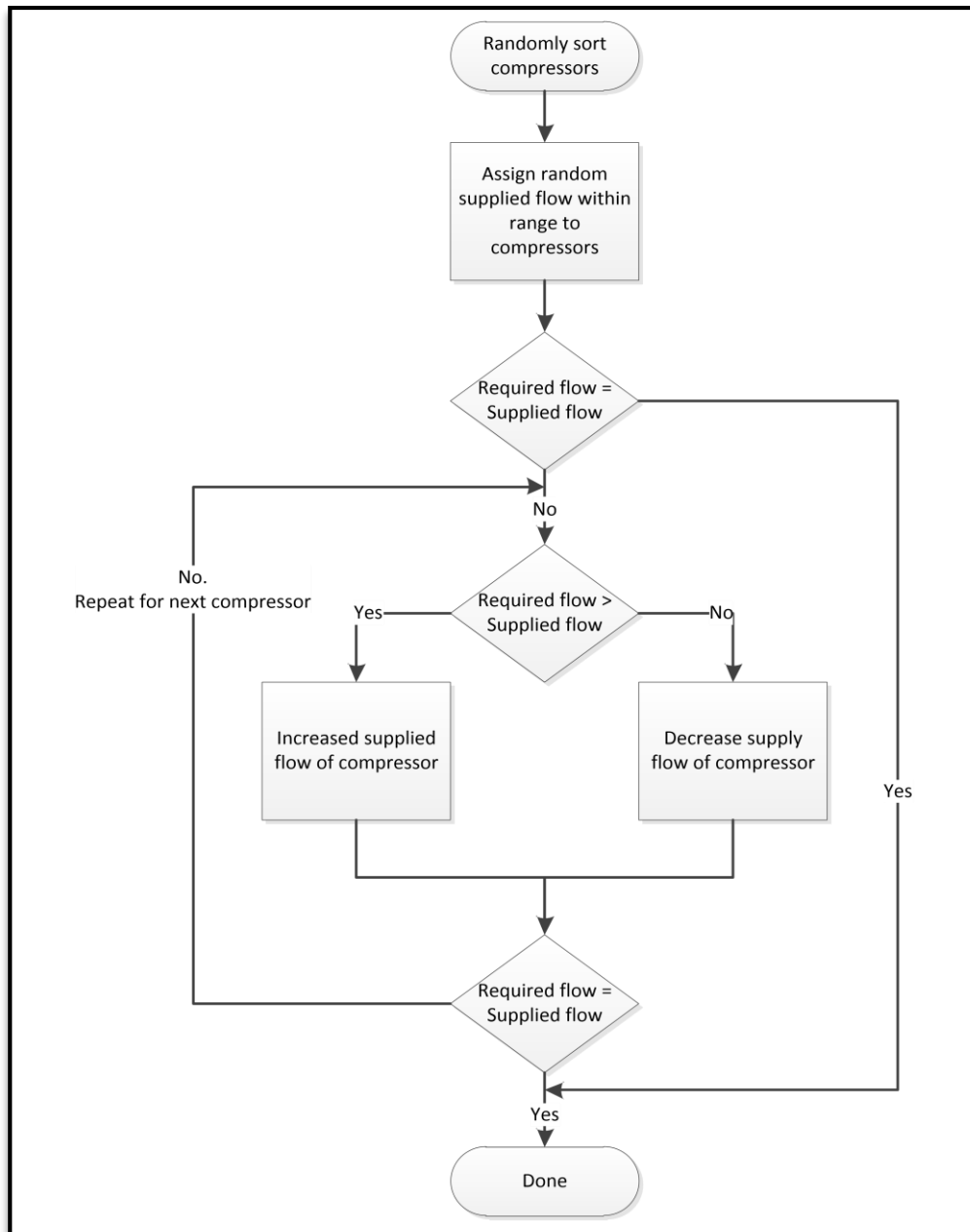


Figure 20: Flow diagram

To determine each individual compressor delivery flow a method was developed that randomly assigns different delivery flow expectancies to each compressor in the simulated combinations. The randomly assigned delivery flow for each compressor is within the flow range of that specific compressor. The total random delivery flow is then compared to the simulated required supply flow. If the total delivery flow is not enough to match the required supply flow, the delivery flow of the compressor with the highest priority will be increased.

If the total delivery flow is still not enough, the delivery flow of the compressor with the second highest priority will be increased. This process will be followed until the total delivery flow matches the required supply flow and vice versa, if the total delivery flow is more than the required supply flow. The delivery flow is then known for each individual compressor house.

If there is more than one compressor combination that passed all the criteria, the most energy efficient combination is selected. The delivery flow and pressure is known for each compressor, therefore the performance characteristics are used to determine the most energy efficient combination.

Before the command is transmitted in order to start or shut down an additional compressor, the power consumption of the simulated compressor combination is compared to actual power consumption. If the difference is not more or less than that of an adjustable power value the command will not be executed. This is done to give precedence to the DCS controller by reducing unnecessary changing of compressors.

The DCS controller is therefore able to automatically control the supply to efficiently match the demand. The feasibility of the DCS controller will be further investigated by implementing the controller on a compressed air network. However, for the DCS controller to be implemented at a mining complex, the following infrastructure is required:

- Pressure control valves installed at consumer;
- Compressed air leak management and demand reduction initiatives;
- Automated compressors with capacity control techniques;
- Field instrumentation, such as pressure transmitters and flow meters; and
- Centralised control room.

Without the mentioned infrastructure installed, the DCS controller cannot be implemented. It is therefore necessary to identify compressed air networks with the above-mentioned infrastructure already installed before the DCS controller can be implemented.

2.5 Conclusion

It was found that compressed air network on most South African mines is monitored and controlled by control room operators. The operators used pre-determined set points to adjust the pressure set point of compressors and to determine what compressor combination should operate. Nevertheless, due to the dynamic nature of compressed air networks, controlling the compressors according to predetermined set point proved inefficient.

A detailed investigation was conducted to identify improvements that can be made to compressed air networks. This was done, by firstly characterising the demand and supply sides of compressed air network. Further investigations identified DSM projects that have been implemented on the demand and supply sides. It was made clear to improve the efficiency of compressed air network, the supply and demand needs to be integrate and controlled as a single system. Otherwise, no electrical savings will be realised by the DSM projects.

The DCS controller was identified as a suitable control system that is able to integrate the demand and supply sides in order to control the supply of compressed air to accurately match the demand requirements. The DCS controller is able to automatically control the supply of compressed air by evaluating the continuously changing demand requirements. The potential energy savings plan could therefore be realised by the improvement made to the control of the compressed air network.

However, in order to implement the DCS controller, some infrastructure is required. A case study will therefore be identified with the required infrastructure already installed. The DCS controller will then be implemented to determine to what extent the compressed air network can be improved. The improvement made to the control of the compressed air network will result in energy cost-savings.

CHAPTER 3. IMPLEMENTING THE DCS CONTROLLER

3.1 Introduction

A deep level gold mining complex was identified as a suitable case study. Due to confidentiality agreements, this mining complex will be referred to as Mining Complex A. Mining Complex A has been identified due to various DSM projects already implemented on the compressed air network, with adequate process data available. In addition, all relevant equipment is controlled at a centralised control room. A SCADA system is used to relay command outputs to PLCs installed on various equipment.

In order to optimise the compressed air network, equipment needs to be controlled by a specialised control system; the DCS controller was identified as the most suitable control system. The DCS controller is able to automatically control and optimise components and equipment of a compressed air network. Optimised control will result in a reduction of total compressor electricity consumption and improve the energy efficiency of the compressed air network.

The chapter will focus on the methods used to integrate the DCS controller into the existing system and the approach followed to optimise the following system components:

- Surface control valves;
- Network pressure;
- Scheduling of compressors;
- Compressors guide vane angles; and
- Compressors blow-off.

With the implementation phase of DCS, certain complications have been encountered. Improvements have been made to the inner workings of the DCS control philosophy. An optimised control strategy has been developed to ensure the deliverables set in section 1.5 are accomplished. The improved control strategy uses the DCS controller as a backbone to establish communication in order to receive process data and relay output commands. The improved strategy developed will also be discussed in this chapter.

3.2 Implementing DCS

3.2.1 Process parameters

In order to implement the DCS controller certain process parameters are required. The DCS controller uses certain process parameters to simulate a proposed schedule for the compressors and to determine compressors pressure set points. Without these parameters, the DCS controller will not be able to simulate control commands to the various equipment. The parameters required to implement the controller are listed in Table 2.

Table 2: Process parameters required

Nr	Process variable description	Unit of measure
1	Compressor discharge mass flow	[kg/s]
2	Compressor discharge pressure	[kPa]
3	Compressor inlet guide vane position	[%]
4	Compressor blow-off valve position	[%]
5	Compressor running status	[0/1]
6	Compressor loaded status	[0/1]
7	Compressor electrical power consumption	[kW]
8	Consumer pressure requirement	[kPa]
9	Consumer pressure downstream of valve	[kPa]
10	Consumer compressed air consumption	[kg/s]

Additional information that will make the simulation more accurate includes the upstream pressure at the consumer's control valves and the open/close position of these control valves. This information is not a necessity but if it is available the information could be used to improve the accuracy of the simulation results.

In order to build the virtual compressed air network into the DCS controller each pipe section's length, diameter and bends are also required for the entire distribution network. The pipe geometry is used to simulate the pressure and air flow throughout the entire network. Therefore a detailed surface layout must be obtained.

Due to frequent changes made to the compressed air distribution network, complete layouts are usually not available. On surface, pipe sections with the same diameters are connected to form the distribution network, therefore the diameter of the different sections is typically easy to obtain.

The pipe lengths and bends can be estimated if the compressed air pipes are visible on Google Earth. Otherwise a GPS plot can be used to estimate the compressed air layout.

The compressed air distribution network of Mining Complex A was visible on Google Earth. The pipe lengths and bends could be measured using the tools in Google Earth. Therefore, an accurate virtual network could be built into the DCS controller that would accurately represent the actual compressed air network. Figure 21 illustrates the compressed air network that is outlined below on Google Earth.

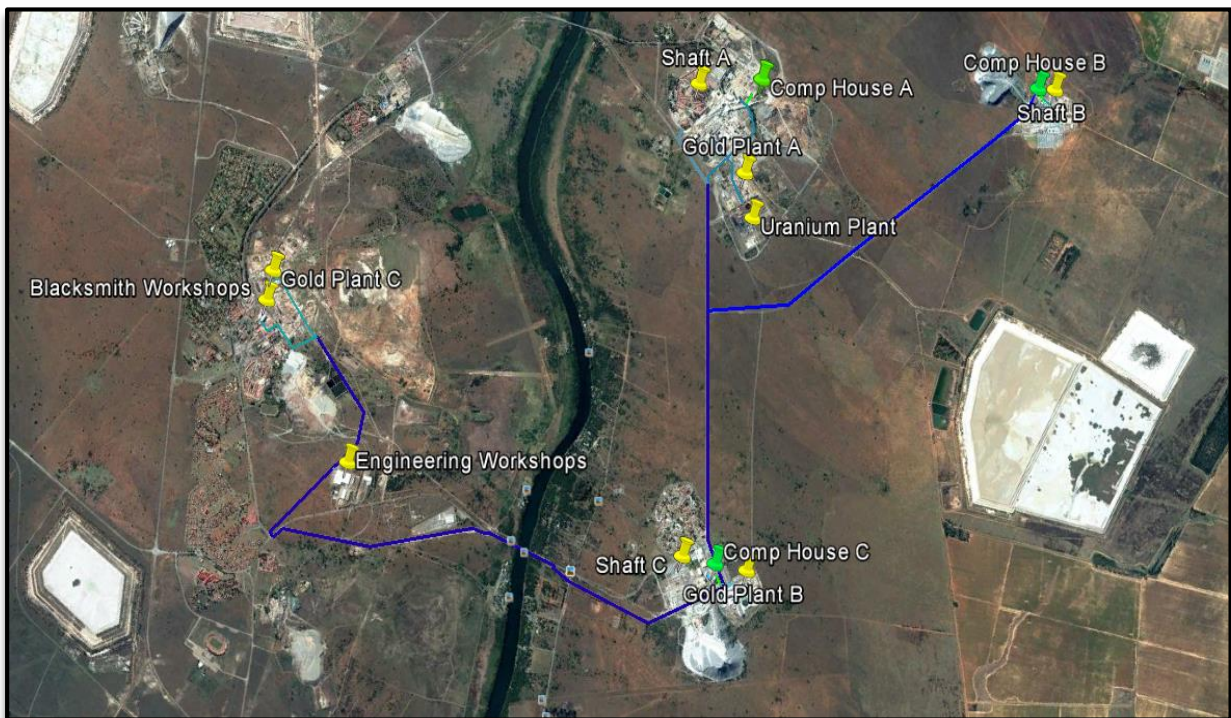


Figure 21: Google Earth surface layout of Mining Complex A

The dark blue line, as illustrated in Figure 21, outlines the compressed air distribution network. The pipe is 750 mm in diameter and is approximately 20 km in total length. The light blue line illustrates the pipe network after each consumer's control valve. The process parameters listed in Table 2 are measured by the field instrumentation and are relayed by the PLCs to the SCADA. The DCS controller receives these values through the OPC from the SCADA. This communication link mentioned will be discussed in the next section.

3.2.2 Functional communication specification

This section describes the functional specifications of the PLCs, the SCADA system and the DCS controller. The communication links between the different systems are illustrated in Figure 22.

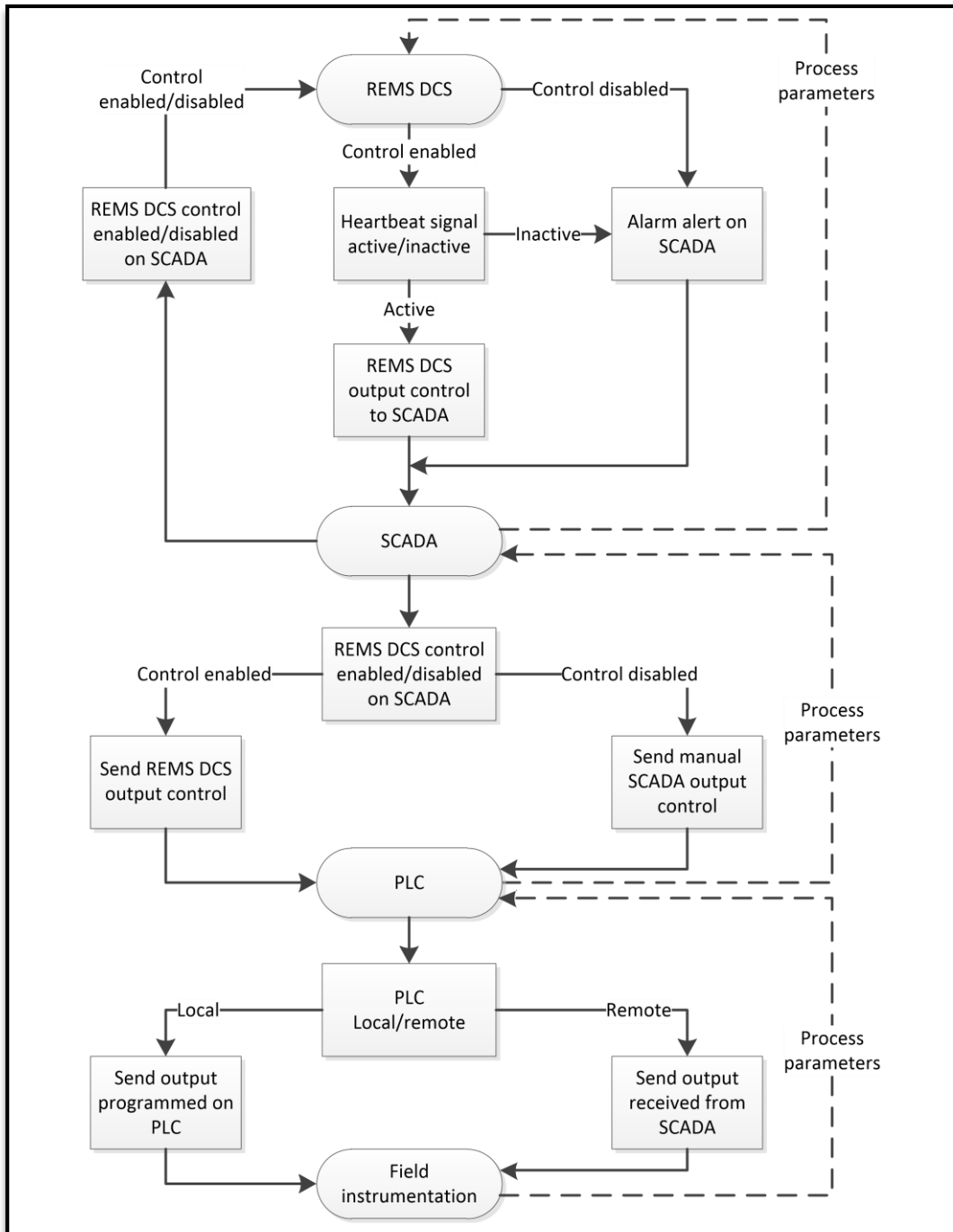


Figure 22: The DCS controller, SCADA and PLC communication link

Figure 22 illustrates the communication links between the DCS controller, the SCADA system and the PLCs. The PLCs communicate directly with the field equipment. Some field equipment related to Mining Complex A includes the inlet guide vanes, blow-off valves, control valves located at each major compressed air consumer and field instruments, such as pressure and flow sensors. The PLCs have the ability to control the field equipment to a certain control command and receive readings from field instruments.

The PLCs can be in local mode or in remote mode. In local mode, the PLCs control the field equipment to certain commands which are pre-programmed on each PLC. In remote mode, the PLC controls the field equipment according to the output commands received from the SCADA. Readings from field instruments are also communicated to the SCADA. If there is a communication failure between the SCADA and a PLC, the pre-programmed commands on the PLC will be executed.

As described in section 1.3.1, the SCADA system is primarily used for remote monitoring and control purposes. The SCADA communicates with the PLCs in order to obtain readings and send control outputs to the PLCs. The SCADA also communicates with the PLCs in order to obtain these process parameters readings. The DCS controller is compatible to receive the process parameters continuously from SCADA through the OPC. These process parameters will be evaluated to determine the proposed set points and control outputs.

It is required that the DCS controller be enabled and disabled from the SCADA system. If the DCS controller is enabled on the SCADA, the DCS controller set points and control outputs will be provided to the PLCs. If the DCS controller control is disabled, set points and control outputs will be ignored and manual inputs from the control room operator will be sent to the PLCs. This will enable the operator to manually control the equipment at any given time, by simply disabling the DCS control.

When the DCS controller is enabled, a continuously changing parameter is evaluated that is called a heartbeat signal. The main purpose of the heartbeat signal is to determine if the connection between the DCS controller and the SCADA is stable. If for some reason the connection is lost, the DCS controller set points and control outputs will not be received by the SCADA. In such a case, an alarm will appear on the SCADA alerting the operator that the DCS controller is unable

to communicate control outputs to the SCADA. Therefore, until the communication is restored, manual inputs from the operator is required.

The DCS controller set points and control outputs will first be thoroughly tested before control is enabled. These communication specifications should be set in place from the start of the development phase.

3.2.3 Existing infrastructure

At Mining Complex A, equipment is controlled from a centralised control room situated at one of three shafts. This shaft will be referred to as Shaft A. The other two shafts, Shaft B and Shaft C, are situated approximately 7 km and 9 km from Shaft A, respectively. Other major consumers on the compressed air ring include four processing plants and two workshops. At this mining complex, the gold plants and workshops do not have standalone compressors. Therefore, the pressure requirements of these small consumers will be taken into account when the DCS controller simulates a required pressure set point.

Control valves are installed at each major consumer that regulates the downstream pressure according to the requirement of each specific consumer. Pressure transmitters and flow meters are installed at the control valves. The upstream pressure, downstream pressure and flow consumption are available for each consumer. The control valve and instrumentations installed at each consumer will be referred to as air stations.

The compressed air consumption at each shaft is further managed at all major underground mining levels. Air stations are installed on the levels that regulate the downstream pressure according to a predetermined pressure set point schedule. The pressure set points of each mining level are superimposed in order to determine the surface control valve pressure set point of the specific gold mine.

In order to get an estimation of the ring pressure, the mine personnel used the upstream pressure at Shaft B as an indication. The required ring pressure is then determined by evaluating the pressure requirements of each major consumer. A daily pressure set point schedule was then compiled. Each compressor's discharge pressure set point is then set according to the determined set point schedule. The compressors will thus share the compressed air supply in order to maintain

the ring pressure according to the determined required pressure. Multistage compressors are used at Mining Complex A due to the efficiency and reliability of this type of compressors.

The compressed air is supplied to the various consumers by seven compressors located at the three shafts. The compressors' installed flow and power capacity vary in size. The installed capacities, flow ranges and locations of each individual compressor are presented in Table 3:

Table 3: Mining Complex A - Installed compressors

Compressor house	Compressor type	Name	Capacity [MW]	Flow Range [kg/s]
A	Sulzer	Sulzer A1	5.9	13-20
	Sulzer	Sulzer A2	5.9	13-20
	Sulzer	Sulzer A3	5.9	13-20
B	VK100	VK100 B1	8.6	20 - 26
	Sulzer	Sulzer B2	4.8	10 - 13
C	Sulzer	Sulzer C1	15	35
	Sulzer	Sulzer C2	15	35

The total installed electrical capacity of the compressed air network is 61.1 MW and can supply a total flow of 169 kg/s. The compressors are controlled from the centralised control room via the SCADA – PLCs communication links. The operator can relay a single command to indicate if a compressor should be running, unloaded or stopped.

Moore controllers are installed on the compressors located at compressor houses A and B. As a result, the guide vanes of these compressors are automated. The Moore controller continuously adjusts the guide vane angle in order to deliver compressed air at a discharge pressure according to the pressure set point. These compressors are also automatically protected against surging. When a compressor is operating near surge conditions, the blow-off valve will automatically open for each compressor. The compressors located at compressors house C do not have capacity control capabilities. Surge protection on these machines involves tripping the compressor when the discharge pressure reaches a certain pressure boundary.

The VK100 B1 and Sulzer B2 have individual flow meters installed; therefore the mass flow of each compressor is available. However, because there is generally limited space available to install flow meters at compressors, one flow meter is installed at compressor house A. The flow meter measures the total mass flow supplied by the Sulzer A1-A3. The same strategy is encountered at

compressor house C. This setup has been a major concern with regard to the simulations of the DCS controller.

The DCS controller requires each compressor's delivery flow in order to simulate the virtual network. The DCS controller also uses the delivery flow to obtain each compressor's performance characteristics used to simulate the most effective compressor combination.

The issue was addressed by assuming that the delivery flow capability is the same for each compressor located at the specific compressor house. This was done by using the internal programmable tags that are available on the DCS controller platform. The logic was to use the total flow measured at each compressor house and divide the mass flow evenly between the compressors running at that particular time.

This resulted in an estimated mass flow obtained for each compressor that required no additional infrastructure or costs. The compressors installed at compressor house A and C have the same capacity; the assumption made is therefore feasible. The location of the control room, compressor houses, major compressed air consumers and air stations is displayed in Figure 23.

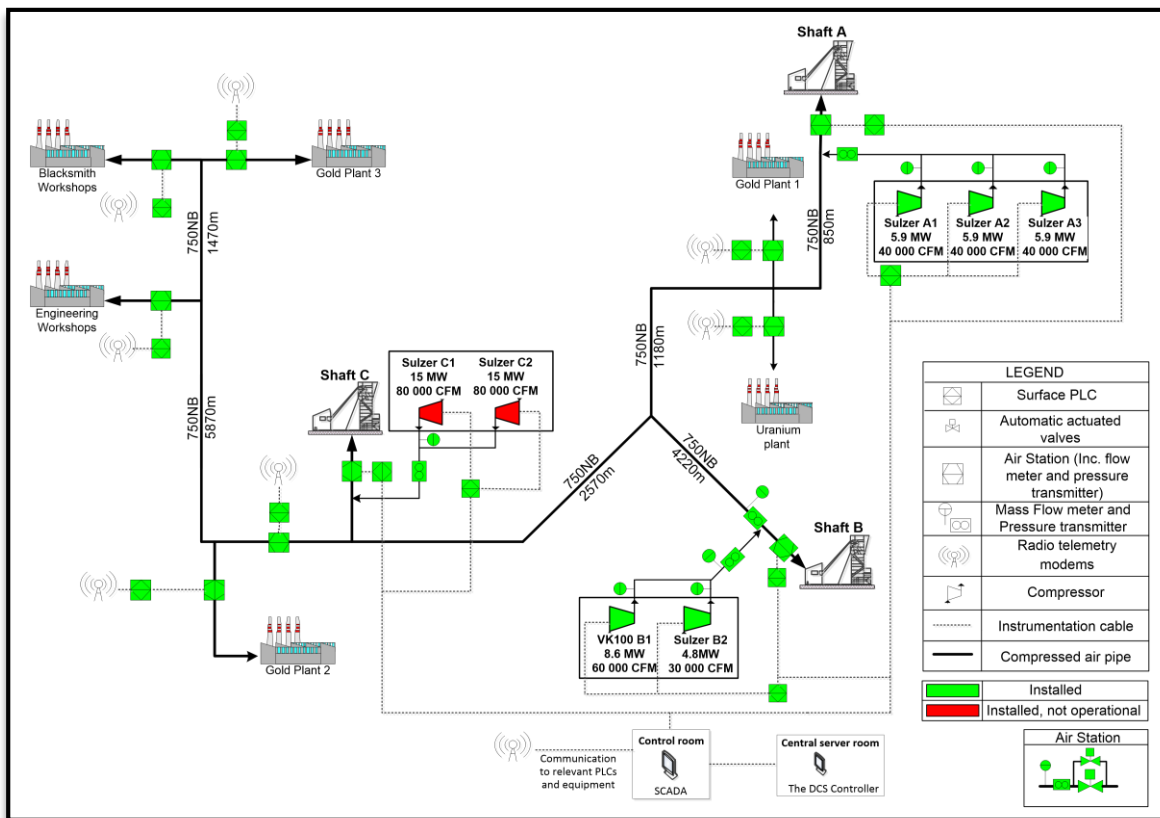


Figure 23: Mining Complex A surface layout

The locations of the different pressure transmitters and flow meters are illustrated in Figure 23. The solid black line represents the compressed air pipe and the dotted black line illustrates the fibre optic cable that is used for communication between the SCADA and the various equipment's PLCs. Radio telemetry modems are also used for communication and automation purposes. The radio telemetry modems are used to transmit instrumentation data and certain commands for different equipment and instrumentation that are at isolated points from the control room.

The average compressed air supply and demand has been calculated for weekdays over a period of three months and is illustrated in Figure 24. Also illustrated in Figure 24 are the typical compressor combinations operated during the three-month period. The compressors operated are scaled according to the supply capability of each specific compressor.

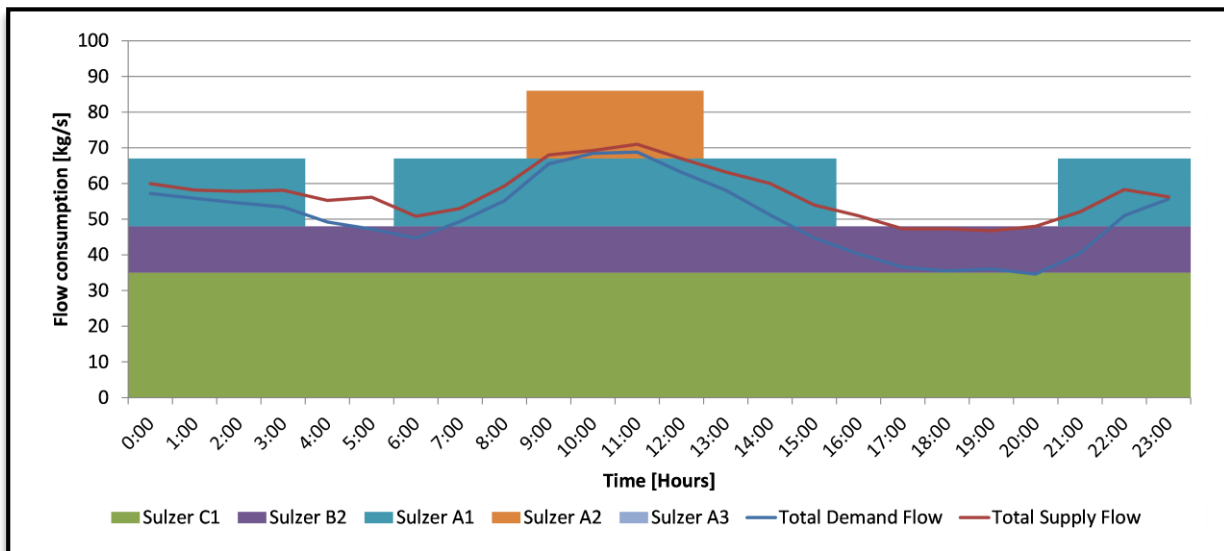


Figure 24: Average compressor running status

The Sulzer C1 and Sulzer B1 are operated continuously as baseload compressors, while the compressors at Mine A are used as the trimming compressors at high demand periods. The VK100 at Mine B was at this stage not in operation due to a major breakdown. The VK100 was however re-commissioned with the implementation of the DCS controller. It is evident from Figure 24 that in low-demand periods the supply flow over-matched the demand flow considerably.

During off-peak periods, the difference between the demand and supply flow is as much as 11 kg/s. This has resulted in an inefficient compressed air network with scope for improvement. The lowered demand flow is due to the control valves that reduce compressed air consumption

during the blasting shift of each gold mine. Control valves are also installed on the processing plants, but as stated earlier the low flow demand and pressure requirements are constant throughout the day.

Further investigation into the pressure requirements of the compressed air ring realises more inefficient control behaviour. During off peak times the gold mines require less compressed air at a lowered pressure. With the compressor over supplying, the ring pressure has been increased significantly during these times. The average ring pressure taken over the same three-month period and the pressure set points of the major consumers are illustrated in Figure 25.

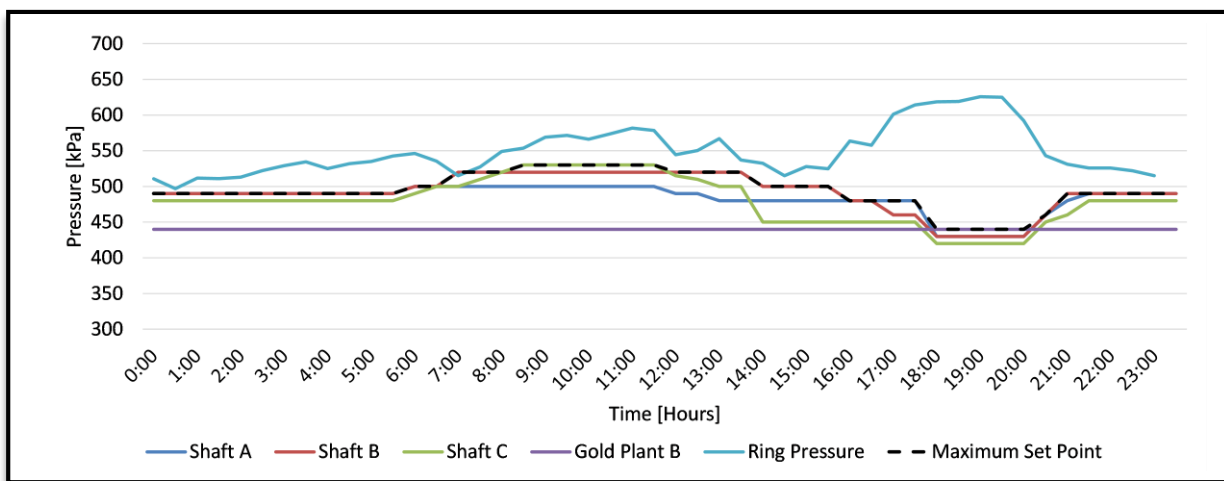


Figure 25: Pressure requirements

Figure 25 illustrates the maximum required pressure that is obtained by superimposing the pressure set points for all major consumers. Only Gold Plant B has been considered regarding the processing plants and workshops. The pressure and flow requirement for Gold Plant B is far above that of the other processing plants and workshops.

If the pressure is maintained above 440 kPa, the pressure requirements of the other processing plants and workshops will be met. It is clear from Figure 25 that the network pressure is far above the maximum required pressure throughout a workday. With the major difference, occurring during the off-peak periods when the pressure difference between the maximum required and the ring pressure reaches approximately 150 kPa.

The compressed air network was controlled ineffectively. This is evident from Figure 24 and Figure 25. The control room operators did not control the supply of compressed air to accurately

match the demand. If the control of compressed air supply is improved, a positive effect on the entire network will be achieved. Less air will be produced that will lead to a decreased ring pressure. With a decreased ring pressure, less air will be lost through leaks in the air distribution network that will finally result in a more efficient compressed air network.

By improving the control of the entire compressed air network, significant energy savings can be achieved. The DCS controller is able to improve the compressed air network by dynamically calculating an optimised required pressure set point and determine an effective compressor combination. The control strategy was proposed to the relevant mine personnel and permission was granted to implement the DCS controller. However, the mine personnel had certain operational constraints that had to be adhered to. The constraints are listed below:

- The 15 MW compressors at Mine C will only be used for emergency purposes because the VK100 was re-commissioned. No control was allowed on the compressors at Mine C;
- Once the 8.6 MW VK100 B1 was re-commissioned, the compressor must be operated as a baseload compressor;
- The 4.8 MW Sulzer B1 must also be operated as a baseload compressor. The compressor was used as a heat-exchange system to generate heat in order to warm water for a nearby hostel;
- The 5.9 MW Sulzer A1-A3 must be used as the trimming compressors. Once a Sulzer A1-A3 is started, the compressor cannot be switched off in less than one hour;
- Regarding the Sulzer A1-A3, a maximum of 10 status changes (off-on or on-off) in total will be permitted in a day;
- Once a Sulzer A1-A3 must be started, the Sulzer A1-A3 that was off for the longest period should be started;
- Once a Sulzer A1-A3 must be stopped, the Sulzer A1-A3 that was on for the longest period should be stopped;
- No offloading of compressors is allowed; and
- The pressure and flow requirements during the peak drilling periods must be met at all cost.

With the relevant mine personnel permission and constraints defined the DCS controller has been implemented. The simulation results obtained with the implementation phase of the DCS controller will be discussed in the following section.

3.2.4 Simulation results

Mining Complex A uses Wonderware™ ArchestrA SCADA systems to relay commands to the PLCs installed on equipment and receives instrumentation data from the entire compressed air network. The DCS controller’s software has been installed on a virtual network and communication to the SCADA system is established through an OPC. OPC tags are created from the SCADA database in order to obtain all relevant process parameters in real time.

The first stage of implementing the DCS controller is to compile and characterise the compressed air network into a virtual network. Figure 26 illustrates the virtual network that was compiled in the DCS controller’s platform.

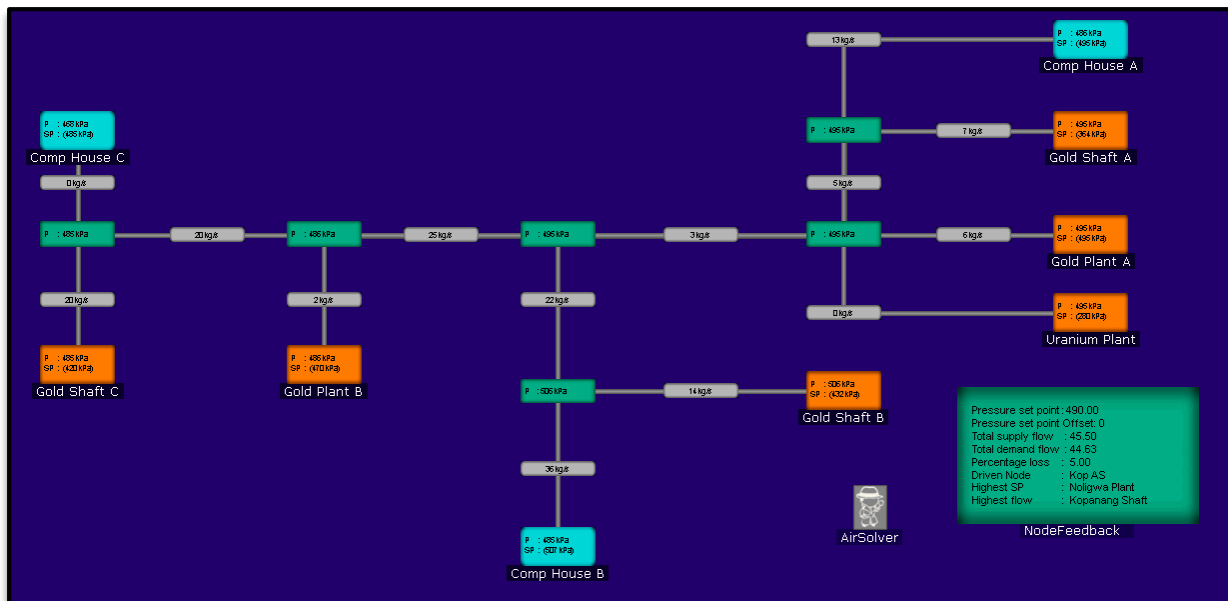


Figure 26: Virtual network of Mining Complex A

This virtual network represents the actual compressed air network and is used to simulate the airflow through the entire network. Once the airflow is simulated, the pressure requirements of the network will be calculated to determine the compressor’s discharge pressure set points. The demand flow and pressure requirements will be evaluated to simulate the most effective compressor combination.

Pipe lengths and bends are estimated by using Google Earth's measuring tools. Mine personnel have confirmed that the pipe diameter of the entire distribution network is 750 mm. The values in kg/s that is visible in the pipe components in Figure 26 are the simulated airflow through the entire network.

The orange nodes represent each major consumer. The pressure and pressure set point visible in the consumer nodes is the simulated required pressure upstream of the control valve. The blue nodes represent each compressor house. The pressure and pressure set point visible in the compressor house nodes is the actual discharge pressure and simulated pressure set point for each compressor house. The green nodes represent the different junctions in the compressed air network and the pressure values visible within the nodes are simulated values.

The DCS controller has been commissioned to obtain all the required average demand flow and pressure set point profiles for each major consumer. The DCS controller calculates the average values for a period of one month. The average values function as the future predicted demand requirements for each consumer and are used to simulate an effective compressor combination.

The compressor characteristics are obtained in this period, which is also essential to simulate the required compressor combination. With all the requirements and specifications of the actual compressed air network integrated in the DCS controller's virtual network, discharge pressure set points and compressors combinations could be simulated.

The relevant mine personnel do not want to give the DCS controller permission to set the discharge pressure set point of compressors or to automatically control the compressors. The mine personnel want to discuss the simulation results before the DCS controller could relay direct commands to the PLCs. Once the simulation results are obtained, a decision can be made with regard to the control permissions of the DCS controller.

The simulation test day involved the operator controlling the compressed air network as he would on a typical day. The DCS controller simulates pressure set point and compressors combinations by evaluating the requirements of the demand and considering the future demand flow and pressure profiles.

The first test phase assesses the pressure set point the DCS controller simulated for each compressor house. Figure 27 illustrates the set point the DCS controller calculated and the actual compressor set points for the test day. Also illustrated on Figure 27 is the maximum set point of all major consumers and the measured ring pressure.

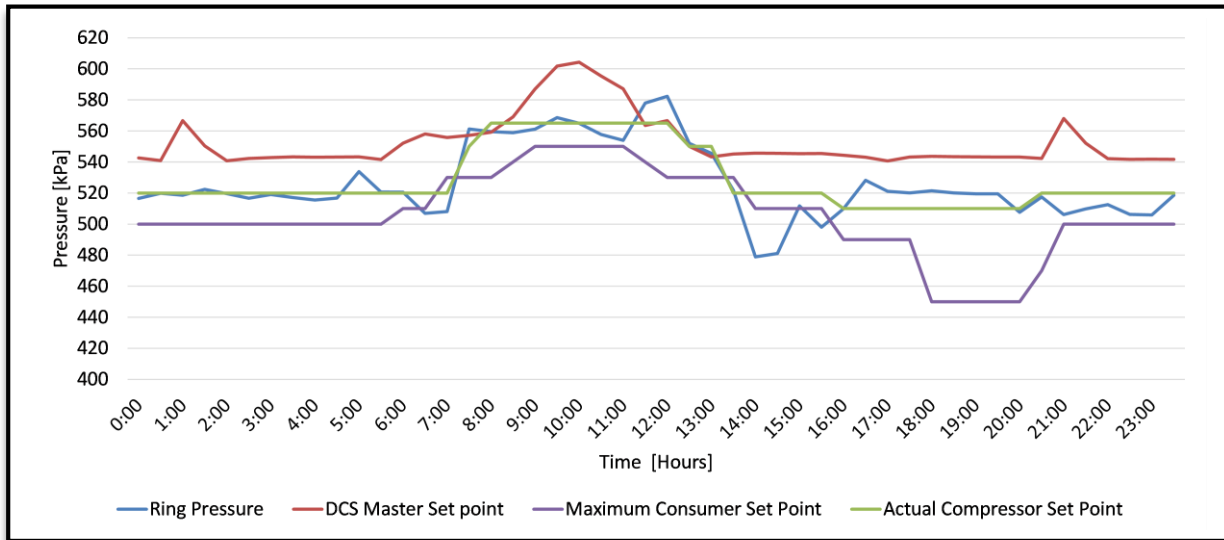


Figure 27: Test phase pressure conditions

When focusing on the ring pressure and actual compressor set point, it is evident that the compressors manage to control the pressure adequately throughout most of the day. However, there are clearly two intervals between 06:00 - 07:00 AM and 14:00 to 15:00 PM, where the ring pressure has decreased with regard to the actual compressor set points. This is because of inadequate compressor combinations being operated.

When the DCS controller’s set point is compared with the actual set point, it is obvious that the DCS set point is higher than the actual set point. This is because pressure drops are encountered in the compressed air network when the point of demand is further away from the point of supply. Therefore, the DCS controller has compensated for the pressure drop.

Figure 28 illustrates the actual running compressors and the supply and demand flow during the test day. The compressors operated are scaled according to the maximum supply capability of each specific compressor.

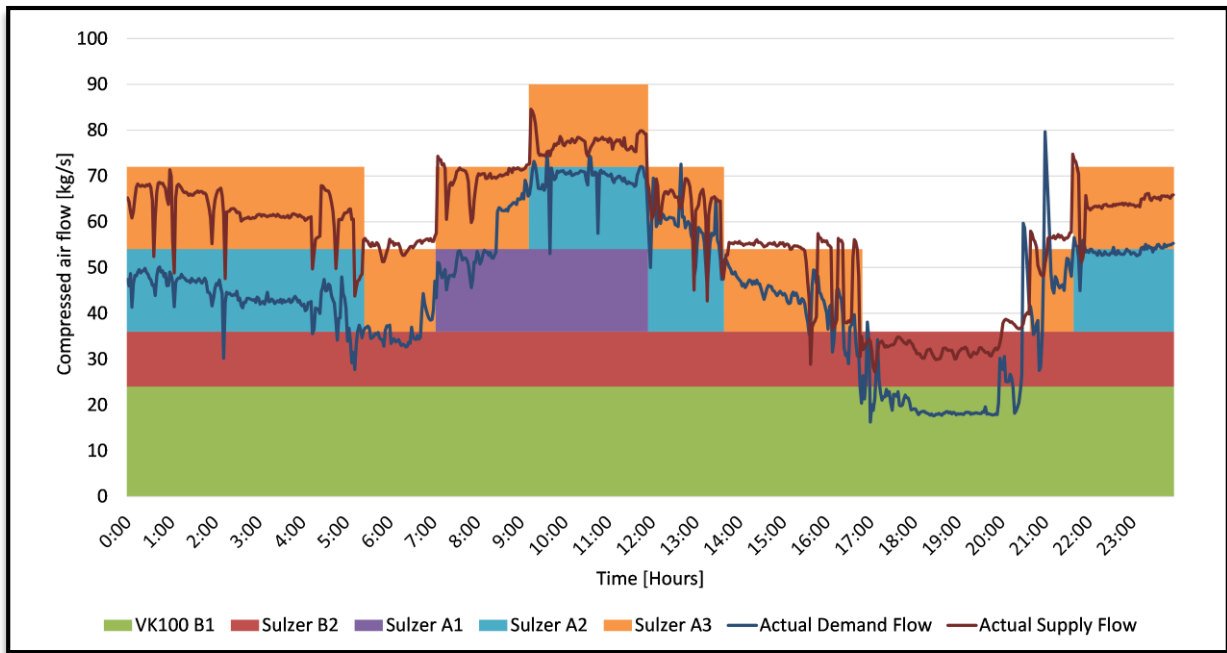


Figure 28: Actual compressors schedule and flow conditions during test day

It is important when focusing on Figure 28 that during certain periods some of the compressors have delivered their minimum flow capabilities. With that said, it is evident that the compressors that are in operation have still over-supplied the compressed air network. The supply is at times more than 12 kg/s more than the demand as a result of inefficient compressor combinations.

The operators' main goal is to ensure that production is not negatively influenced by inadequate supply flow. With the large installed capacity of the trimming compressors, it makes it more difficult for the operator to control the compressors in an energy efficient manner. This issue together with the operational constraints will make it more challenging for the DCS controller to control the compressed air network efficiently.

Because the client did not give the DCS controller permission to automatically control the compressor, a simulation was conducted to evaluate the proposed control. The simulation used the same process data for the test day, which were available in real time. Figure 29 illustrates the simulated running compressors, simulated supply flow and the actual demand flow during the test day. The compressors operated are scaled according to the maximum supply capability of each specific compressor.

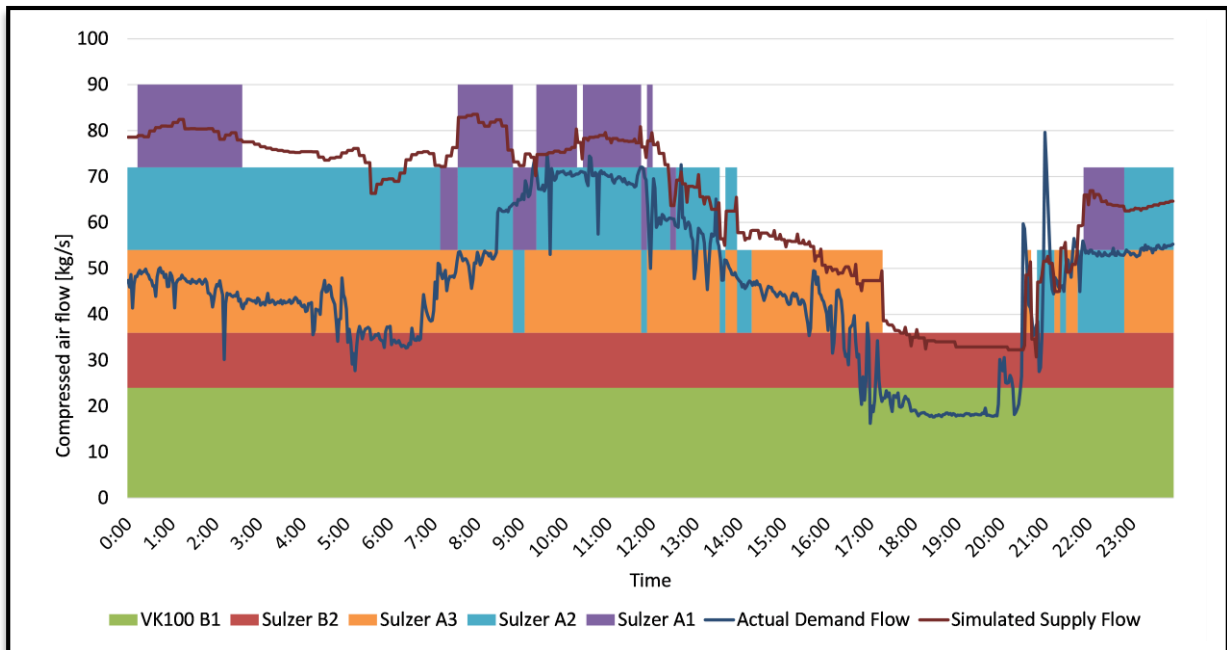


Figure 29: Simulated compressors schedule and flow conditions during test day

From Figure 29, it can be seen that the DCS controller cycled compressors (frequently switching compressors on or off) significantly when compared to the actual running compressors, displayed in Figure 28. The reason for this is the simulation reacted to actual compressors stopping and starting. In some situations, the DCS controller stopped or switched compressors, but the actual compressor did not stop, the controller perceived that it was off which caused increased compressor cycling.

Another issue is that certain times in the test day the actual demand flow was higher than the actual supply flow. When Figure 28 is evaluated, this occurrence can be seen at approximately 13:00, 14:00, 20:30, and 21:30, respectively. This led to the compressor being stopped or switched in the simulation only to return to the previous combination the moment after the supply flow increased to more than the demand flow.

This is caused by the demand flow adjustments determined by Equation 8. When the demand flow is more than the supply flow, each consumer's demand flow is adjusted to a value lower than the actual measured demand flow. This will cause a total reduction in demand flow and therefore unnecessary stopping of compressors. Fluctuations in the demand flow occur due to various valves on surface or underground opening or closing at once.

For example, the pressure set points of various control valves would increase during certain periods of the day. In order to increase the downstream pressure at each control valve to reach the required set point, the valve will open. This will occur when various valves underground open at the same time at the start of the drilling shift.

The same scenario occurs when the pressure set points of various valves decrease, for example at the end of the drilling shift. What generally happens is when the set point of a control valve decreases and the valve closes, the downstream pressure is decreased to a point where it is less than the pressure set point. The valve will then open again to increase the downstream pressure.

These two occurrences can lead to a significant increase in demand flow for a short period. This can be observed in the demand flow fluctuations visible in Figure 29 from 12:00 until 14:00, which is the end of the drilling shift. When the fluctuation in demand flow returns to stable conditions, the adjustment to the demand flow is higher than the measured flow and therefore the current compressor combination is insufficient and a compressor is scheduled to start.

The demand flow adjustment determined by Equation 8 also caused the simulation to schedule additional compressors to run unnecessarily. From Figure 28, it can be seen that the compressor that was running during 00:00 until 08:30 constantly oversupplied the compressed air ring. When the difference between the actual supply and demand flow is estimated during this time, the average difference is 15 kg/s. This results in an adjustment to the total demand flow being high and causes the DCS controller to schedule unnecessary compressors during this time.

When focus is shifted back to the simulated compressor discharge pressure displayed in Figure 27, the simulated compressor discharge set point was higher than the actual set point for the entire day. This is a result of the supply matching the demand inefficiently high. As explained, the demand flow of each consumer is adjusted to include the flow loss in the distribution network. The adjustment is a function of the supply flow versus the demand flow. If the difference between these parameters is higher than required, the simulation will also calculate a higher pressure set point than required. This will result in the compressed air network being supplied with more flow at a higher pressure set point, which will in turn reduce the energy savings significantly.

It can be argued that if the DCS controller had permission to control the compressors' discharge pressure set point and automatically stop and start the compressors, the difference between the

supply and demand will be reduced. This can be a solution but because of the dynamic nature of compressed air networks, there will always be fluctuations in the demand flow that will furthermore cause fluctuations in the difference between the supply and demand. For this reason, the DCS controller will be unable to accurately simulate an effective compressor combination on Mining Complex A.

The results have been presented to the client, but because of the long list of operational constraints and limitations of the DCS controller, it was decided that a new strategy would be developed. A systematic method will be followed in order to optimise the compressed air network. If the compressed air network is controlled in an efficient manner the potential electrical cost-savings can be achieved. The methodical approach to develop a new control strategy will be discussed in the following section.

3.3 Developing an improved control strategy

3.3.1 Introduction

In order to optimise the compressed air network, the control of supply flow and network pressure must be improved. This is achieved by evaluating the demand and supply as one system. The new control strategy will therefore be developed by integrating the supply and demand sides on the compressed air network. Figure 30 present the systematic approach that will be used to develop the control strategy.

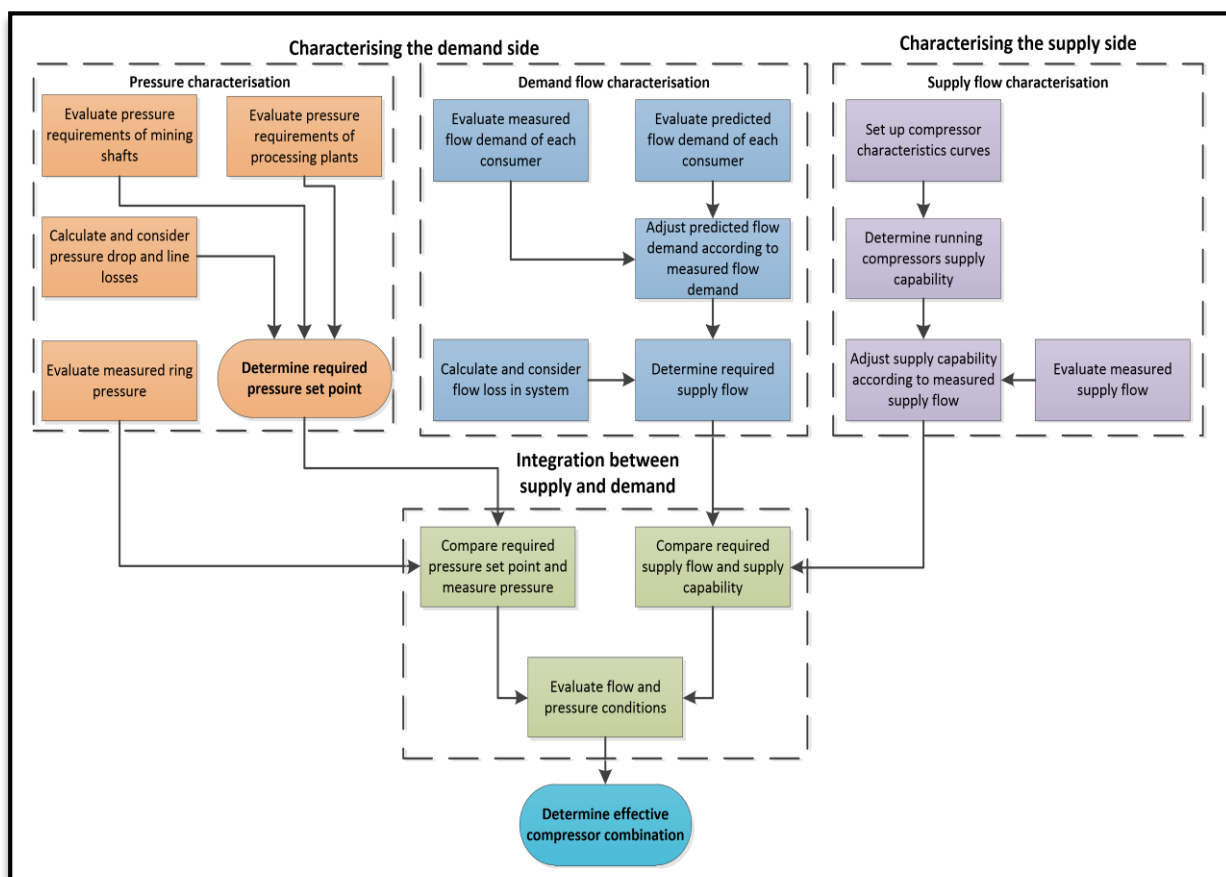


Figure 30: Systematic approach to develop control strategy

The DCS controller is implemented on Mining Complex A. Communication to different equipment and field instrumentation PLCs has already been established. The control strategy will use the DCS controller as a backbone for the established communication links. Therefore, process data can be received in real time and control commands could be relayed to equipment without additional infrastructure required.

The DCS controller has the functionality of internal programmable tags. These tags are similar to OPC tags but they are only visible within the controller's GUI. The internal tags can be programmed to represent a control logic. These internal programmable tags will be used to develop a script in order to execute the developed control strategy. This section discusses the control logic established through the internal programmable tags.

The improved control strategy will determine compressor pressure set points and schedule efficient compressor combination automatically, as shown in Figure 30. A detailed characterisation of the demand side will be established to adequately evaluate the requirements of the consumers. This will be done by considering the flow loss, pressure drop and frictional loss in the distribution network. The DCS controllers' predicted flow and pressure profiles will also be used to estimate future requirements. An accurate required supply flow and pressure set point can then be determined.

To ensure the flow demand and pressure requirements are matched the supply side will be characterised. Compressor characteristics curves will be set up to estimate the supply capability of the different compressor combinations. The required supply flow can then be compared to the supply capacity of each compressor to establish whether the current compressors combination will efficiently match the demand requirements.

The pressure conditions will be evaluated by comparing the ring pressure with the calculated pressure set point. The flow and pressure conditions of the supply and demand sides are evaluated next to determine the most effective compressor combination. The new control strategy evaluates the requirements of the demand to control the compressed air supply pressure and flow continuously.

The pressure supply set points to each major compressed air consumer will be relayed by the DCS controller. These pressure supply set points are sent to the PLCs through the SCADA system. The PLCs control the valves to maintain the actual supply pressure for each major consumer at the set point provided. This section will describe the methodology used to deliver the pressure supply set point of each major consumer.

3.3.2 Control valves

In auto mode, the DCS controller will supply downstream pressure set points to the SCADA and the PLC. The control valves located at each major compressed air consumer are controlled according to these set points. For the shafts, these pressure set points are determined by superimposing pressure requirements of each mining level of the specific gold mine. The processing plants pressure set points are constant. Each processing plant's set point is determined according to the pressure requirements of the pneumatic equipment in operation.

The valves maintain the specified downstream pressure set point by utilising P&ID control loops programmed in the PLCs. Figure 31 displays the components used by the DCS controller to control each consumer's surface control valve.

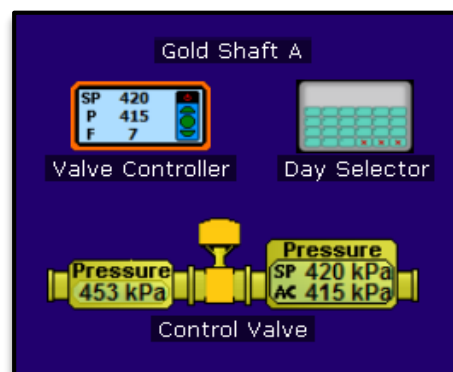


Figure 31: Control valve components

The control valve component is responsible for supplying the pressure set points to the PLCs of each surface valve. The actual upstream- and downstream pressure are displayed in the component. The pressure set point to which the valve will regulate the downstream pressure is also visible within the component. The control valve component requires the following process parameters via OPC tags:

- Downstream pressure [kPa];
- Upstream pressure [kPa];
- Air flow [kg/s];
- Pressure set point [kPa]; and
- Valve position [%].

The control valve component logs the process OPC tags and writes the pressure set point into the designated OPC control tag. The control valve component receives the pressure set points from the defined schedules in the Valve Controller. Daily pressure set point schedules for each type of production day are defined in the Valve Controller. The different types of production days include weekdays, on-Saturdays, off-Saturdays and Sundays. The actual downstream pressure, mass flow consumption and the pressure set point are displayed in the Valve Controller for each consumer.

The different pressure set point schedules for each particular day that will be relayed to the control valve can be specified within the Day Selector component. The pressure set point schedules can be selected in advance for a three-month period, therefore ample time is available to select the correct production day. These set point schedules can be updated from time to time as production activities change. The operator also has the option to override the set point for a specified time, if required.

This following section will describe the methodology used to determine the required upstream pressure of each major consumer. The highest required upstream pressure will be the compressors' discharge pressure set point. Each major consumer's required pressure, together with pressure drops and line losses, will be considered to calculate the discharge pressure set points of the compressors. This will be discussed in the following section.

3.3.3 System pressure requirements

As discussed in section 3.3.2, the DCS controller will supply the pressure set points for which the control valves maintain the supply pressure to each major consumer. In order to determine the optimal required ring pressure, the pressure requirement of all major consumers will be evaluated. The DCS controller will be utilised to relay the required pressure set points to the compressors in order to maintain the calculated optimal ring pressure.

Each consumer is evaluated in terms of the pressure needed at the point where the ring pressure is measured in order to provide sufficient pressure at the location of each consumer. Friction loss, pressure drops and the effect of auto compression will be taken into consideration when the pressure requirement is determined. The consumer, which requires the highest pressure at the

point where the ring pressure is measured, will become the compressors' pressure set point driver. As mentioned in section 3.2.3, the ring pressure is the measured upstream pressure of Shaft B.

The upstream pressure requirement of each shaft will be determined by evaluating the pressure requirements of the underground level that requires the highest surface pressure, taking the effect of auto compression into consideration. These levels will be referred to as the control levels. For the three shafts, the following levels are identified as the control levels:

- Gold Shaft A - 85 level
- Gold Shaft B - 51 level
- Gold Shaft C - 42 level

The supply pressure towards the underground levels at each shaft is controlled according to pre-determined pressure set points. The difference between the actual pressure supply and the pressure supply set point at the control levels mentioned above will be monitored. The difference in actual pressure supply and the pressure supply set point will be used to continuously calculate the desired upstream pressure for each shaft on surface. The pressure drop over the surface valve is taken into consideration. Figure 32 shows the parameters used to calculate the desired surface upstream supply pressure at each shaft.

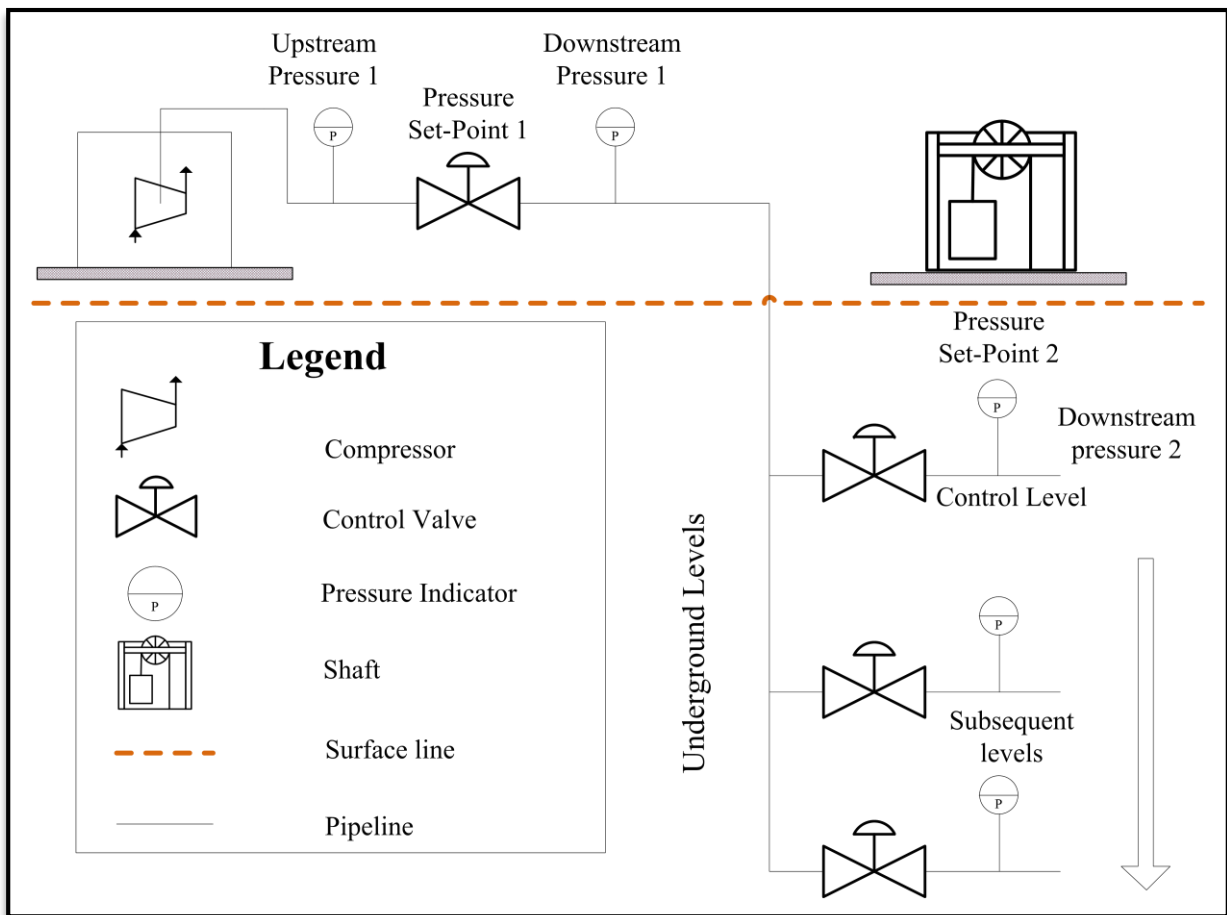


Figure 32 Parameters to calculate the desired surface pressure supply at each shaft

In Figure 32, downstream pressure 1 is the desired surface pressure downstream of the control valve at the shaft. The upstream pressure 1 is the pressure that will be taken into consideration when the pressure set point of each compressor is calculated. Pressure set point 1 is the pressure supply set point to which the surface control valve will control the pressure supplied to the shaft. With an optimised system, the upstream pressure 1 should be slightly higher, but never lower than pressure set point 1.

Downstream pressure 2 is the pressure to which the control valve on the selected control level will maintain the pressure. Pressure set point 2 is the pressure supply set point for the selected control level. The required upstream pressure on surface is calculated by utilising Equation 9. This pressure will be the required pressure for upstream pressure 1 in Figure 32.

Equation 9: Calculating the desired upstream supply pressure at each shaft

<i>Supply pressure = A + (Pressure set point 2 – B) + C</i>	
<i>Pressure setpoint 2 = Pressure set point of the control level</i>	<i>[kPa]</i>
<i>A = Downstream pressure 1</i>	<i>[kPa]</i>
<i>B = Downstream pressure 2</i>	<i>[kPa]</i>
<i>C = Pressure drop over the surface valve</i>	<i>[kPa]</i>

By utilising Equation 9, the required upstream pressure for each shaft is calculated. In order to determine the required upstream pressure for the processing plants and workshops, only Gold Plant B will be considered. As explained in 3.2.3, the pressure and flow requirement for Gold Plant B is far above that of the other processing plants and workshops. Therefore, if the pressure requirements of Gold Plant B is matched, the pressure requirements of the other processing plants and workshops will be met. The required upstream pressure of Gold Plant B will be calculated by using Equation 10.

Equation 10: Calculating the desired upstream supply pressure at Gold Plant B

<i>Supply pressure = Pressure setpoint 1 + A</i>	
<i>Pressure setpoint 1 = Pressure set point of the control level</i>	<i>[kPa]</i>
<i>A = Pressure drop over the surface valve</i>	<i>[kPa]</i>

The required upstream pressure of Gold Plant B will be calculated by taking the pressure set point of the control valve and adding the pressure loss over the valve. This will ensure that the pressure upstream of the control valve will be sufficient to match the set point.

By using Equation 9 and Equation 10, the required upstream pressure for the major consumers can be calculated. In order to evaluate the pressure requirement of each consumer in reference to the pressure needed at the point where the ring pressure is measured, the pressure drops in the distribution network will be considered. Figure 33 illustrates the pressure drop from Shaft B to the other major consumers.

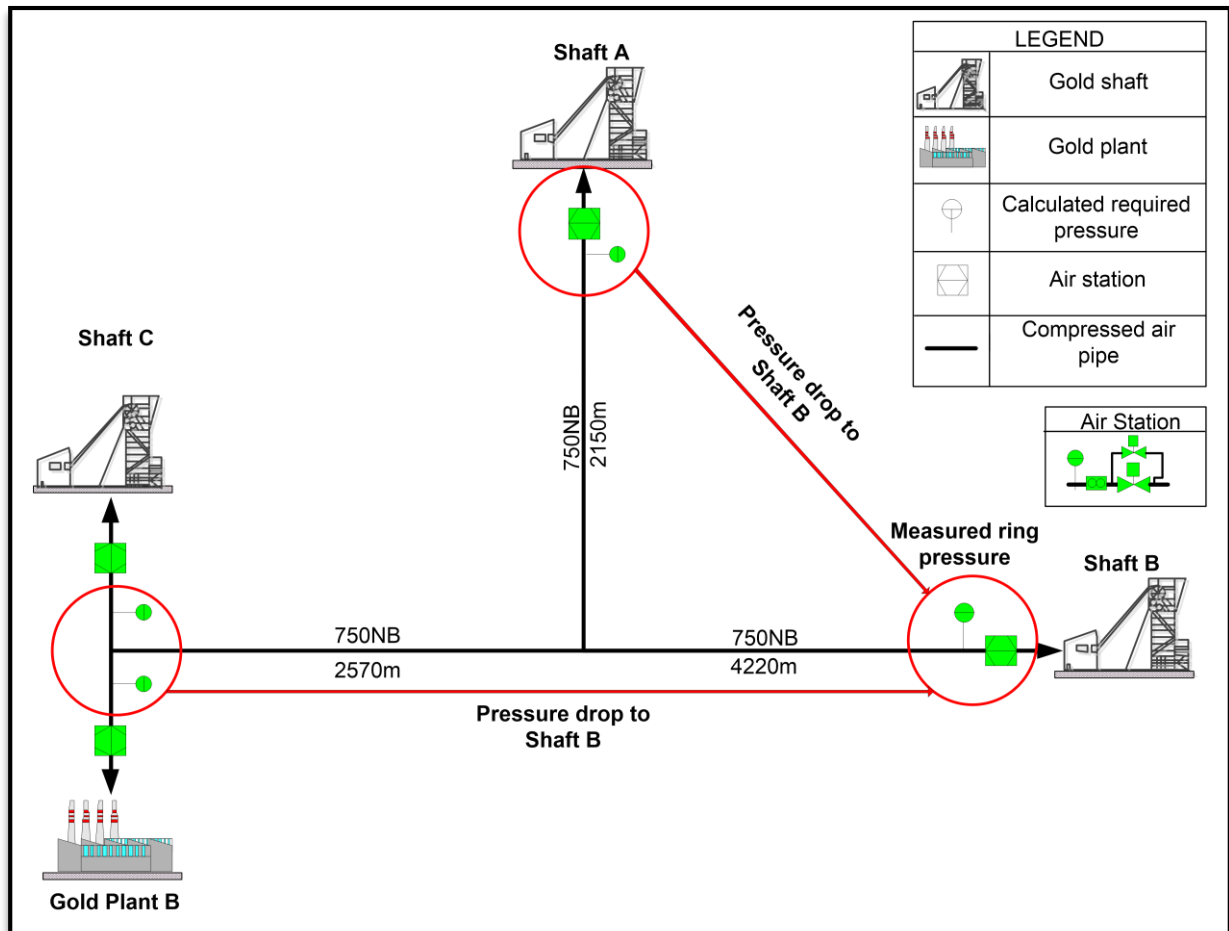


Figure 33: Calculating each consumer's pressure requirement including pressure drop

The calculated required upstream pressure for each major consumer is indicated by the red circles in Figure 33. The pressure drop from Shaft B to Shaft A is evaluated by calculating the difference between the measured upstream pressure at Shaft A and the ring pressure (upstream pressure at Shaft B). The pressure drop is added to the calculated required upstream pressure of Shaft A in order to evaluate pressure requirement of Shaft A from Shaft B. This calculated pressure will be referred to as the driven pressure set point of Shaft A.

The same method is used to calculate the required pressure of Shaft C and Gold Plant B at the point where the ring pressure is measured. The location of the control valves at Shaft C and Gold Plant B are in close proximity to one another, therefore the upstream pressures will be nearly the same.

The pressure drop from Shaft B to Shaft C and Gold Plant B will therefore be calculated by determining the difference of the upstream pressure at Shaft C and the ring pressure. The pressure

drop is then added to the greater calculated required upstream pressure of Shaft C and Gold Plant B. This calculated pressure will be referred to as the driven pressure set point of Shaft C.

The driven pressure set point of Shaft B is the calculated required upstream pressure determined by using Equation 9. There is not a pressure drop added because the ring pressure is taken as the upstream pressure of Shaft B.

With all the pressure requirements of all major consumers calculated with reference to the point Shaft B, a suitable compressor pressure set point can be determined. If the ring pressure is maintained according to the highest calculated driven set points, the requirements of each consumer will be matched.

The pressure set point of each compressor will consequently be set as the highest driven set point of the major consumers. This pressure set point will be referred to as the optimal required ring pressure of the compressed air network. The compressors will maintain the ring pressure according to the optimal required ring pressure in order to provide sufficient pressure at the location of each major consumer.

The next section will discuss the development of the strategy that will be used to schedule an effective compressors combination. The scheduled compressors combination should supply sufficient compressed air in order to maintain the optimal required ring pressure.

3.3.4 Scheduling of compressors

The compressors will be divided into two groups, namely the baseload compressors and the trimming compressors. The baseload compressors will operate throughout the day. The trimming compressors will be started and stopped as the compressed air demand increases and decreases during the day. Factors such as the availability of the compressors and the operating hours of each compressor can have an influence on which compressors are allocated as baseload compressors.

With normal operating conditions and considering the client's requests, the VK100 B1 and Sulzer B2 will be allocated as the baseload compressors. However, this compressor baseload combination may change as the system changes. The system will constantly be re-evaluated in order to determine the optimal baseload compressor combination.

The Sulzer A1-A3 will be used as trimming compressors. In order to evenly spread the operating hours between the trimming compressors, start and stop priorities will be allocated to the available trimming compressors. The start and stop priorities of each Sulzer A1-A3 will be changed according to every stop or start.

The trimming compressor that was off for the longest period will be the compressor that will be prioritised to start when necessary. Once that trimming compressor is started, the start priority is relocated to the next trimming compressor that was off for the longest period. This procedure will be followed to determine which trimming compressor will be started for every compressor start.

The same applies to the trimming compressor that will be stopped i.e. the trimming compressor that has been in operation for the longest period will be the compressor that is prioritised to be stopped. Once that trimming compressor is stopped, the stop priority is relocated to the next trimming compressor that has been in operation for the longest period. This procedure will be followed to determine which trimming compressor will be prioritised to stop for every compressor stop.

This will ensure that the operating hours of each Sulzer A1-A3 is evenly spread. If one of the baseload compressors is not available, the trimming compressor with the highest start priority will be allocated as a baseload compressor. Figure 34 illustrates the procedure that will be followed if a baseload compressor is not available to operate.

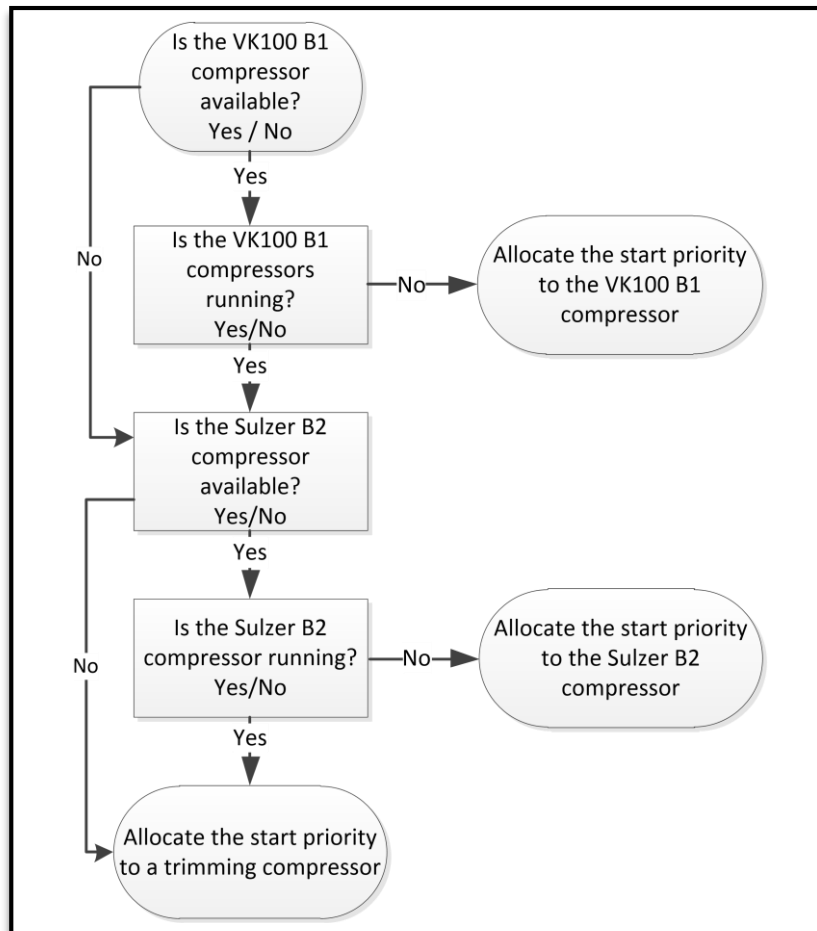


Figure 34: Compressors start priority allocation

As discussed in section 3.3.3, the optimal required ring pressure is calculated according to the pressure requirements of the compressed air consumers in reference to Shaft B. The DCS controller then supplies pressure set points to each compressor in order to maintain the ring pressure according to the optimal required ring pressure. The compressed air consumption is constantly monitored in order to determine when to start and stop trimming compressor to maintain the optimal ring pressure.

The compressed air consumption of the entire ring includes the consumers and flow loss through leaks. To evaluate the consumers' consumption the measured flow in real-time of each consumer is totalised. Equation 8 is used to estimate the flow loss in the system and adjust each consumer accordingly, but as discussed in section 3.2.4 this has resulted in inaccurate simulations.

In order to accurately estimate the compressed air lost through leaks an alternative approach will be followed. Figure 35 presents the logic that is used to calculate an estimated flow loss in the compressed air ring continuously.

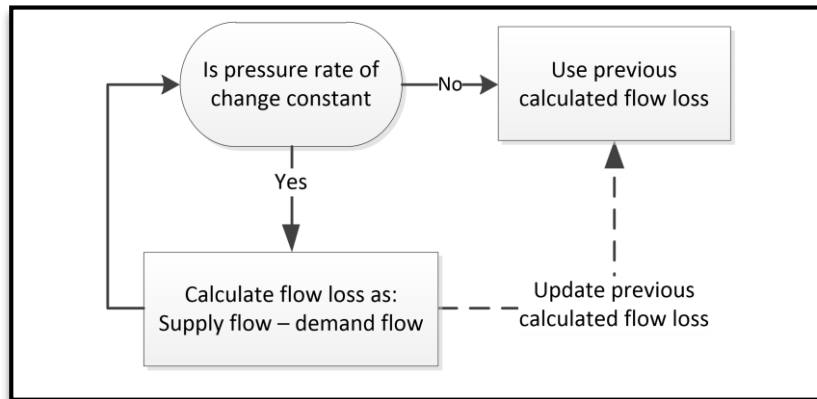


Figure 35: Estimation of flow loss in system

The pressure rate of change is the measured pressure change in one minute [kPa/min]. If the pressure increases or decreases by less than 1 kPa/min it is assumed that the ring pressure change is constant. The ring pressure is constant when the compressed air supply matches the total demand in the system.

Therefore, the flow loss in the system can be calculated as the difference between the supply and consumers' demand flow. The smoothed real time flow values are used to calculate the difference (Figure 16). This will ensure if fluctuations in demand flow occur, it will not affect the calculated flow loss. If the pressure change is not constant, the flow loss that was calculated at constant pressure change will be used for further calculations. This flow loss will be updated once the pressure change is constant again.

It can be argued that the demand flow will be adequately matched if the compressors maintain a supply flow that matches the consumers' flow and the calculated flow loss. However, future flow and pressure requirements of consumers will consequently not be considered and a one-dimensional controller will be developed.

The future requirements of the consumers will be considered when the required supply flow is calculated. The required supply flow is calculated by using Equation 11 that was derived from the equation of continuity.

Equation 11: Calculating the required supply flow

$$F_{supply} = \frac{\left(\frac{P_{req@30min}V}{RT} - \frac{P_{actual}V}{RT}\right)}{t} + F_{demand@30min} + F_{leaks}$$

F_{supply} = Required supply flow [kg/s]

$F_{demand@30min}$ = Predicted demand flow after 30 minutes [kg/s]

F_{leaks} = Flow loss over the time period [kg/s]

P_{actual} = The actual ring pressure [kPa]

$P_{req@30min}$ = Predicted required pressure after 30 minutes [kPa]

V = Volume of the ring [m^3]

R = Universal gas constant of air [$Jkg^{-1}K^{-1}$]

T = Temperature of the air in the ring [K]

t = Time period [s]

Equation 11 determines the required supply flow by considering the current and future flow demand and pressure requirements. The DCS controller continuously calculates average predicted flow and pressure profiles for Weekdays, Saturdays and Sundays. The pressure required at intervals of 30 minutes is obtained by using the average predicted pressure profiles. The predicted flow required at intervals of 30 minutes is also determined by the average predicted flow profiles.

The predicted flow profiles are used to determine the following demand flow values:

- Current predicted demand flow;
- Predicted flow at 30 minutes; and
- Predicted demand flow at 60 minutes.

To ensure an accurate required supply flow is calculated, the predicted demand flow at 30 minutes (Equation 11) is adjusted according to the measured flow demand in real time. The predicted flow at 30 minutes is adjusted according to the difference between the measured demand flow and current predicted demand flow. The predicted profiles change at half-hourly intervals, therefore

interpolation is used to get an accurate flow prediction between the half-hourly intervals. The current to 30 minutes and 30 minutes to 60 minutes predicted flow values are interpolated, separately. Figure 36 illustrate the method used to adjust the predicted flow out at 30 minutes according to the actual flow conditions.

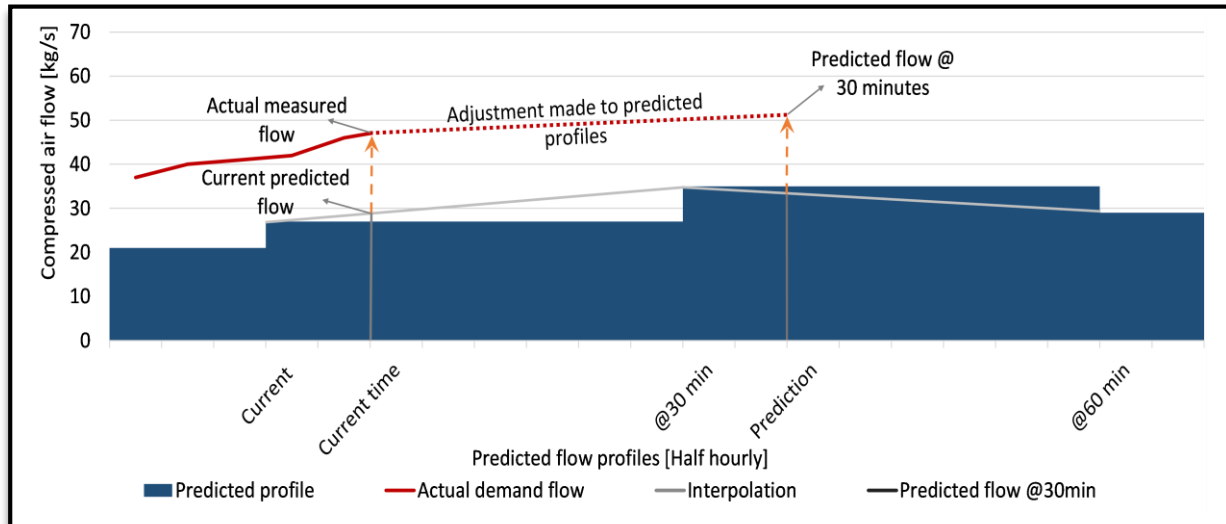


Figure 36: 30 minute predicted demand flow adjustment

These adjustments are made due to the dynamic nature of compressed air networks. If the predicted demand profiles are scaled according to the actual demand, an accurately predicted demand flow can be estimated. This will result in an accurate required supply flow calculated by Equation 11. The required supply flow is continuously calculated and considered before a trimming compressor is stopped or started.

At this point, the optimal required ring pressure and supply flow can be calculated. Future conditions and losses in the system are considered to calculate the required pressure and supply flow. Therefore, if the compressors maintain the optimal required pressure and supply flow the requirements of the consumers will be accurately matched.

In order to evaluate if the compressors can maintain these requirements, the flow capacity of each compressor will be characterised. This will be achieved by setting up compressor characteristic curves for each compressor. The characteristics curve will be used to estimate the delivery flow capabilities at certain guide vane angles. However, before the characteristic curves can be estimated, each compressor's minimum guide vane angle must first be determined.

Each compressor’s minimum guide vane angle is a function of the compressor’s discharge pressure. The compressor will operate near the surge line if the guide vane angle is reduced beyond the minimum guide vane angle. The compressor will therefore go into blow-off conditions to protect itself from surging. This will result in compressed air being wasted in the atmosphere and will consequently be avoided.

As mentioned in section 3.2.3, Moore controllers installed on the compressors will automatically open the blow-off valve. The Moore controllers also communicate a value that represents the current operating distance from the surge line. This distance is referred to as the blow-off point. The compressor will go into blow-off conditions if the blow-off point reaches a negative value. This occurrence will be further discussed in section 3.3.6.

In order to determine each compressor’s minimum guide vane angle the delivery pressure at a certain guide vane angle where blow-off occurred was evaluated. Figure 37 present a scattered plot of the delivery pressure and guide vane angle at blow-off conditions for the Sulzer A1. In other words, each point on the Figure 37 represents the compressor operating on the blow-off limit line.

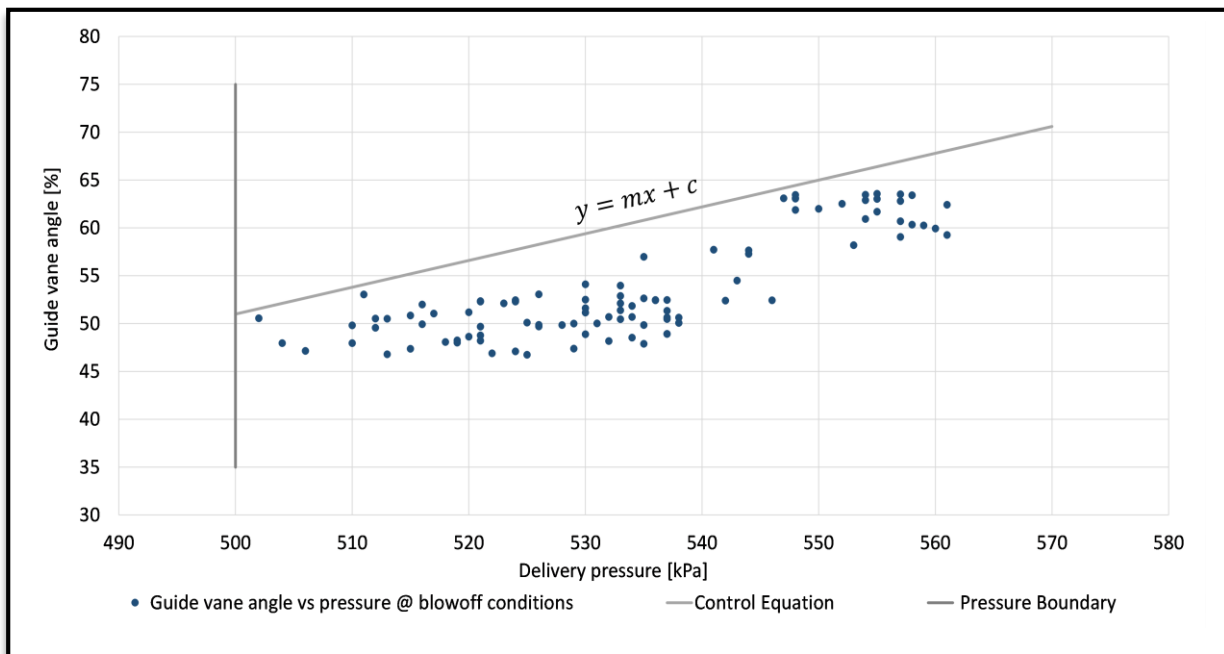


Figure 37: Minimum guide vane angle regression model

It is evident from Figure 37 that blow-off occurs at a higher guide vane angle as the delivery pressure of the compressor increases. A fixed minimum guide vane angle can therefore not be used. Otherwise, the estimated minimum delivery capacity of the compressor will be inaccurate. This could result in ineffective scheduling of compressor combinations.

Therefore, in order to determine the minimum guide vane angle of each compressor the delivery pressure must be taken into consideration. This is achieved by determining a control equation as illustrated in Figure 37. The control equation represents the boundary where the minimum guide vane angle can be determined at certain pressures where blow-off will not occur.

Table 12 lists the control equations for each compressor's minimum guide vane angle that was determined by the method explained.

Table 4: Compressor's minimum inlet guide vane angles

Compressor	$y = mx + c$	
	m	c
Sulzer A1	0.14	-24.5
Sulzer A2	0.19	-46
Sulzer A3	0.1	-13.1
VK100 B1	0.11	-11.1
Sulzer B2	0.065	3

With the minimum guide vane angle at certain pressures known for each compressor the characteristics curves can be determined. Figure 38 presents the characteristics curve of the Sulzer A1.

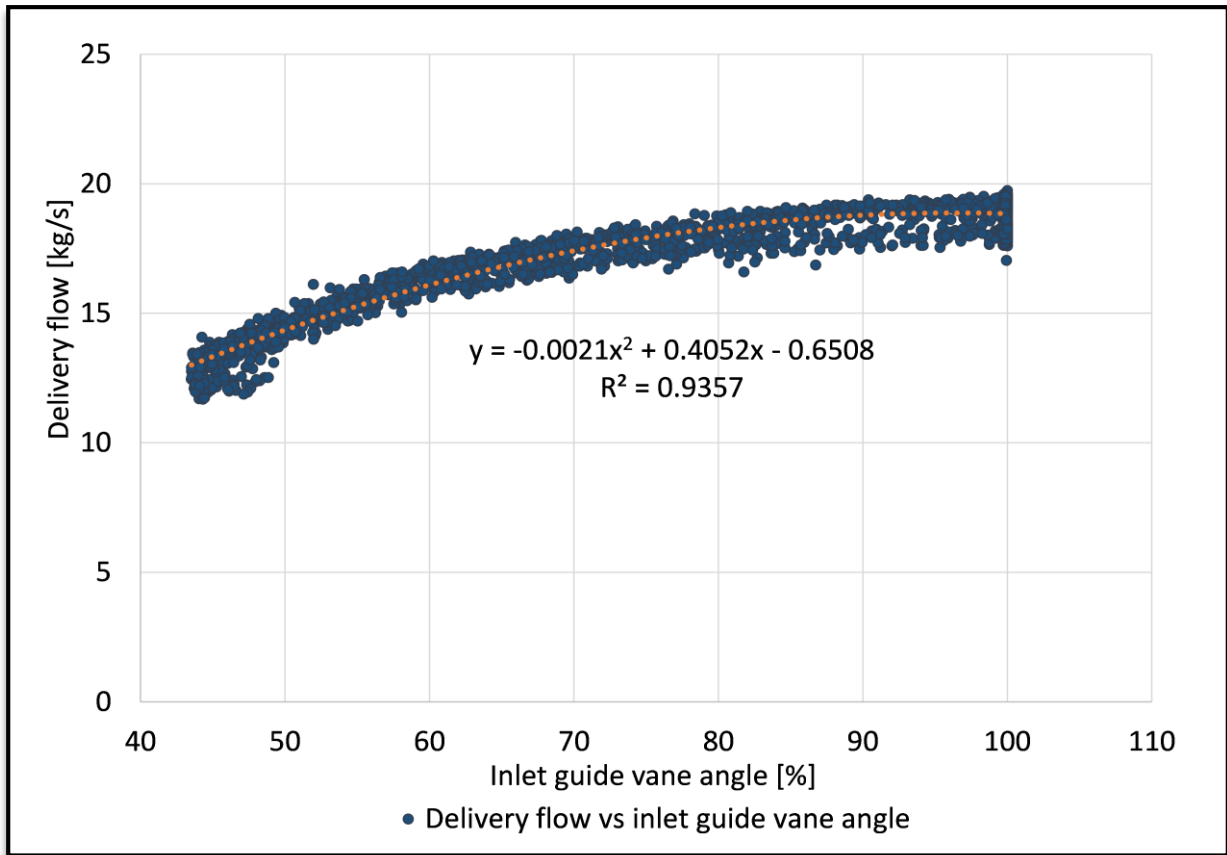


Figure 38: Characteristics curve of Sulzer A1

The characteristics curve is a scattered plot of the compressor's delivery flow (y – axis) at different guide vane angles (x – axis). The following filtering was done to ensure the plots represent acceptable operating points of the compressor:

- Filtering was done by limiting the guide vane angle to the minimum angle at certain pressures.
- Filtering was also done by only considering operation points where the compressor blow-off point is above zero.

A quadratic equation can be determined by using regression modelling that is visible in Figure 38. The quadratic equation is used to determine the compressor delivery flow at different guide vane angles. Equation 12 is the quadratic equation that is determined by the regression modelling of the compressors characteristics curve.

Equation 12: Quadratic equation

$$y = ax^2 + bx + c$$

$y =$ Compressors delivery flow [kg/s]

$x =$ Compressors inlet guide vane angle [%]

$a, b, c =$ Numerical coefficients [-]

The flow delivered at any given guide vane angle of the compressors can be determined by using Equation 12. The pressure was not considered in obtaining the equation. This can be observed on Figure 38, by examining the delivery range at a certain guide vane angle. Nonetheless, a R^2 value of 0.94 was obtained, indicating the equation will provide a good correlation of actual conditions.

As discussed in section 3.2.3, one flow meter is installed at compressor house A. The flow meter measures the total mass flow supplied by the running compressors. Therefore, the regression models for every compressors combination available at Shaft A was obtained.

Because the compressors at Shaft B have individual flow meters installed; the mass flow of each compressor is available. The regression models could therefore easily be individually obtained for the compressors. The R^2 values obtained for each regression model is in the range of 0.75 to 0.99. This confirms that by using the regression models, a good estimation of actual conditions can be obtained. The regression models for each individual compressor and compressors combination are listed in Table 5:

Table 5: Compressors regression models

Quadratic equation numerical coefficients		a	b	c
Individual compressors	Sulzer A1	-0.00211	0.403	-2.36
	Sulzer A2	-0.00211	0.403	-0.5
	Sulzer A3	-0.0019	0.35	3.1
	VK100 B1	-0.0015	0.2875	12.026
	Sulzer B2	-0.0011	0.2178	3
Compressor combinations	Sulzer A1&2	-0.0038	0.7243	2.8859
	Sulzer A1&3	-0.0039	0.735	2.9
	Sulzer A2&3	-0.0039	0.735	4.5
	Sulzer 1&2&3	-0.0058	1.1049	3.8

These compressors flow regression models will be used to evaluate if the running compressors can maintain the required optimal ring pressure and supply pressure. As discussed in this section, the start and stop priorities have already been assigned to the trimming compressor. It is therefore known which trimming compressors are scheduled to start and which trimming compressors are scheduled to stop. These priorities will change once a trimming compressor has started or stopped.

The delivery flow capabilities of alternative compressors combinations can therefore be estimated. The following compressor delivery flow capabilities will be continuously determined by using the regression models listed in Table 5:

Running compressors maximum delivery flow capability

- Delivery flow calculated at a guide vane angle of a 100% for individual compressor and/or compressors combination

Running compressors minimum delivery flow capability

- Delivery flow calculated at a minimum guide vane angle for individual compressor and/or compressors combination

Compressors delivery flow capability after a trimming compressor is stopped

- Delivery flow calculated at a guide vane angle of 100 % for running compressors, excluding the delivery flow of the trimming compressor that will be stopped.

The delivery flow capabilities, together with the following parameters will be continuously evaluated to determine the optimal running schedules of the trimming compressors:

- compressed air consumption and supply at a specific time;
- the required supply flow at a specific time;
- actual and required ring pressure at a specific time;
- pressure rate of change at a specific time;
- guide vane angles of the compressors in operation; and
- the supply capacity of new compressor combinations.

With the supply side and demand side characterised and integrated as a single system an effective compressors combination can be determined. Once the actual ring pressure is decreasing with reference to the required pressure and the predicted flow demand is increasing over the next 30 minutes, the decision about starting a compressor will be considered. Figure 39 illustrates the procedure that will be followed to start a compressor.

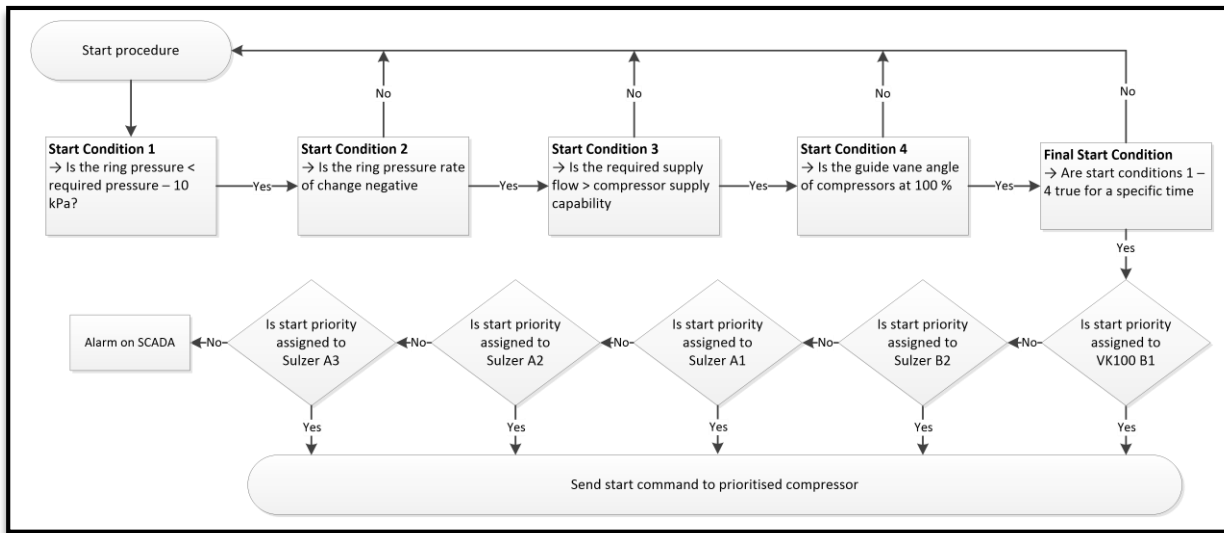


Figure 39: Conditions evaluated for compressor start procedure

Figure 39 illustrates the conditions of the compressed air ring that will be evaluated before a compressor is started. The following conditions will be evaluated to determine if a compressor should be started.

1. The actual ring pressure and the required ring pressure will be evaluated. If the actual ring pressure is more than 10 kPa below the required pressure the process of starting a compressor is continued.
2. The pressure rate of change per minute [kPa/min] will be evaluated. If the pressure rate of change is constant or decreasing, the process is continued. If the pressure rate of change were increasing, it would not be considered to start a compressor and the process will return to the beginning.
3. If the flow capacity of the compressors running is not able to match the calculated required supply flow, it could be said an additional compressor should be started. Therefore, the process of starting a compressor is continued.

- The inlet guide vane angles of the running compressors are evaluated next to ensure that maximum flow is delivered by each compressor. Starting a compressor will only be considered if the inlet guide vane angle for each compressor is at 100 %.

The prioritised compressor will be started if these conditions are true for a specific period. In ideal conditions the VK100 B1 and Sulzer B2 will not need to be considered in the start procedure. However, unforeseen circumstances do occur at times. For instance, if a baseload compressor trip and the supply capacity of the remaining running compressors do not meet the measured demand flow, an available trimming compressor will be started immediately.

Otherwise, the start conditions mentioned will be evaluated and when all conditions apply to the specific time an available trimming will be started. If the baseload compressor is available to start again rather than switching the baseload compressors with a trimming compressor, it will only be considered starting the baseload compressor when the requirements of the ring justify a start.

Once the actual ring pressure is increasing regarding the required pressure and the predicted flow demand is decreasing over the next 30 minutes, it will be considered to stop a compressor. Figure 40 illustrates the procedure that will be followed to stop a trimming compressor. Only the trimming compressors will be considered in the stop procedure.

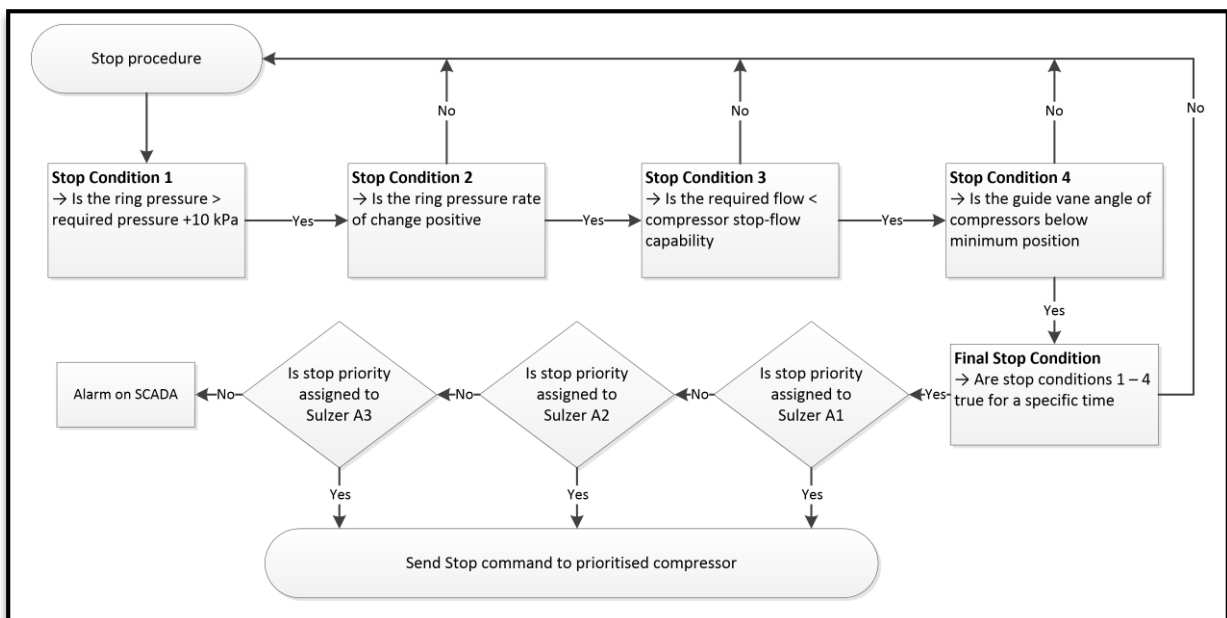


Figure 40: Conditions evaluated for compressor stop procedure

The following conditions will be evaluated to determine if a compressor should be started.

1. The difference between the actual pressure and the required ring pressure will be evaluated. If the difference is higher than 10 kPa the process of stopping a compressor is continued.
2. The pressure rate of change per minute [kPa/min] will be evaluated. If the pressure rate of change is equal or increasing, the stop process is continued. If the pressure rate of change were decreasing, it would not be considered to stop a compressor and the process will start at the beginning.
3. If the flow capacity after stopping the prioritised compressor running is able to match the required supply flow, the compressor could be stopped.
4. The inlet guide vane angles of the running compressors are evaluated next. If each compressor is operating at the minimum guide vane angle, calculated by using the equations in Table 4, it will be considered to stop a compressor.

The prioritised compressor will be stopped if these conditions are true for a specific period. When a compressor is stopped there is a significant gap in the supply flow of the new compressor combination. The guide vane angles of the running compressors will therefore be adjusted in a situation where a compressor is stopped. This will ensure the compressors running after the stop provide sufficient supply flow in order to match the demand requirements.

An optimal guide vane angle for each compressor will also be continuously calculated. The guide vane angles of the running compressors will be set to the optimal guide in a situation where the network pressure is unstable. The following section will discuss the methodology used to control the guide vanes.

3.3.5 Compressors guide vane angle control

At Mining Complex A, inlet guide vane control together with a surge avoidance control strategy is implemented on the compressors mentioned in section 3.2.3. The guide vanes of the compressors are controlled from the PLCs through P&ID control loops in order to maintain the pressure set point. As mentioned in section 3.3.3, the pressure set point will be relayed to each compressor. The inlet guide vanes will regulate the inlet flow of each compressor to supply compressed air in order to match the pressure set point.

The existing inlet guide vane control together with the surge avoidance control strategy will be used to automatically control the compressor delivery pressure to match the pressure set point. The P&ID variables are programmed to maintain stable control once the compressors are in operation and the demand for compressed air steadily increases and decreases during the day.

The guide vane angles of the compressors will be controlled from the PLCs through P&ID control loops. However, as part of the new control strategy the guide vane angles of each compressor will be set to an optimal position when there are major disturbances in the system. The guide vanes will be controlled under the following conditions:

- Compressor combination change; and
- Sudden changes in demand flow

When a compressor is stopped or started, there is a gap in the supply flow range of the new compressor combination. Therefore, the guide vane angles of the running compressors will be adjusted in order to provide the required supply flow. The sudden changes in demand flow occur at the start/end of a drilling shift where various valves are open or closed in the same period. In order to stabilise the network pressure an optimal guide vane angle is set for each compressor for different scenarios.

Figure 41 illustrates the flow range of the different compressor combination. The graph demonstrates the supply flow capabilities of different compressor combinations at maximum and minimum guide vane angles.

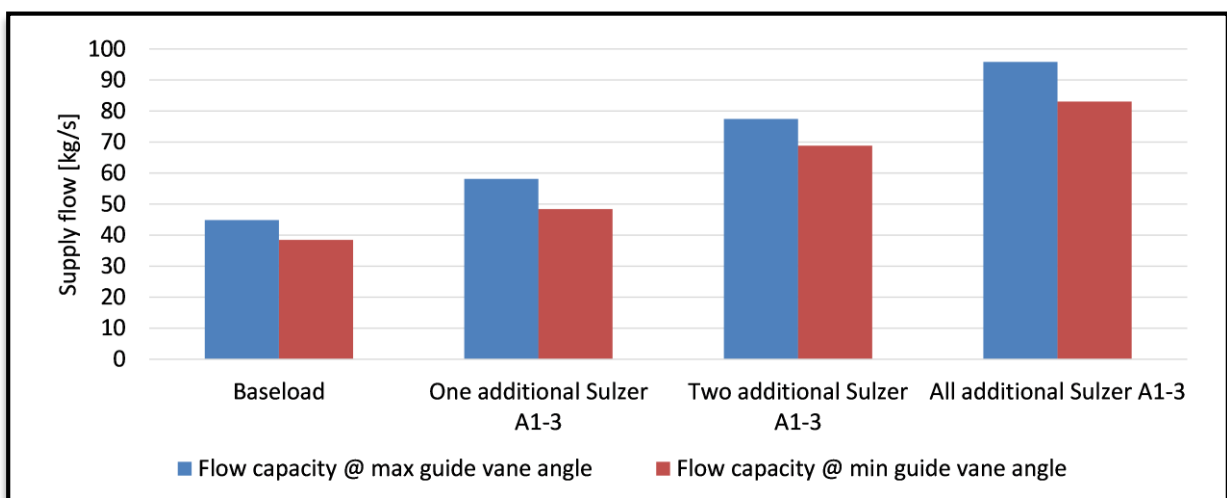


Figure 41: Compressors combinations flow range

The flow ranges illustrated in Figure 41 start with the baseload compressor combination. As stated earlier, the VK100 B1 and Sulzer B2 are allocated as the baseload compressors and will run throughout the entire day. On Figure 41 the average flow capabilities of the different trimming compressor combinations are added to the flow capabilities of the baseload combination.

It is evident from Figure 41 that gaps in flow occur between different compressor combinations. The biggest supply flow gap occurs with the transition from two trimming compressors to one trimming compressor. The difference between the minimum flow capability of two trimming compressors and the maximum flow capability of one trimming compressor is approximately 10 kg/s. As stated in section 3.3.4, when determining if a compressor can be stopped the flow capacity of the compressors that will be running after stopping the prioritised compressor is evaluated against the required supply flow. If the compressors that will be running are able to match the required supply flow, the prioritised compressor will be stopped. The other stop conditions must consequently also be true.

The flow capability of the compressors that will be running is calculated at a maximum guide vane angle. However, before the compressor is stopped the guide vane angles of all running compressors will be cut back to a minimum. Therefore, in order to ensure sufficient compressed air will be supplied after the stop, the guide vane angles of the compressors that will be running after the stop are set to a maximum angle of a 100%.

The prioritised compressor will then be stopped, once the guide vane angle of the running compressors reaches a 100%. The guide vanes will be controlled from the PLCs after the stop if the ring pressure has stabilised or is increasing. Figure 42 illustrates the procedure as described in this section. This method will be used for every stop procedure.

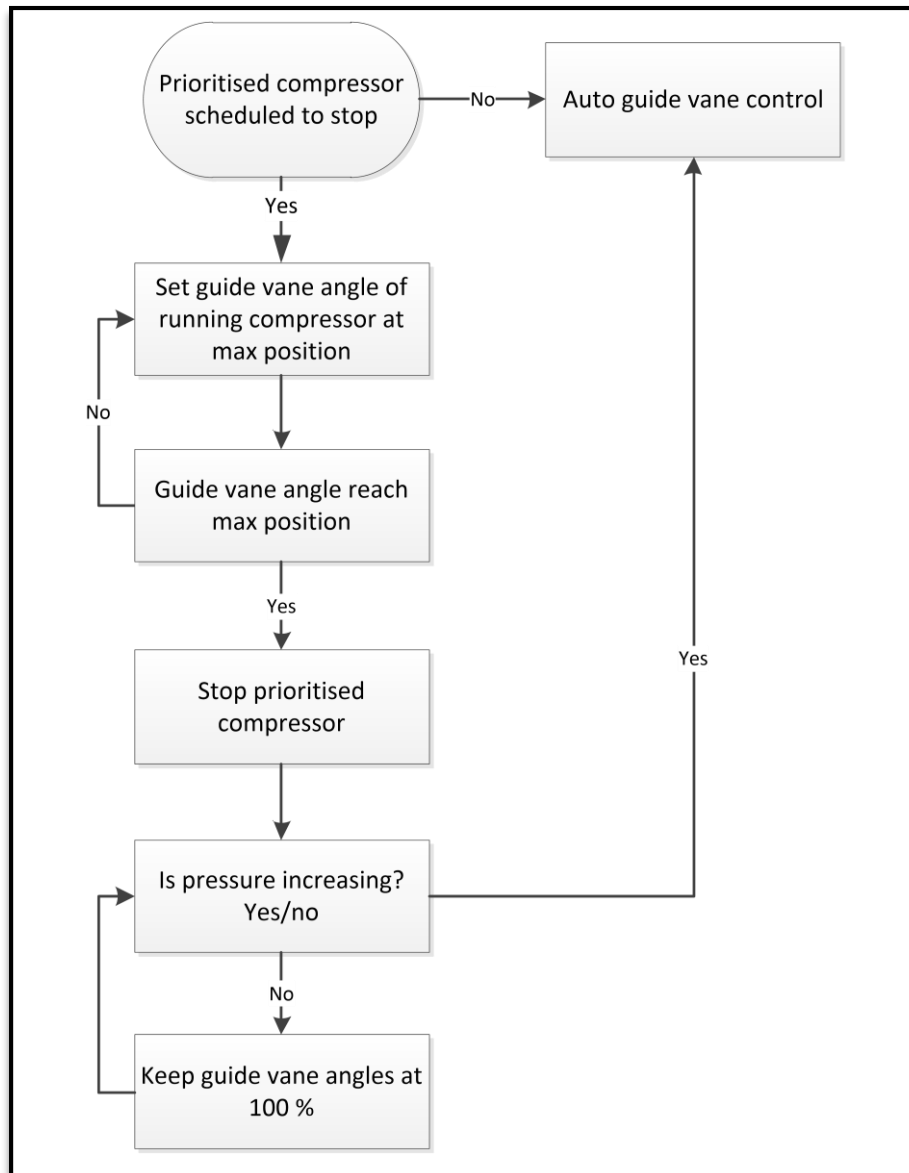


Figure 42: Compressor guide vane control – Stop procedure

The flow gap encountered between transitioning from different trimming compressors makes it difficult to know exactly when a compressor can be stopped. By using the procedure illustrated in Figure 41, an improvement to the system control is achieved. This is realised by setting the guide vane angles of all running compressor to a maximum position to over supply the demand requirements for the specific time. This results in an increase in network pressure.

As soon as the compressor is stopped, the sudden drop in supply flow causes the network pressure to decrease significantly. Nevertheless, because the ring pressure has been increased prior to the

stop and the running compressors are supplying the maximum amount of compressed air, the required ring pressure would still be maintained.

The procedure described in Figure 41 can also be used as a safety feature for a scenario when a compressor trips. As mentioned in section 3.3.4, if a compressor trips and the supply capacity of the remaining running compressors does not meet the measured demand flow and calculated flow loss, an available trimming compressor will be started immediately.

The same procedure displayed in Figure 42 will be followed in a scenario where a compressor has tripped. The guide vane angles of all running compressors will be set to a 100%, regardless of an additional trimming compressor starting or not. The guide vanes of the running compressors will be kept at a 100% until the network pressure has stabilised and/or increased. When the ring pressure has stabilised or is increasing for a specific time, the guide vanes will be controlled from the PLCs once again.

This can be described as a safety feature of the new control strategy. Because the controller steps in instantaneously when a compressor trips, the ring pressure will be stabilised within seconds. Production will not be negatively influenced when a compressor trips, which is a significant benefit.

The guide vane angles of running compressors will also be adjusted when there is a major disturbance in the network. The guide vane angles of the running compressors will be set to an optimal position in an attempt to stabilise the network pressure in any instance where the pressure rate is increasing or decreasing at a specified rate.

For example, in a scenario where the network pressure has decreased below the required ring pressure and the running compressors are unable to meet the demand flow, a compressor will be scheduled to start. As previously mentioned, the network pressure is below set point, therefore the P&ID control loops will keep the guide vane angles of the running compressors at a 100% to reach the pressure set point. With the additional compressor started, the supply flow is significantly higher than the demand flow, therefore the pressure will increase at a high rate.

Because the network pressure is increasing at a high rate, the P&ID control loops will react slowly to adjust the guide vane angles in order to maintain the network pressure at the required ring

pressure. The network pressure will therefore surpass the required pressure. This results in power waste because more compressed air is supplied than what is required.

In order to stabilise the network pressure before it surpasses the required pressure, the guide vane angles of the running compressors will be set to an optimal position. The optimal position is the guide vane angle required to produce flow by each compressor to match the measured demand flow and the calculated flow loss. This optimal guide vane position is continuously calculated for each compressor.

Figure 35 illustrates the method used to calculate the flow loss. When the pressure rate is constant, the flow loss is calculated as the difference between the supply and the measured demand flow. In a scenario where the network pressure is increasing at a high rate, the network pressure would stabilise if the total supply flow matches the demand flow and the calculated flow loss.

The first step to calculate the optimal guide vane angle for each compressor is to determine the required flow for each compressor. The total required flow for each compressor must match the measured demand flow and calculated flow loss. When the required supply flow is known for each compressor, the regression models listed in Table 5 will be used to determine the guide vane angles of each compressor. This will be the optimal guide vane angle.

In order to estimate the supply flow required by each compressor, the efficiency of each compressor at certain guide vane angles first needs to be evaluated. The compressor efficiency was calculated by determining the power each compressor uses to produce a kilogram of compressed air at a pressure range of 500 – 550 kPa. The compressor efficiency was calculated at different guide vane angles for each compressor as shown in Figure 43. The efficiency of the compressor will be considered to determine the supply flow required by each compressor.

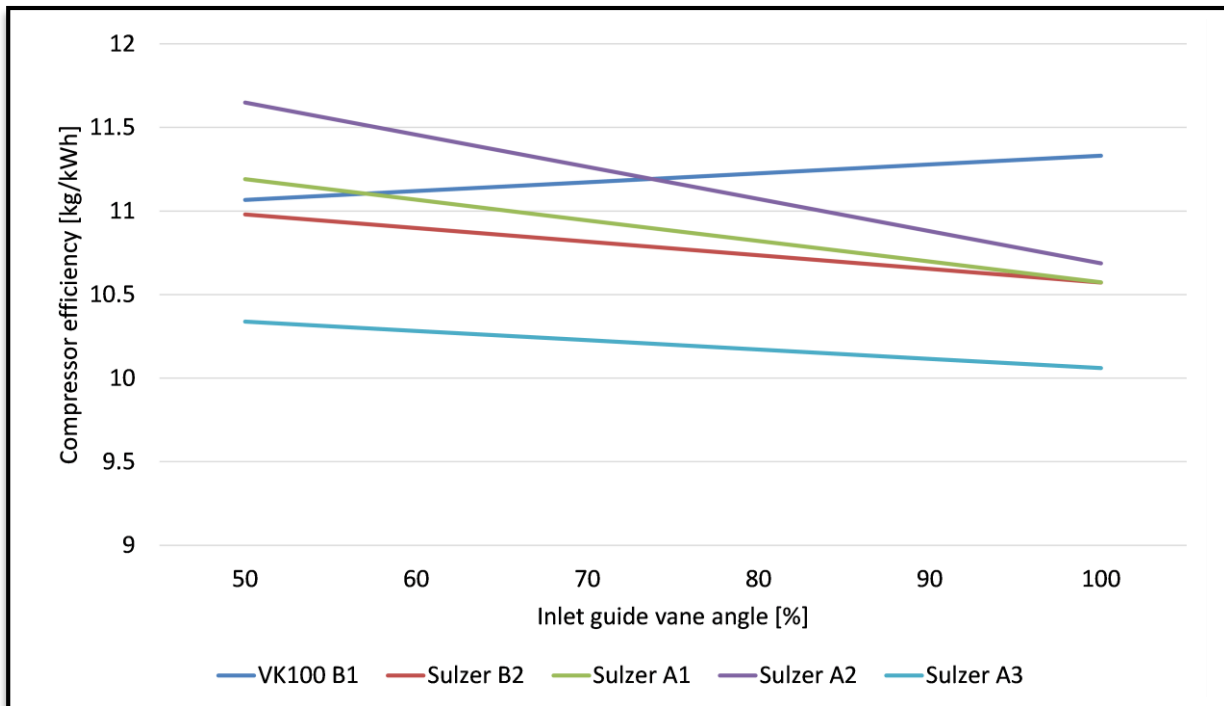


Figure 43: Compressor efficiency at different guide vane angles

It is evident from Figure 43 that the efficiency of the compressors decrease at higher guide vane angles, with the exception of the VK100 B1. The efficiency of the VK100 B1 increases as the guide vane angles increase. It is evident from Figure 43 when the required flow for each compressor is calculated, the VK100 B1 must be set at the maximum possible angle. The guide vanes angles of Sulzer B2 and Sulzers A1-3 must be set at the minimum possible angle. This will improve the efficiency of the compressed air network.

As explained, the compressors will deliver compressed air to match the measured demand flow and the flow loss in a situation where the network pressure needs to be stabilised. In order to determine if the VK100 B1 can be set at a guide vane angle of a 100%, the remaining supply flow required by the Sulzer B2 and Sulzers A1-3 is evaluated.

If the total minimum supply capability of the Sulzer B2 and Sulzers A1-3 and the maximum supply capability of the VK100 B1 is less than the required supply flow, the VK100 B1 will be set to a maximum guide vane angle. The guide vane angles of the Sulzer B2 and Sulzers A1-3 will therefore be determined to supply the remaining required supply flow.

The remaining flow required by the other compressors is therefore the remaining supply flow with the maximum flow capability of the VK100 B1 excluded. In order to determine each compressor's required supply flow the remaining required flow will be scaled according to the flow capability of each running compressor. The following equations are used to determine the required flow of the Sulzer B2 and Sulzers A1-3, respectively:

Equation 13: Required flow of the Sulzer B2 and Sulzers A1-3

$$Sulzer\ B2_{req\ flow} = Y * \frac{Sulzer\ B2_{flow\ capability}}{Sulzer\ B2_{flow\ capability} + Sulzer\ A1 - 3_{flow\ capability}}$$

$$Sulzer\ A1 - 3_{req\ flow} = Y * \frac{Sulzer\ A1 - 3_{flow\ capability}}{Sulzer\ B2_{flow\ capability} + Sulzer\ A1 - 3_{flow\ capability}}$$

$Y = Required\ supply\ flow - VK100\ B1\ max\ flow\ capability$ [kg/s]

$Sulzer\ B2_{flow\ capability} = Sulzer\ B2\ max\ flow\ capability$ [kg/s]

$Sulzer\ A1 - 3_{flow\ capability} = Sulzer\ A1 - 3\ max\ flow\ capability$ [kg/s]

Equation 13 is used to calculate the flow required by the Sulzer B2 and Sulzer A1-3, if the guide vane angle of the VK100 B1 is set to 100%. The max flow capability is calculated using the regression models listed in Table 5. If a compressor is not running, the max flow capability will be zero. It is important to also keep in mind that the regression model for any combination of Sulzer A1-3 has been calculated.

It is evident that Equation 13 could still be used when the Sulzers A1-3 are not running. The max flow capability of the Sulzers A1-3 will be zero, consequently the required flow as well. The Sulzer B2 required flow will then be calculated as the total remaining flow required, if the VK100 B1 is delivering maximum flow capability.

In the case where the minimum supply capability of the other compressors and the maximum supply capability of the VK100 B1 is more than the required supply flow, the guide vane angles of the Sulzer B2 and Sulzers A1-3 will be set to a minimum angle, respectively. The guide vane angle of the VK100 B1 will therefore be determined to supply the remaining required supply flow.

Figure 44 displays the procedure that is followed when the required flow of each compressor is calculated.

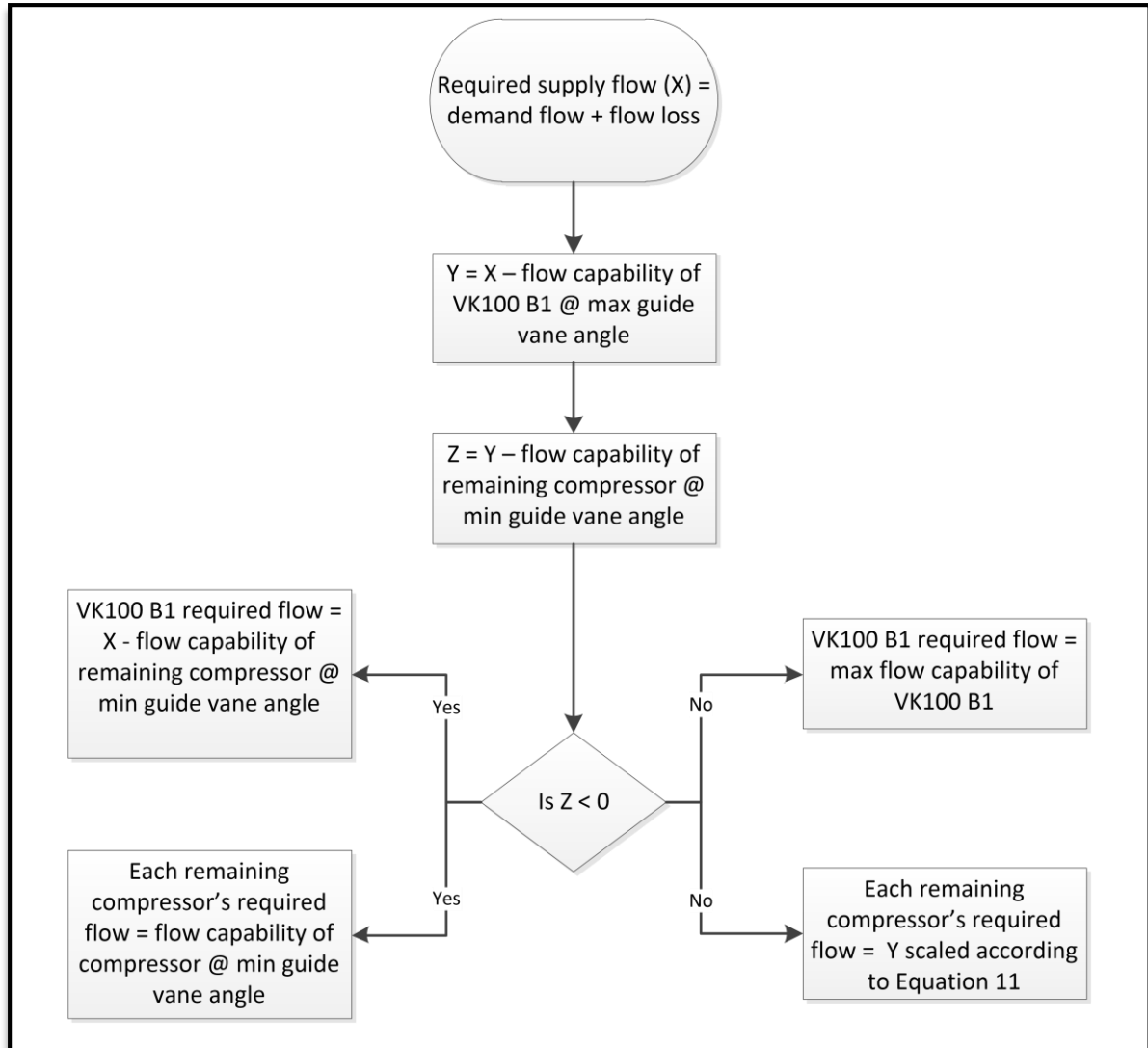


Figure 44: Determining the required supply flow for each compressor

Figure 44 illustrates the procedure that will be followed to continuously calculate the required flow for each running compressor. The total calculated required flow equals the measured demand flow and calculated flow loss for any situation. Therefore, when the network pressure is unstable the delivery flow of the running compressor can be adjusted according to the calculated required flow. This will be achieved by setting each compressor's guide vane angle at the optimal position. In theory, this will re-stabilise the network pressure in order to improve the efficiency of the compressed air network.

The optimal position is calculated by using the quadratic equation obtained from regression modelling. Equation 11 represents the quadratic equation that was obtained. The quadratic equation calculates the delivery flow at different guide vane angles for each compressor. The procedure displayed in Figure 44 is used to calculate the flow required for each compressor to match the measured demand and flow loss. Therefore, the delivery flow for each compressor is known. In order to calculate the guide vane angle to deliver the calculated required flow for each compressor the quadratic formula is used.

Equation 14: Quadratic formula

As discussed in section 3.3.4, the following quadratic equation is obtained from regression modeling:

$$y = ax^2 + bx + c \quad \text{Equation 12}$$

$$0 = ax^2 + bx + c - y$$

With the calculated required flow known for each compressor setting $d = c - y$ the following quadratic equation is obtained:

$$0 = ax^2 + bx + d$$

The quadratic formula is the solution to the above quadratic equation:

$$x = \frac{-b \pm \sqrt{b^2 - 4ad}}{2a}$$

$y = \text{Compressor calculated required delivery flow}$ [kg/s]

$x = \text{Compressor inlet guide vane angle}$ [%]

$a, b, c, d = \text{Numerical coefficients}$ [-]

By using Equation 14, the optimal guide vane angle for each compressor is continuously calculated. When the guide vane angle of each compressor is set to the optimal position it will be referred to as guide vane stability control. In order to decide when the guide vane stability control needs to be executed the following conditions are evaluated:

- Pressure rate of change [kPa/min]; and
- Network pressure relative to the compressor pressure's set point.

A stable network pressure will result in a small change in the pressure rate of change. Therefore, the pressure rate of change will be used to determine if stability control is required. The network pressure relative to the required pressure will also be evaluated. If the network pressure is within a certain boundary with regard to the required pressure the guide vane stability control will be executed. Figure 45 illustrates when stability control will be activated.

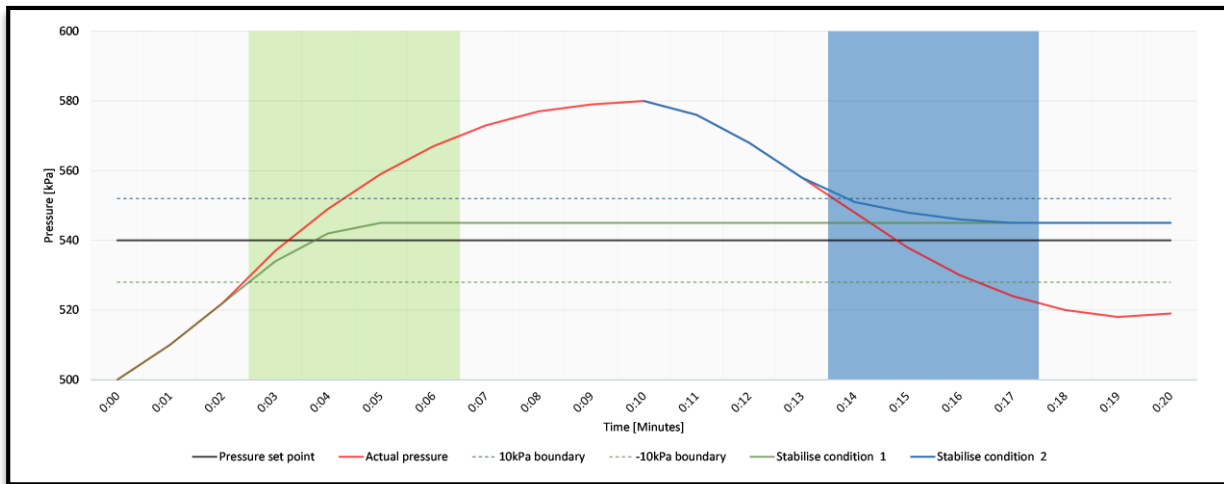


Figure 45: Compressor guide vane control – Stability control

Condition 1 is active under the following conditions

- Pressure rate of change is increasing at a rate higher than 5 kPa/min; and
- The network pressure is 10 kPa below the pressure set point.

Condition 2 is active under the following conditions

- Pressure rate of change is decreasing at a rate lower than -5 kPa/min; and
- The network pressure is 10 kPa above the pressure set point.

When either Condition 1 or condition 2 is active, the inlet guide vane stability control will be triggered. As soon as the guide vane angles have been set to their optimal positions, the network pressure rate of change will stabilise. When the network pressure is stable, condition 1 and condition 2 will not be active and as a result, stability control will be deactivated. The P&ID control loops programmed in the PLCs will then be used to control the guide vanes of the compressors accordingly.

The pressure boundary condition is evaluated because when the network pressure is below the required pressure, P&ID control loops programmed in the PLCs will increase the guide vane angles

of each compressor in order to increase the supply flow, which will consequently increase the network pressure. This will result in an increase in the pressure rate of change. However, the network pressure needs to be within a ± 10 kPa boundary with regard to the set point before the network pressure can be stabilised. The reason for this is to ensure the network pressure is increased as quickly as possible to reach the pressure set point and then stabilised, not to overshoot the pressure set point.

The same can be said when the network pressure is far above the pressure set point. The P&ID control loops programmed in the PLCs will decrease the guide vane angles of each compressor in order to decrease the network pressure with regard to the pressure set point. The stability control will however be activated when the network pressure is within 10 kPa of the pressure set point to ensure the pressure does not undershoot the pressure set point.

3.3.6 Reducing compressors' blow-off

Each compressor has blow-off valves installed, which can be opened to prevent the compressor from surging. Moore controllers installed on the compressors will automatically open the blow-off valve when a compressor is operating on the blow-off curve. The compressor will operate near the blow-off curve if the guide vane angle is reduced beyond the minimum guide vane angle.

Due to the large amount of compressed air being lost into the atmosphere, utilising the blow-off valves are an inefficient method to prevent compressors from surging. It is important to therefore prevent any unnecessary blow-off.

In a situation where this is not possible, the ring pressure will rather be increased. If the ring pressure is increased a compressor can rather be switched off, than compressor blow-off occurring. As mentioned in section 3.3.4, the Moore controller communicates a value that represents the current operating distance from the compressor's blow-off curve i.e. the blow-off point. When this blow-off point reaches zero, the compressor's blow-off valve will open automatically. Figure 46 displays a typical compressor surge line, blow-off curve and blow-off point.

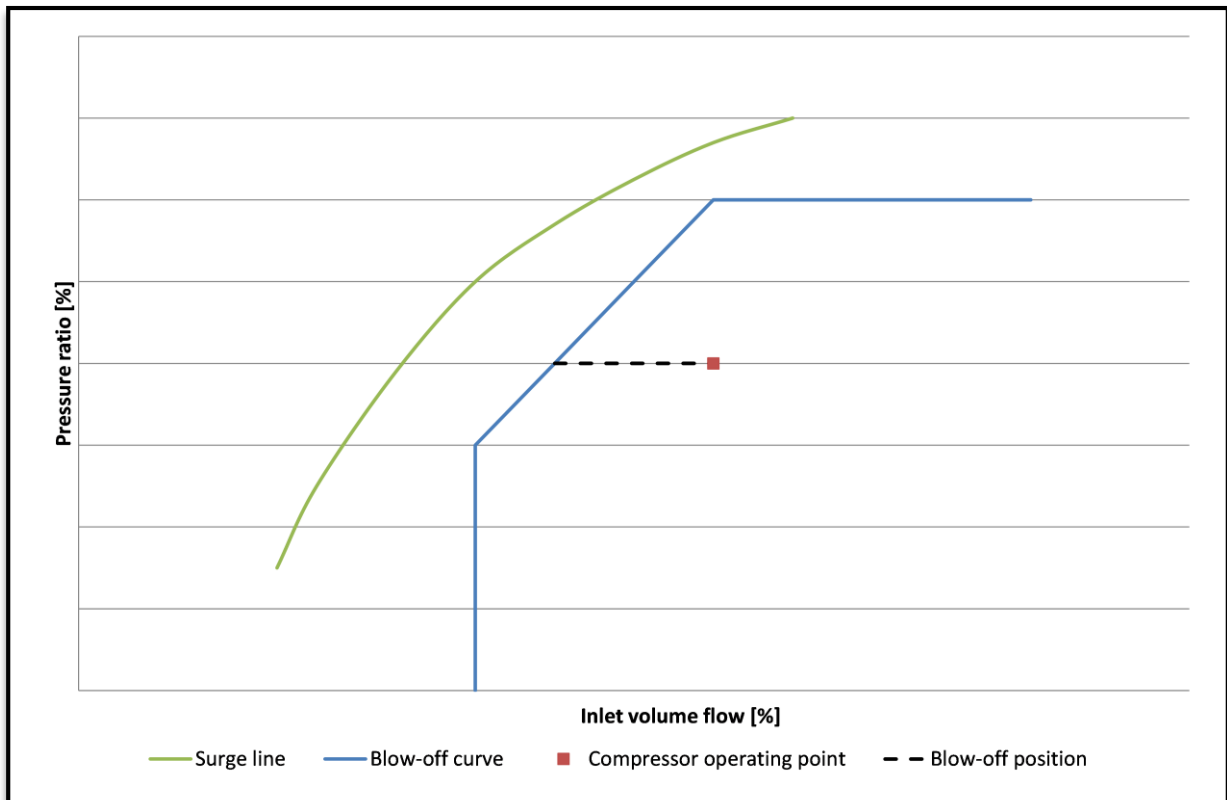


Figure 46: Compressors' blow-off curve

In order to prevent blow-off from occurring the guide vane angle of the compressor will be increased. This will be achieved by adjusting the programming on the PLC of each compressor in order to prevent the compressors from opening the blow-off valve.

If the guide vane angle of the compressor is increased, it will result in more air being produced at a higher pressure, the operation point will therefore move away from the blow-off curve. This will be achieved through the PLC control illustrated in Figure 47.

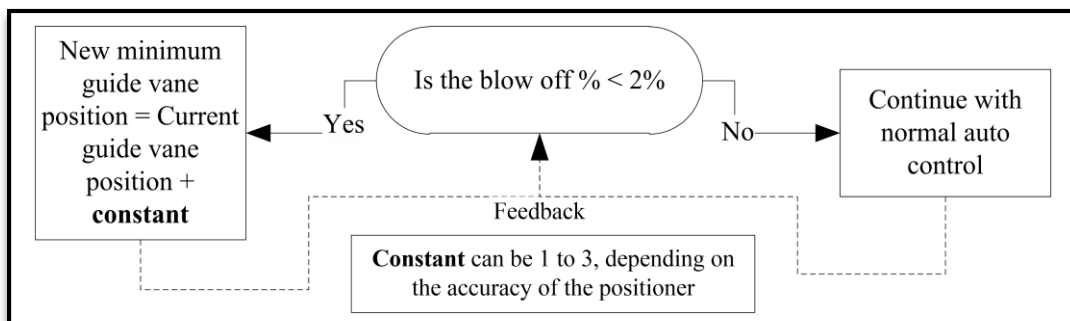


Figure 47: PLC compressors blow-off avoidance control strategy

As displayed in Figure 46, if the guide vane angle of the compressor is increased the discharge pressure and flow will also increase. This will result in the operating point moving in an upper rightward direction. This will ultimately prevent blow-off occurring on the compressor. However, as displayed in Figure 46, the blow-off curve has an upper limit. Therefore, blow-off will occur when the pressure has increased to high levels in order to prevent the compressor from surging.

By using this method to reduce blow-off, the network pressure will be increased. It is assumed that by increasing the network pressure a trimming compressor can be switched off rather than blow-off occurring. This will improve the efficiency of the compressed air network.

3.4 Verification

As discussed in section 3.2.3, the relevant mine personnel did not want to allow the automatic setting of the discharge pressure set or to automatically control the compressors. A detailed investigation was therefore conducted to verify the feasibility of the improved control strategy developed in this chapter.

The discharge pressure set points and compressors combinations were simulated using real time data. The simulation results will indicate the energy cost-savings potential. The results could then be used to gain the confidence of the relevant mine personnel in the new control strategy. Permission to fully test the new proposed control strategy could then be motivated, if the results proved acceptable.

The first phase of the simulation tests was to assess the pressure set point simulated for each compressor house. This was done by using real time values for a typical production day. The proposed strategy developed in section 3.3.3 was used to calculate the optimal required pressure set point. Figure 48 illustrates the ring pressure, maximum demand required set point and the results for the simulated pressure set point.

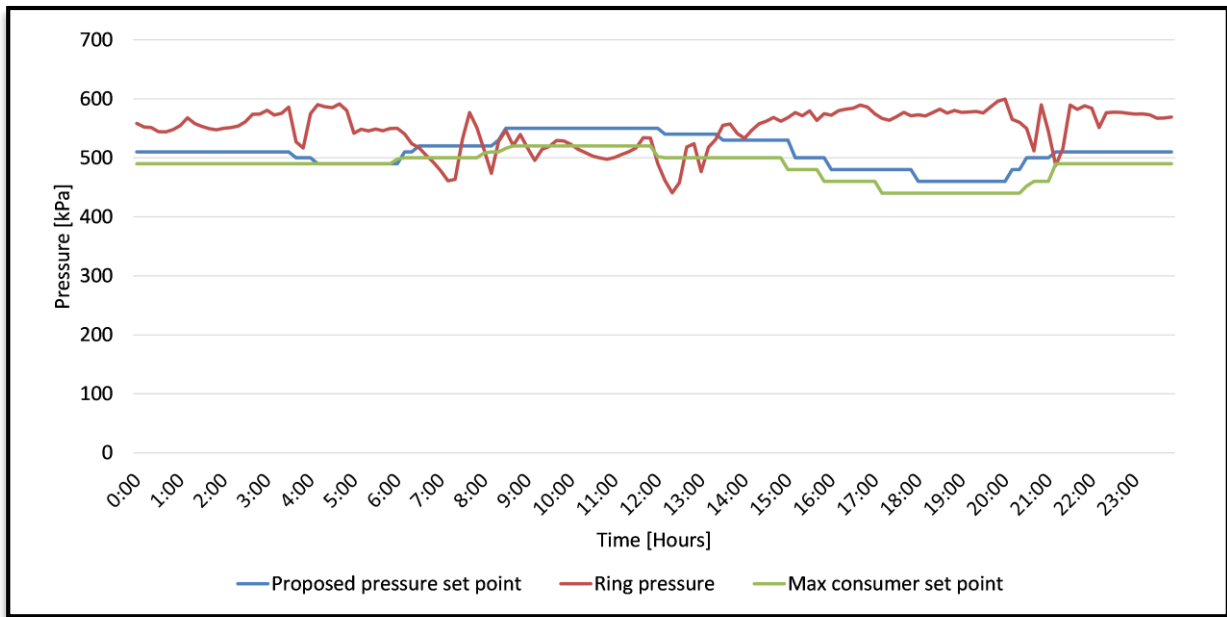


Figure 48: Simulation results for compressors pressure set point

When comparing the maximum pressure requirements of the consumers and the ring pressure on Figure 48, the ring pressure was for most of the day unnecessarily high. If the ring pressure had matched the requirements of the consumers more accurately, less air would have to be supplied and therefore significant energy savings could have been achieved.

When focusing on the proposed pressure set point, the consumer's requirements will have been matched more accurately if the ring pressure was maintained at the proposed set point. In addition, if this were the case an improvement in the energy efficiency of the compressed air network would be realised.

It is evident from Figure 48 that an improvement can be made by controlling the compressor discharge pressure set point according to the proposed pressure set point. However, the increased ring pressure with regard to the requirements of the consumers could also be a result of inefficient compressor combinations running at certain periods. Figure 49 illustrates the actual demand and supply flow for the simulation test day.

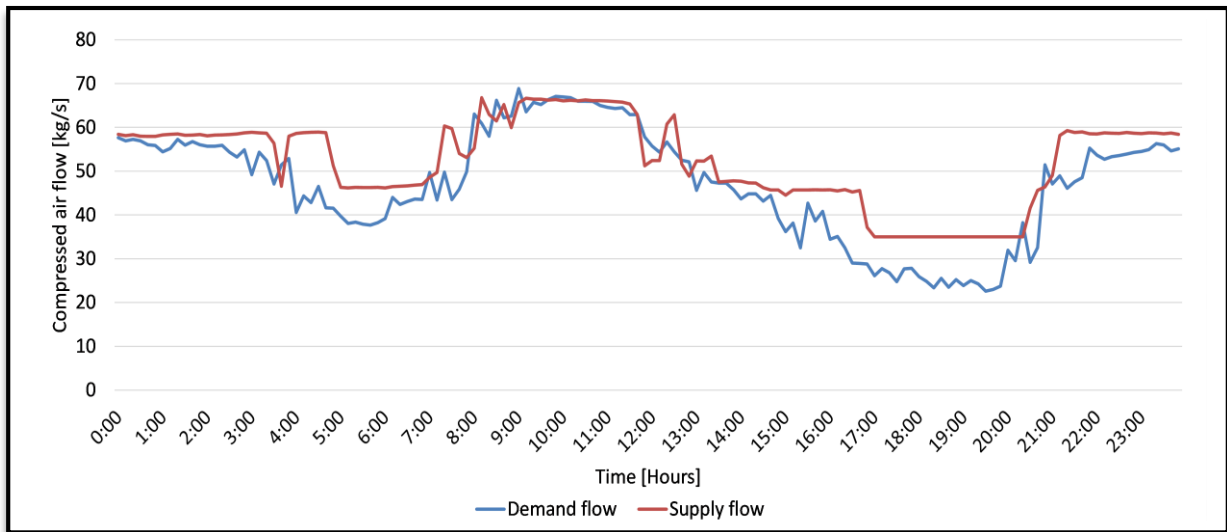


Figure 49: Actual supply and demand flow

When the supply and demand flow are compared in Figure 49, it can be seen that during certain periods of the day the supply significantly over-matched the demand flow. This is a result of operating inefficient compressors' compressor combinations and therefore oversupplying the compressed air network.

The biggest difference in demand and supply flow occurring in the morning and evening off peak drilling periods. During these periods, the control valves reduced the compressed air consumption of the shaft.

Using Equation 11, the required supply flow was calculated. Equation 11 requires a future pressure set point but because the future pressure set point required at half-hourly intervals was not available, a predetermined profile was used to calculate the required supply flow. Figure 50 illustrates the result obtained from simulating the required supply flow.

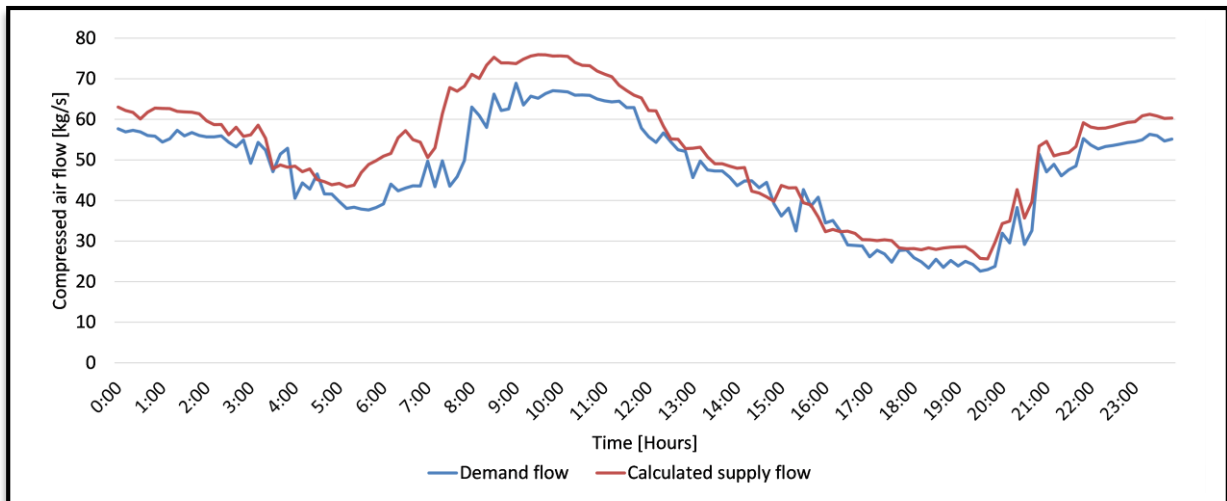


Figure 50: Simulation results for required supply flow

From Figure 50 it can be seen how the required supply proved accurate, as the required supply flow matched the demand flow throughout the day. It is evident that by using the future demand flow and pressure profiles an accurate required flow can be obtained. The simulated required flow considered the flow loss in the system. It for this reason the simulated required supply flow is more than the demand flow.

If Figure 49 and Figure 50 are compared, it is evident that the simulated required supply flow matches the demand flow more accurately. If the compressors maintained a supply flow according to the simulated supply flow, less air would have been supplied. This would have resulted in an energy saving.

The starting and stopping of compressors were simulated according to the developed strategy discussed in section 3.3.4. The actual conditions, such as guide vane angles and pressure conditions differed from what would have happened if the developed strategy were executed automatically. For this reason assumptions were made to simulate the proposed compressor schedules. The following assumptions were made:

- The guide vane angle for the stop and start conditions was not considered;
- The actual ring pressure versus the required ring pressure for the stop and start conditions was not considered; and
- The pressure rate of change for the stop and start conditions was not considered.

It was therefore only the required supply flow condition that was evaluated to simulate a proposed compressor schedule. The regression models listed in Table 5 was used to estimate the flow capabilities of various new compressor combinations. If the running compressors flow capabilities could not match the required supply flow for more than two minutes, the prioritised compressor was started.

The same applied for stopping a compressor, if the flow capability after stopping the prioritised compressor is able to match the required supply flow for longer than two minutes, the prioritised compressors were stopped. Figure 51 illustrates the compressors combination that was scheduled to run throughout the test day.

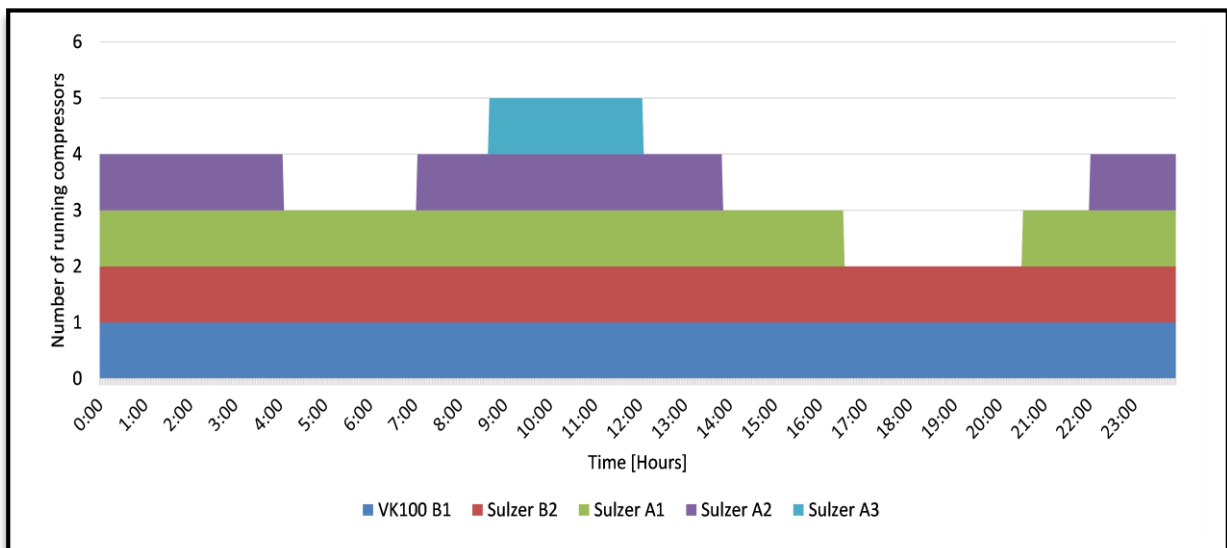


Figure 51: Simulation results for compressors scheduling

The proposed compressor schedules illustrated in Figure 51 also adhered to all the operational constraints defined by the mine personnel. It can also be argued that the proposed compressor schedules could further be optimised if the guide vane angle and pressure conditions for stopping and starting a compressor were considered. Figure 52 illustrates the actual power profile and proposed power profile that were obtained from the simulation for the simulation test day.

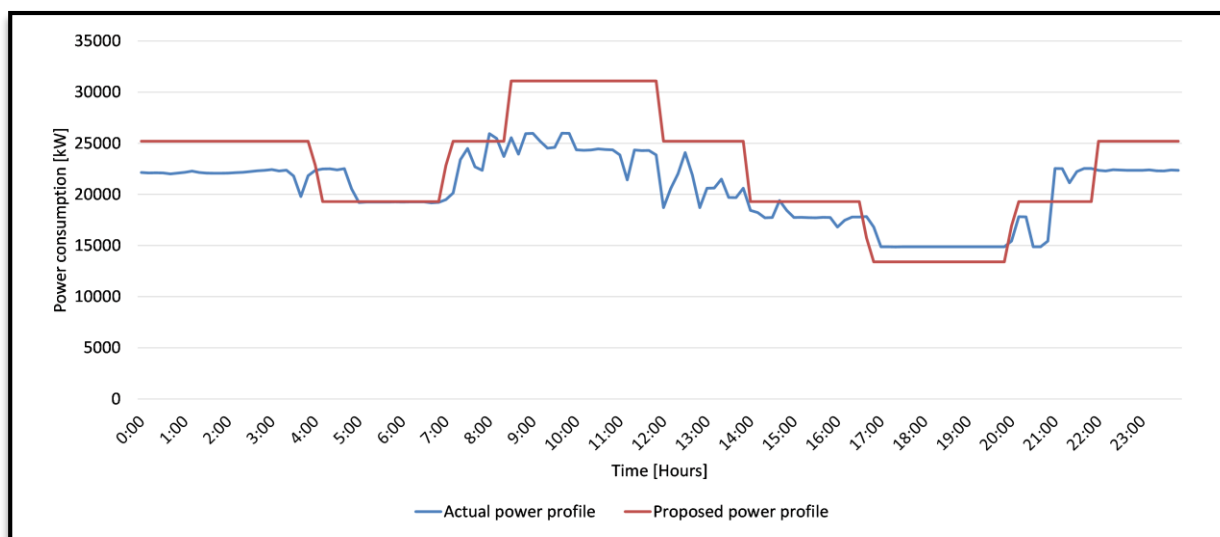


Figure 52: Simulation result for power profile

The proposed power profile illustrated in Figure 52 was obtained by assuming the compressors operated at full power capacities throughout the day. Power and flow have a direct correlation to one another. When the actual demand flow profile in Figure 49 is compared to the actual power profile in Figure 52 a close correlation is evident. It can therefore be said the proposed power profile will represent the supply flow that would have been delivered, if the compressors were controlled according to the proposed compressor schedules illustrated in Figure 51.

When the actual power profile is compared to the proposed profile, it can be argued that the proposed control is less efficient. However, the proposed power profile will be less in practise because the proposed power profile was calculated according to the full power capacities of each running compressor. During certain times in the day, compressors would have cut back which would have resulted in a decrease in total power consumption.

In Figure 52 the proposed power profile clearly shows a reduction in power during this time. The project was submitted to Eskom as an evening peak clipping project. Eskom's evening peak time is between 18:00 and 20:00. The simulated power saving resulted in average peak clip saving of 1.4 MW. This meant the project is feasible because a peak clip saving is possible.

As mentioned the simulated profile was obtained by assuming the compressors are operating at full capacity. The simulated savings of 1.4 MW can therefore be higher if the compressors cut back during Eskom's evening peak period. The results were presented to the relevant mine personnel who approved the commissioning of the improved control strategy.

3.5 Conclusion

The DCS controller was implemented on a deep level gold mining complex that was identified as a suitable case study. The DCS controller was identified as a control system that could be implemented to optimise the equipment on the compressed air network. Process parameters measured by the field instrumentation are relayed by the PLCs to the SCADA. The communication links were established through the OPC from the SCADA to receive process parameters and relay output commands.

With the implementation of the DCS controller certain control limitations were experienced. A new control strategy was developed to improve the compressed air network. The control strategy used the DCS controller as a backbone for the established communication links. Internal programmable tags within the DCS controller's GUI were used to develop the improved control strategy.

Components of the DCS controller will be used to relay downstream pressure set points to control valves of each major consumer. In order to determine the optimal required ring pressure, the pressure requirement of all major consumers are evaluated. Each consumer is evaluated in terms of the pressure needed at the point where the ring pressure is measured in order to provide sufficient pressure at the location of each consumer. Friction loss, pressure drops and the effect of auto compression is taken into account.

The trimming compressors will be stopped and started in order to maintain the optimal required ring pressure. Stop and start conditions were identified to determine when prioritised trimming compressors will be started or stopped. If a compressor trips, the control strategy has been developed to evaluate if an available trimming compressor should be started instantaneously.

If a compressor is stopped or tripped, the guide vanes of the running compressors will be set to 100 % to ensure the optimal required ring pressure is maintained. When the network pressure is unstable, the guide vane angles of each compressor will be set to an optimal angle to ensure the compressors deliver compressed air to equal the demand flow and the calculated flow loss. This will be done in an attempt to re-stabilise the network pressure.

Compressor blow-off will also be reduced, as the network pressure will be increased. It is assumed that by increasing the network pressure a trimming compressor can be switched off rather than blow-off occurring.

The verification results were presented to the relevant mine personnel, who approved further testing. A soft commissioning phase was conducted after the approval. The soft commissioning phase was done by controlling the compressed air network according to the proposed control strategy outputs. The results of the commissioning phase will be used to validate the simulation results of the improved control strategy. This will be discussed in the following chapter.

CHAPTER 4. RESULTS AFTER IMPLEMENTATION

4.1 Introduction

In this chapter, the results obtained from implementing the improved control strategy will be discussed. The implementation phase consists of two commissioning phases. The first phase is the soft commissioning phase. This involved controlling the compressed air network manually according to the proposed outputs of the control strategy.

The relevant mine personnel accepted the results obtained from the soft commissioning phase and subsequently the final commissioning phase has commenced. The final commissioning phase involves implementing the control strategy to automatically control the compressed air network. The results obtained in the soft- and final commissioning phase will be discussed in detail.

4.2 Commissioning results

As explained, the soft commissioning phase involves manually controlling the compressed air network according to the proposed control outputs of the control strategy. This is done by evaluating the outputs received from the control strategy and manually entering the outputs on the SCADA system. The following system components are controlled manually during the soft commissioning phase:

- Each consumer's downstream pressure set point;
- Compressors delivery pressure set points;
- Compressor combinations; and
- Compressors guide vane angles.

4.2.1 Pressure set point control

The pressure set point of each major consumer will be controlled according to the strategy developed in section 3.3.2. The control valves at each major compressed air consumer control the downstream pressure according to the pressure set points received. In order to determine the optimal required ring pressure, the pressure requirement of all major consumers has been

evaluated. The compressors' discharge pressure set point has been set to maintain the optimal required ring pressure.

Figure 53 compares the compressors' discharge pressure set point and the ring pressure. To establish if the pressure requirements of the consumers has been matched, the maximum required pressure set point of the major consumers is also illustrated in Figure 53.

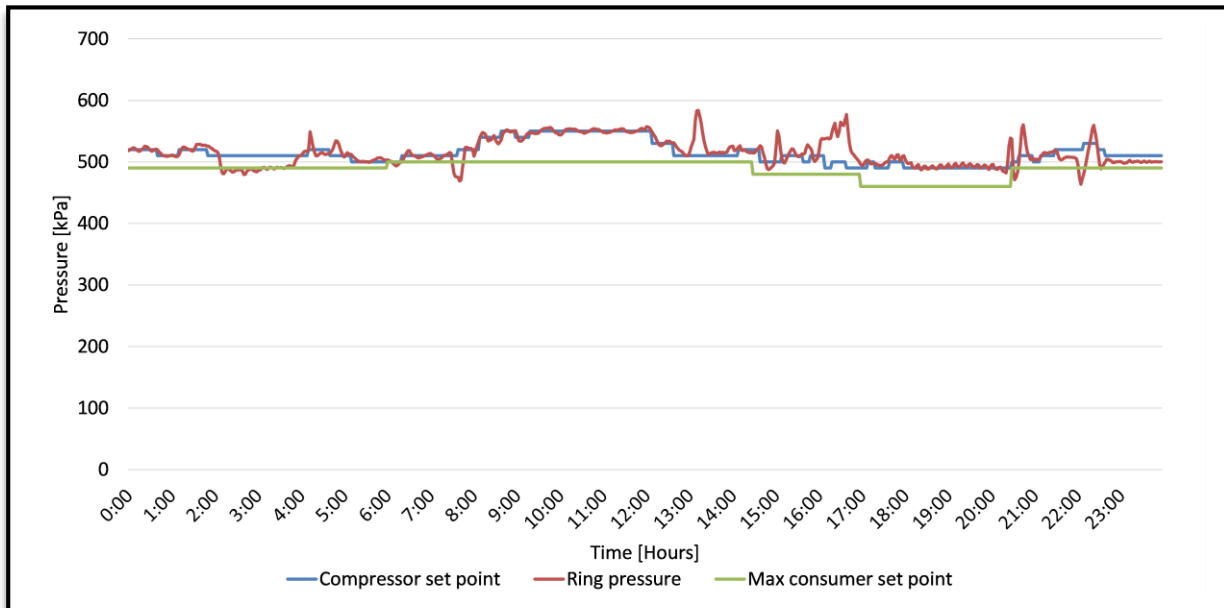


Figure 53: Results for pressure requirements

Pressure drops and losses have been considered, when the optimal required ring pressure was determined. It is for this reason that the ring pressure over-matched the highest consumer's pressure set point during the day. When the pressure profiles in Figure 53 is evaluated, it can be seen that the ring pressure has been maintained according to the compressor's set point. The compressors therefore supplied adequate compressed air to maintain the optimal required pressure throughout the day.

4.2.2 Scheduling of compressors

In order to maintain the optimal required ring pressure, compressors are stopped and started according to the demand flow requirements. Equation 11 is used to calculate the required supply flow. By using Equation 11, the current and future flow demand and pressure requirements are taken into account. Figure 54 illustrates the calculated required supply and demand flow for the day.

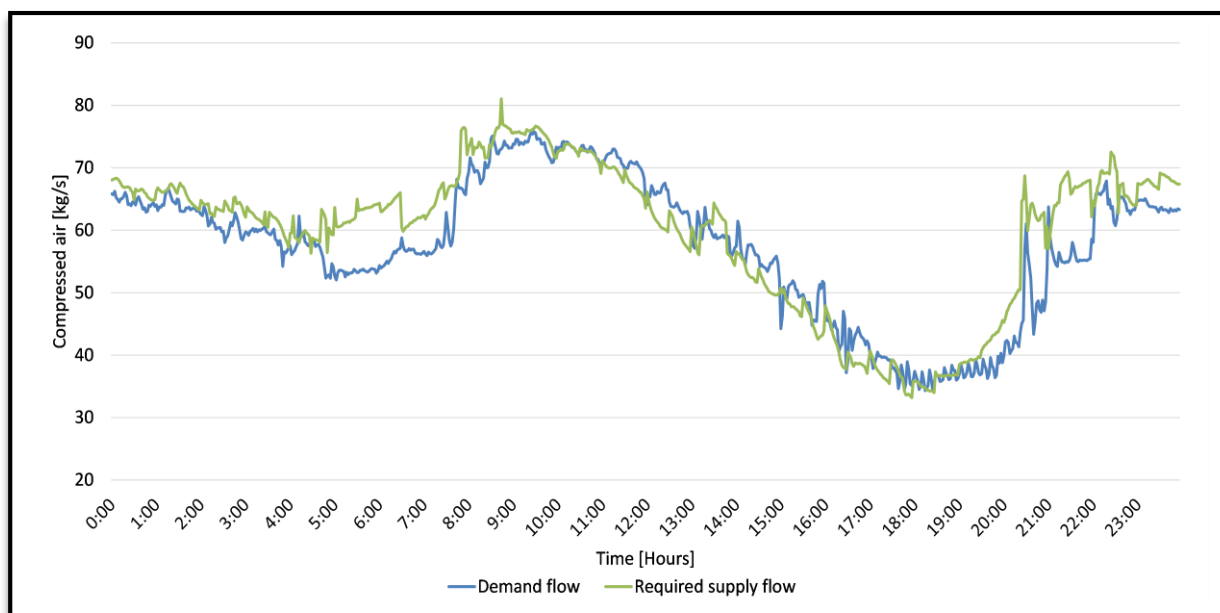


Figure 54: Results for required supply flow and demand flow

From Figure 54, it can be seen the required supply flow has accurately predicted the demand requirements during the day. At certain periods the required supply flow are over and under matching the demand flow. This is a result of the future demand flow and pressure profiles used to calculate the required supply flow. The flow loss is also continuously calculated and taken into consideration.

It is evident that by using Equation 11 an accurate required supply flow can be calculated. During the simulation test discussed in section 3.2.4, the actual conditions did not correspond with what would have happened if the control strategy were executed automatically. To simulate the compressor schedule during the simulation test day, certain assumptions had to be made. Consequently, only the required supply flow condition has been evaluated to simulate the compressor schedules.

In the soft commissioning phase all the conditions discussed in section 3.3.4 have been evaluated to schedule the required running compressors. If a start or stop condition was active, a one would be returned from the internal programmable tag and if the conditions inactive a zero.

The start and stop conditions have been logged. The logged results for the start and stop conditions are illustrated respectively in Figure 55 and Figure 56.

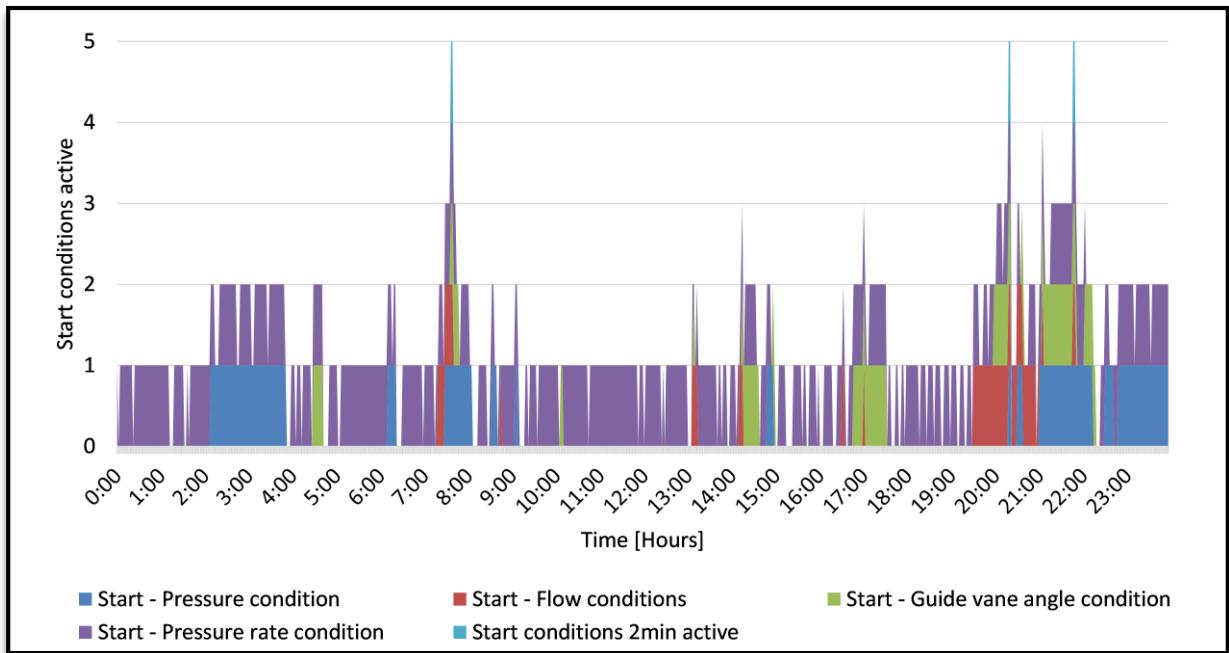


Figure 55: Results for start conditions

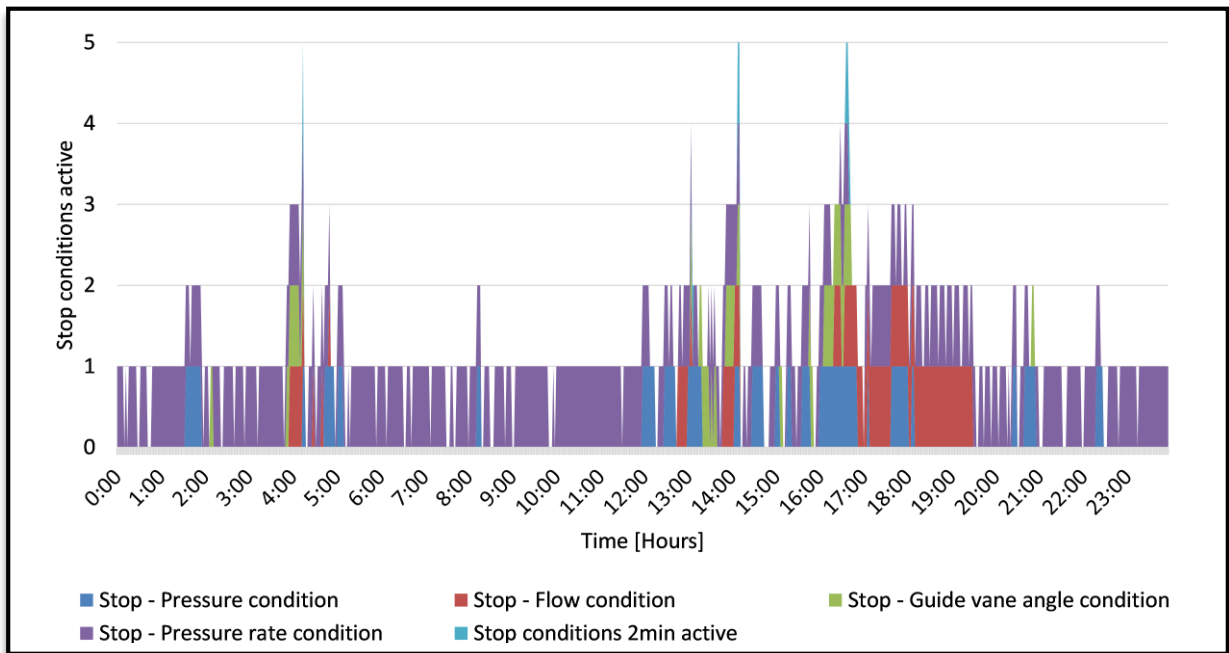


Figure 56: Results for stop conditions

The start and stop condition is used to indicate when the prioritised trimming compressors should be stopped or started. The compressors that was scheduled to run during the day are illustrated in Figure 57.

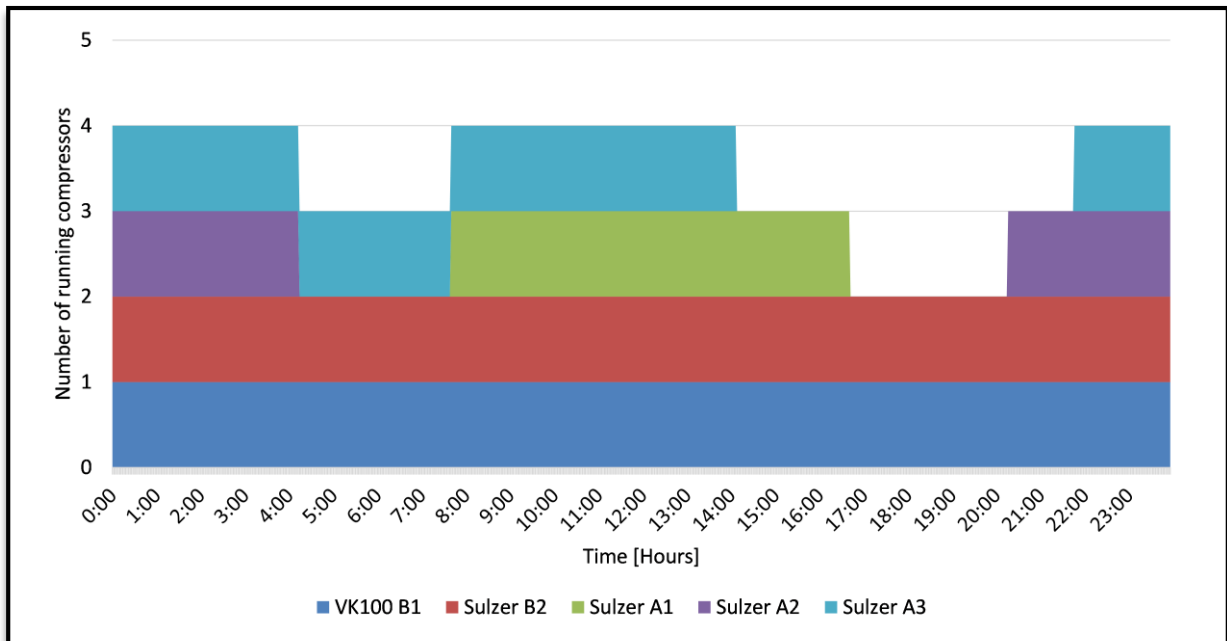


Figure 57: Results for compressor scheduling

The trimming compressors were prioritised to start and stop adequately during the day. The trimming compressor that was off for the longest period was the trimming compressor that was started when required. This can be seen from Figure 57, at approximately 8:00 the Sulzer A1 was prioritised to start, rather than the Sulzer A2. The Sulzer A2 was running earlier and therefore the Sulzer A1 was started.

When the running period of the Sulzer A1 is compared to the running period of the Sulzer A3 at approximately 14:00, it is clear the Sulzer A3 has been on for a longer period. It is for this reason the Sulzer A3 was the trimming compressor that was prioritised to stop. The correct trimming compressor was therefore prioritised to stop and start during the day.

The compressors were not only prioritised correctly but have also been stopped and started as the requirements of compressed air changes during the day. This can be seen in Figure 58, which illustrates the actual supply and demand flow.

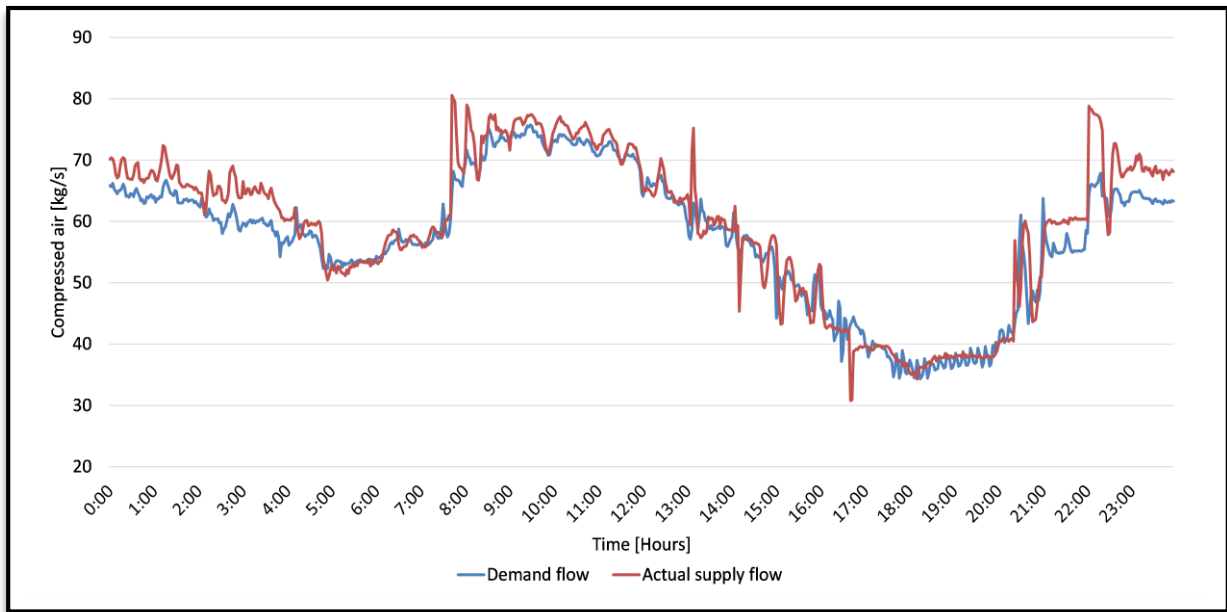


Figure 58: Results for supply and demand flow

When the supply and demand flow are compared in Figure 58, it can be seen that the supply has matched the demand flow during the entire day. Some fluctuations can be observed at certain periods during the day. This is the result of compressor combinations changing and/or operating shifts changing.

The supply flow fluctuations are caused before a compressor has been stopped. As explained in section 3.3.5 the guide vane angle of the running compressors is set at 100%. The compressors have therefore over-supplied the network for those specific periods. In addition, before a compressor is started, the running compressors are delivering maximum flow. With the additional compressor started, the supply flow over-matched the demand flow significantly.

Even with the fluctuations in supply flow, it is evident that the compressors have accurately supplied the demand flow throughout the entire day. An improvement in compressed air supply control is evident. This can be observed when Figure 58 is compared with the actual supply and demand flow of the simulation test day in Figure 49 (Section 3.4).

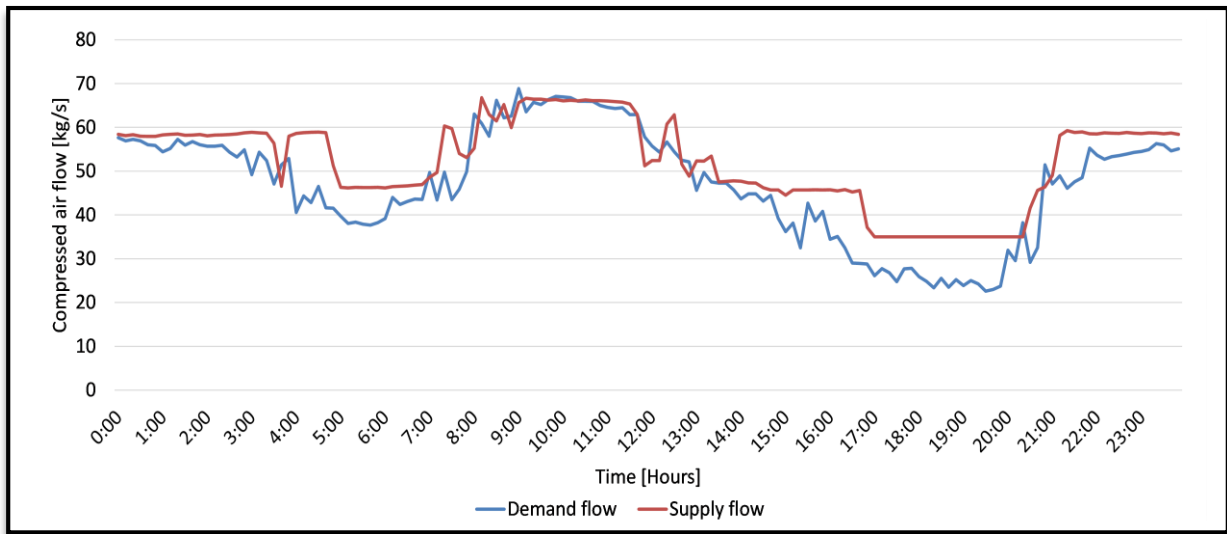


Figure 49: Actual supply and demand flow

The matching of supply and demand flow is far more accurate in Figure 58 when compared to Figure 49. However, the fluctuations in supply flow will cause an unstable network pressure, which is undesirable. The guide vane stability control developed in section 3.3.5 has therefore been tested in order to re-stabilise the network pressure. This will be discussed in the following section.

4.2.3 Compressors guide vane angle control

As explained in section 3.3.5, the guide vane angles of the compressors will be controlled from the PLCs through P&ID control loops in stable conditions. When a compressor is stopped, there is a significant gap in the supply flow range of the new compressor combination. Therefore, the guide vane angles of the running compressors have been set to a 100 % before the stop in order to provide the required supply flow.

When Figure 58 is evaluated, it is evident that the supply flow matches the demand flow adequately throughout the entire day. Therefore, by setting the compressors guide vane angle at 100 % before a compressor is stopped, the supply flow adequately matches the demand after the compressors have been stopped. To further improve the compressed air network, the network pressure has been stabilised when there are major disturbances in the system.

This has been achieved by setting the guide vane angles of each compressor to the calculated optimal positions. Condition 1 and condition 2, defined in section 3.3.5 have been developed to determine when this must happen.

For the soft commissioning phase, when the stability control has been triggered the guide vane angles of each running compressor is set to the calculated optimal positions on the SCADA. This is done to test if the guide vane stability control will stabilise the network pressure. During the soft commissioning, there was numerous times when the guide vane stability control was triggered. Figure 59 illustrates each particular time condition 1 or condition 2 was active.

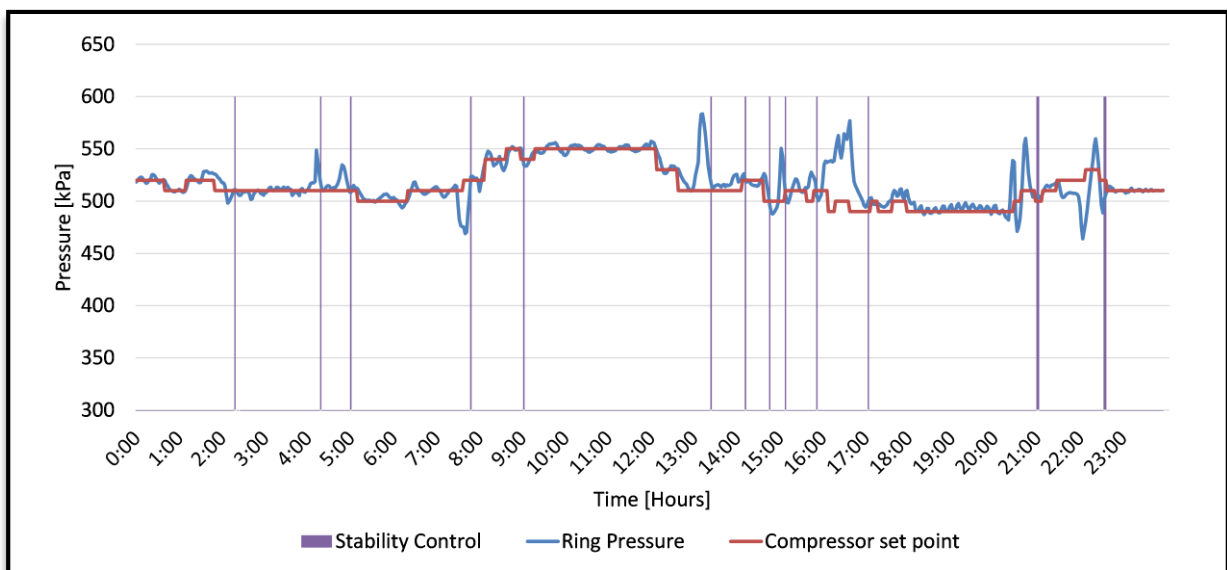


Figure 59: Pressure stability control

In each particular time, the running compressor's guide vane angles have been set to the calculated optimal positions. To illustrate the effect of the guide vane stability control in more detail the following two cases will be discussed.

The first case is where the guide vane stability control has been triggered because condition 1 was active. Figure 60 illustrates the ring pressure and compressor set point between 07:30 and 8:00 for the soft commissioning test day. In Figure 60 on the secondary axis, the corresponding pressure rate of change is illustrated and the moment the guide vane stability control has been triggered.

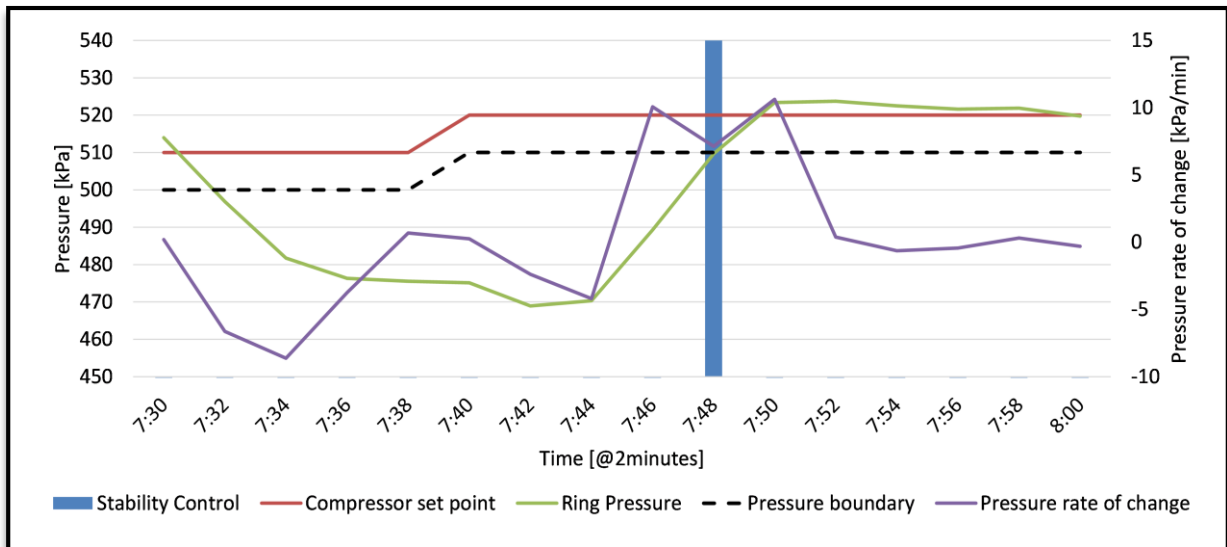


Figure 60: Results for guide vane angle stability control – Condition 1

When Figure 60 is compared with Figure 55 it can be seen that all the start conditions have been active at approximately 07:44 and therefore an additional compressor was started. When the additional compressor was started, the supply flow over-supplied the compressed air network. Consequently, the ring pressure and the pressure rate of change increased which is visible on Figure 60.

The P&ID control loops programed in each compressors PLC kept the guide vane angle of each compressor at 100% to supply maximum flow to increase the ring pressure to the set point. However, because an additional compressor has started, the supply flow is significantly higher than the demand. The ring pressure therefore increases at a rate of 10 kPa/min. If the guide vane angles are not adjusted, the ring pressure will increase far above the required pressure set point. Adjusting the guide vane angles to prevent this from happening is the main objective of the guide vane stability control.

Once the optimal guide vane angles have been set for each compressor the ring pressure stabilised within four minutes. This is evident when the pressure rate of change before the guide vanes have been adjusted (07:48) is compared to the pressure rate of change after the guide vanes were adjusted (07:52). The pressure rate of change was stable after the guide vane angles were adjusted and in addition, the network pressure acutely matched the required pressure set point.

If the guide vanes angles are adjusted to early, the ring pressure may not reach the required set point. It is for this reason that the stability control is triggered once the ring pressure is within the 10 kPa boundary illustrated on Figure 60.

Figure 61 illustrates the second case where the guide vane stability control has been triggered because condition 2 was active. Figure 61 illustrates the ring pressure and compressor set point between 13:10 and 13:40 for the soft commissioning day. The corresponding pressure rate of change and the moment the guide vane stability control is triggered is also included in Figure 61.

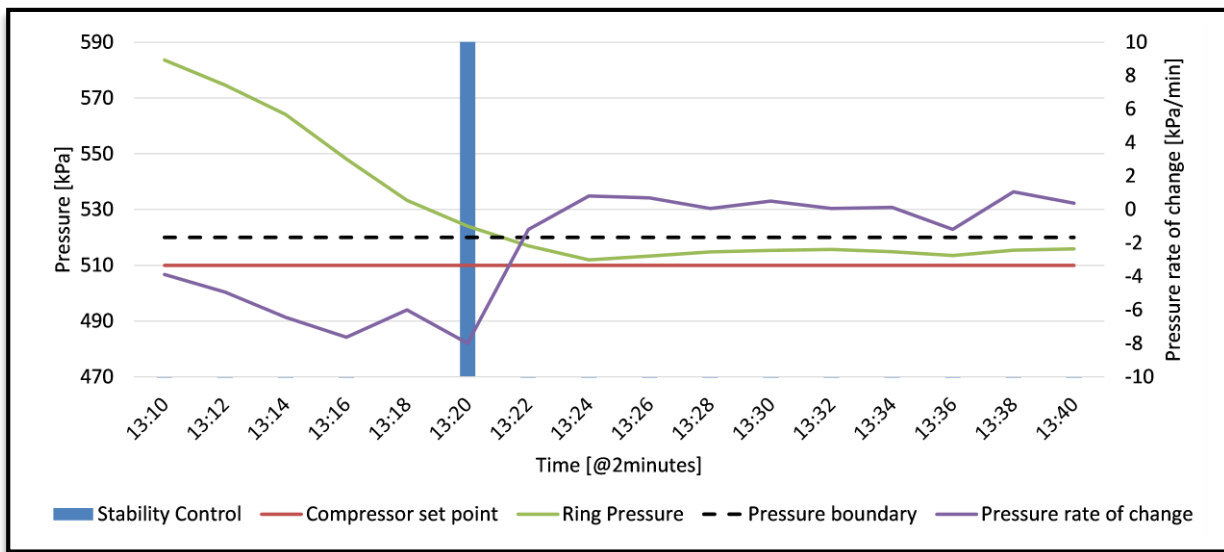


Figure 61: Results for guide vane angle stability control – Condition 2

For the second case, the ring pressure is far above the required pressure set point. The P&ID control loops programed in each compressors PLC adjusted the guide vane angle of each compressor to a minimum position. This is done to ensure the supply flow is reduced in order to decrease the ring pressure to the pressure set point. The pressure rate of change therefore decreased at a rate of 7 kPa/min.

As soon as the ring pressure is within the 10 kPa pressure boundary, the guide vane stability control has been triggered. The optimal guide vane angles of each compressor was adjusted according to the optimal position and within two minutes, the ring pressure has stabilised. This can be observed in Figure 61.

4.2.4 Compressor trip

As discussed in section 3.3.3, compressors trip on occasion. In a situation where this occurs the guide vane angles of each compressor will be set to 100% instantaneously. This will ensure that the running compressor is supplying maximum flow after the trip occurred. If the supply capability of the running compressor does not meet the demand flow requirements, an available trimming compressor will be started.

In order to demonstrate this control, a day is considered where the Sulzer B1 has tripped. The compressor tripped at approximately 13:56. Figure 62 illustrates the ring pressure and the required pressure set point during the compressor trip phase.

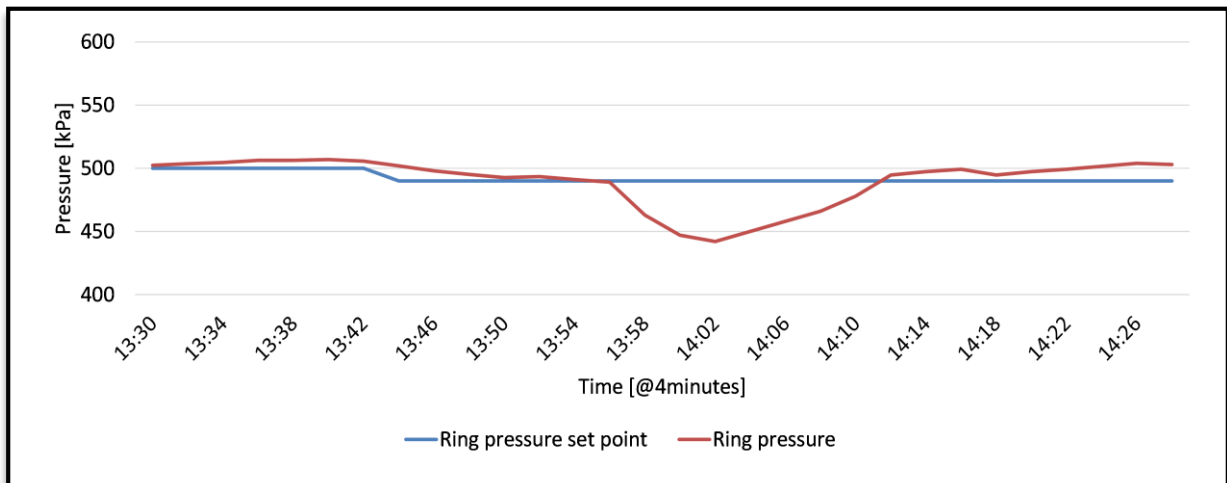


Figure 62: Ring pressure vs. Ring pressure set point

It can be seen in Figure 62, the ring pressure dropped rapidly after the compressor tripped. The guide vane angles of the running compressors have been set at 100% after the trip. With the compressors supplying maximum compressed air, it was still not enough to maintain the required pressure. It was therefore required to start an available trimming compressor. Figure 63 illustrates the compressor combination during the compressor trip phase.

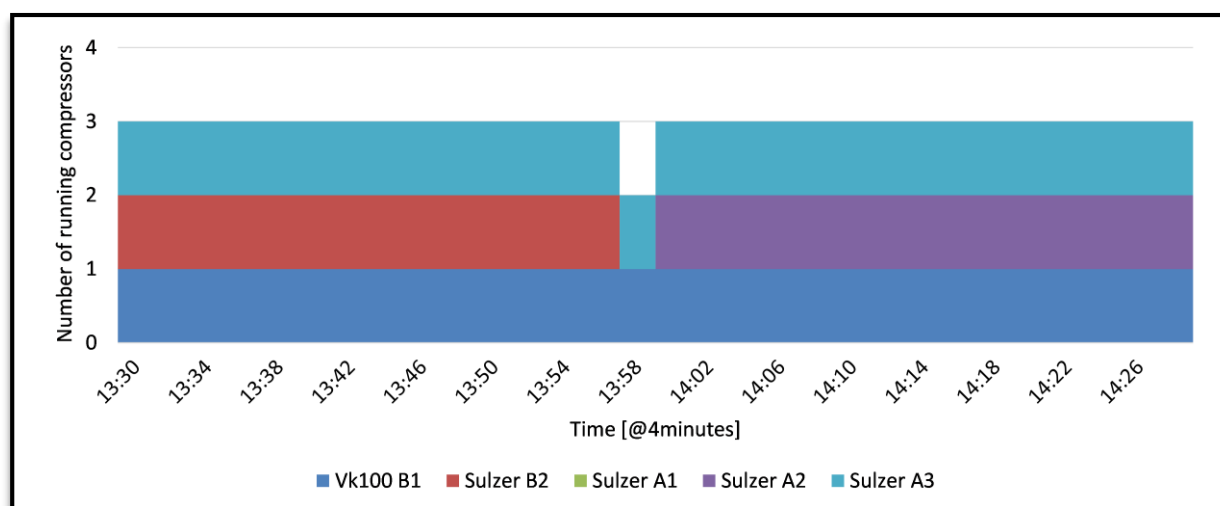


Figure 63: Sulzer B2 trip

Figure 62 illustrates the moment the Sulzer B2 tripped and the moment the Sulzer A2 was started. After starting an additional trimming compressor the supply flow matched the demand and the ring pressure can be maintained according to the pressure set point. The controller reacted instantaneously after the trip, which ensured that the compressed air supply is controlled to adequately match the demand requirements automatically. In an event of a compressor tripping the production will not be affected by executing the control discussed.

4.2.5 Summary

The relevant mine personnel approve the results obtained from the soft commissioning phase. The final commissioning phase was commenced. This involves implementing the control strategy to automatically control the compressed air network. The necessary communication to relay control output commands was established. The control strategy could therefore automatically control the compressed air network. The following control outputs could be relayed to the equipment's PLCs:

- Each consumer's downstream pressure set point;
- Compressors discharge pressure set point;
- Compressor's running status; and
- Compressor's guide vane angle set points.

The control strategy improved the overall efficiency of the compressed air network. The compressors discharge pressure set point was dynamically changed as the pressure requirements of the major consumers changed.

The required pressure set point was maintained by selecting the correct compressor combinations as the requirements of compressed air change. The supply flow matched the demand flow accurately. The guide vane stability control further increased the efficiency by ensuring a stable network pressure was maintained. The electrical cost impact after the strategy was implemented will be discussed in the following section.

4.3 Control strategy impact after implementation

With the improved control strategy successfully implemented, the cost impact of the project can be evaluated. This is done by evaluating the power consumption before and after implementing the project. A pre-implementation power profile is calculated by averaging the weekday power consumption over a period of three months. The three-month period is from September 2015 to November 2015.

As discussed in section 1.3, this project was submitted to Eskom as an evening peak clipping project. The performance assessment phase of this project started in May 2016. This involves an independent third party evaluating the project's performance for three months to determine if the proposed electrical saving target has been achieved. The energy target submitted to Eskom is 1.65 MW.

Figure 64 illustrates the pre-implementation power profile and post-implementation power profile. The post-implementation power profile is the average weekday power consumption from May 2016 to July 2016.

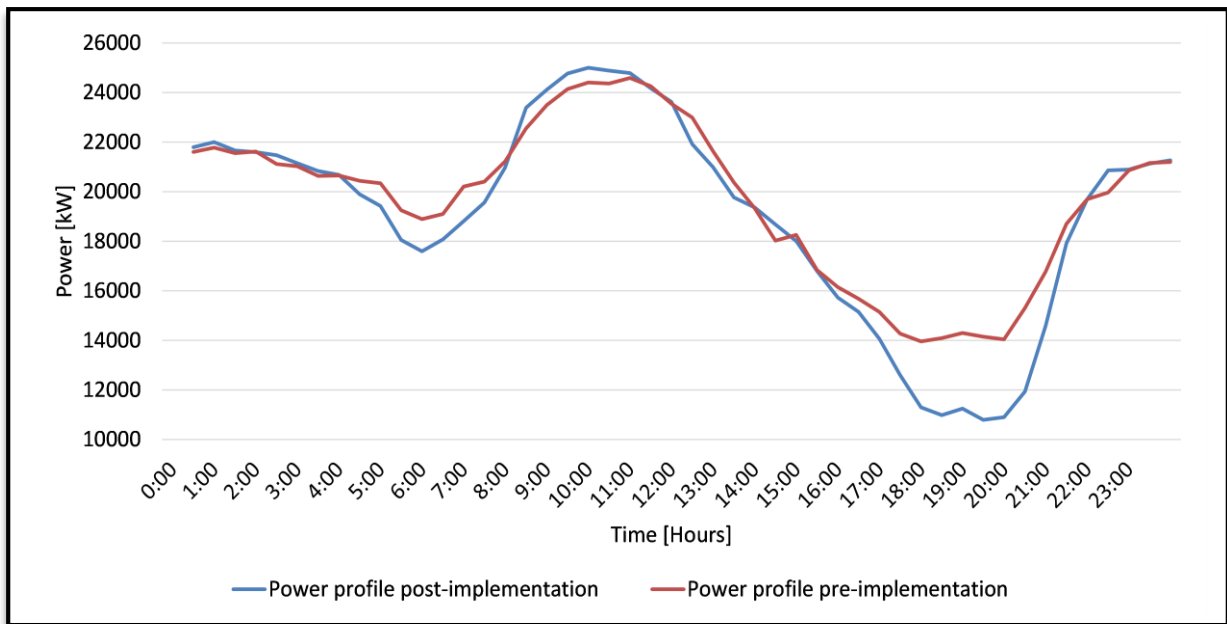


Figure 64: Electrical cost impact after implementation

It is evident from Figure 64 that the implementation of the control strategy has improved the energy efficiency of the compressed air network. Not only has the implementation of the control strategy achieved a peak clip saving but it has also optimised most of the power usage during the day. The electrical impact of the first performance assessment period is illustrated in Table 6.

Table 6: Power savings achieved

	May-16	Jun-16	Jul-16
Average evening impact [kW]	3572	3050	3270
Average daily impact [kW]	618	559	649
Total energy saving [MWh]	420	323	383

From Table 6 it is clear that that the control strategy has improved the energy efficiency of the compressed air network. An average evening peak saving of 3.3 MW was achieved over a period of three months. This proves the control strategy can achieve sustainable savings.

4.4 Study validation

4.4.1 Simulation results

A detailed investigation has been conducted to verify the feasibility of the control strategy developed in section 3.3. Real time data was used to simulate a proposed compressor schedule. The results was used to gain the confidence of the relevant mine personnel and to motivate further testing of the proposed control strategy. Figure 65 illustrates the proposed power profile obtained from the simulation and the actual three-month average power profile, post-implementation.

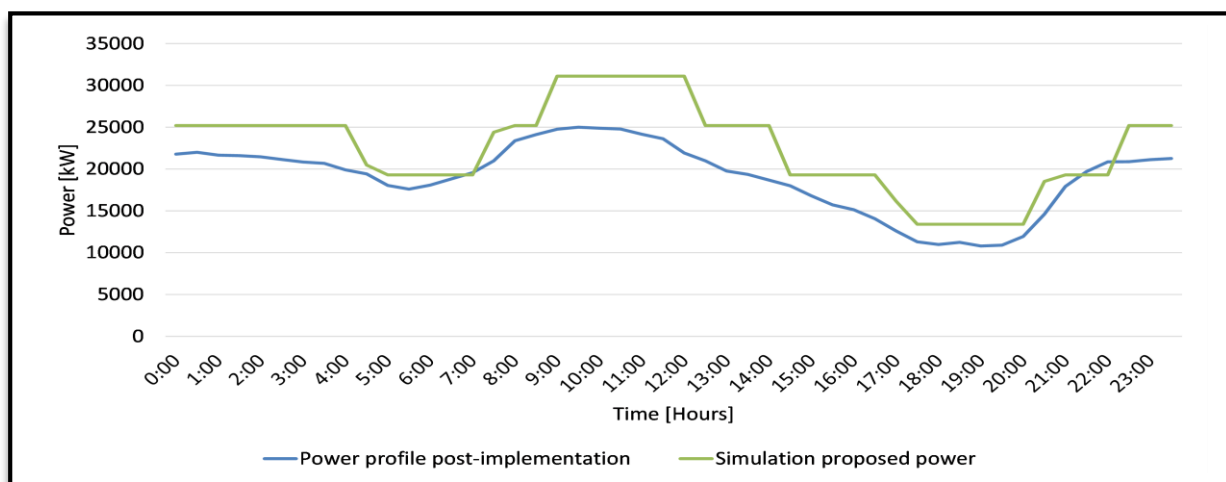


Figure 65: Simulated and post-implementation power profile

The power saving achieved with the simulation test day shows that an average peak clip saving of 1.4 MW is possible. As discussed in section 4.3, after implementation an average peak clip saving of 3.3 MW has been achieved over the three-month performance assessment period.

The reason for the difference in the actual savings and simulated savings are the following:

- Certain assumptions was made to determine the proposed compressor schedule; and
- The proposed power profile is obtained by assuming the compressors operated at the full power capacities.

As explained in section 3.4, only the required supply flow condition has been evaluated to simulate a proposed compressor schedule. After automating the compressors control all the stop and start conditions was evaluated. Furthermore, the compressors running did not operate at full capacity during the day. It is for this reason the simulated savings differ from the actual power savings.

4.4.2 Compressor characterisation

As explained in section 3.3.4, characteristics curves has been determined for each compressor. These characteristic curves are determined by a scattered plot of the compressor's delivery flow at different guide vane angles. A quadratic equation is determined by using regression modelling on the scattered plot. The flow delivered at any given guide vane angle of each compressor can be determined by using the quadratic equations.

The quadratic equations for each compressor is listed in Table 5. These quadratic equations are used to determine if new compressor combinations will supply adequate compressed air to match the compressed air demand. The quadratic equations are further used to determine the optimal guide vane angle of each compressor, which has been used to stabilise the network pressure.

The compressors characterisation is therefore a crucial part of the development of the control strategy. To determine if the regression models reflect actual conditions the actual supply flow of each compressor has been compared with the flow calculated by using the quadratic equations.

The regression model flow was calculated by using the actual guide vane angle of each compressor. Figure 66 to Figure 68 illustrate this comparison for the VK100 B1, Sulzer B2 and the Sulzer A1-3 combinations respectively.

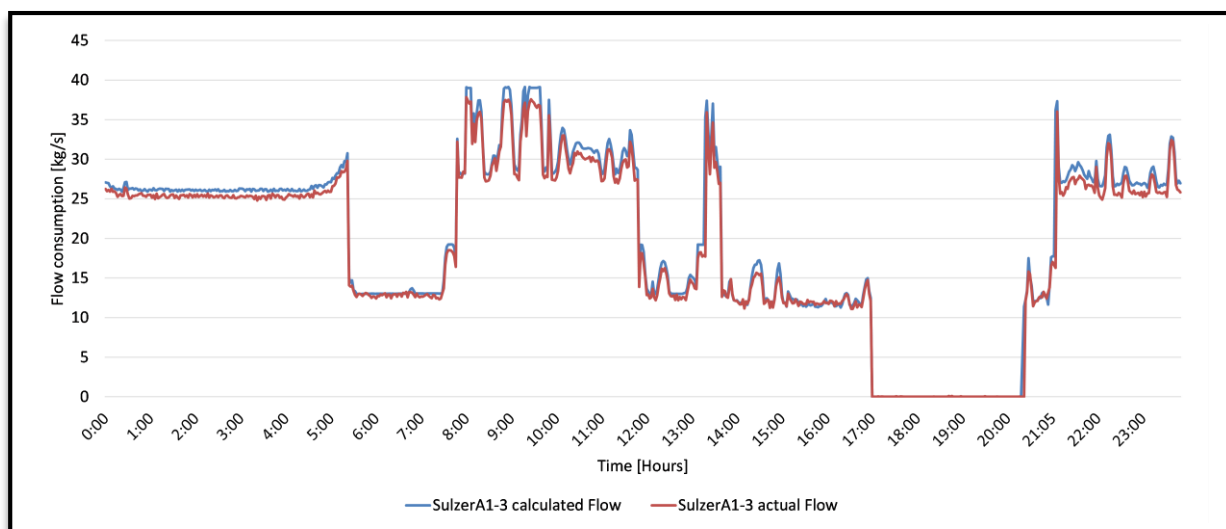


Figure 66: Regression model flow vs. actual flow for Sulzer A1-3

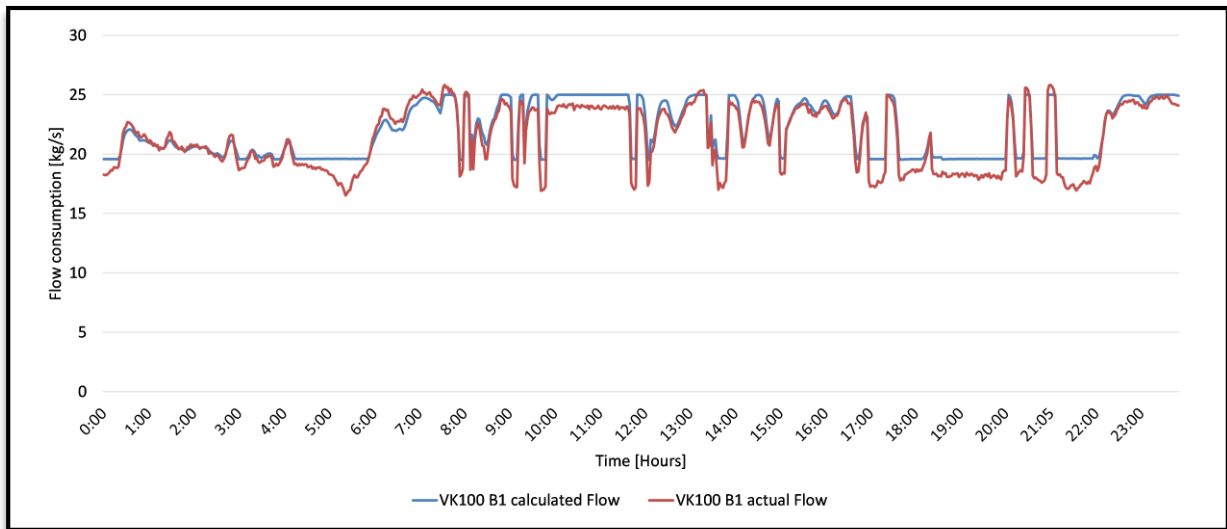


Figure 67: Regression model flow vs. actual flow for VK100 B1

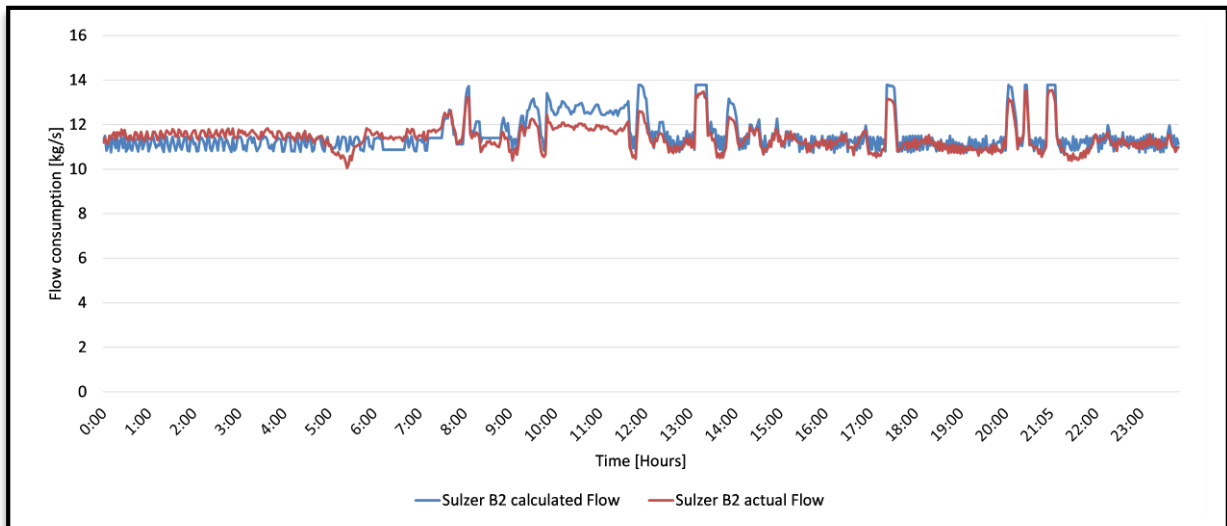


Figure 68: Regression model flow vs. actual flow for Sulzer B2

By focusing on Figure 66 to Figure 68, it is clear that the supply flow determined by using the regression models is a close match to the actual measured supply flow. If the regression models are not accurate, incorrect compressor combinations will be operated and the optimal guide vane angles of each compressor will be imprecise.

The accuracy of the regression models therefore directly affects the accuracy of the developed strategy. The percentage error for each compressor's regression model is listed in the Table 7:

Table 7: Regression model accuracy

Regression model flow percentage error	
SulzerA1-3	3.8%
VK100 B1	3.0%
Sulzer B2	0.9%

An average percentage error of 2.6% is realised by the regression models. It is evident that this is a small percentage. The characterisation of the compressors has therefore been done accurately. The percentage error of each compressor's regression model must be monitored to ensure the output command of the control strategy remains precise.

4.5 Conclusion

In this chapter, the results of the commissioning phase have been discussed. The results have been evaluated for the soft commissioning phase. Improved compressor pressure set point control and compressor scheduling have been achieved in the soft commissioning phase. The compressed air network has been further improved by controlling the guide vane angles of the compressors in order to maintain a stable network pressure.

After the soft commissioning phase, the results were discussed with the relevant mine personnel. With the approval of the mine personnel, the control strategy has been commissioned. This resulted in compressors discharge pressure set points being controlled automatically. The most efficient compressor combination has also been scheduled to operate automatically.

The chapter proved that the control strategy improved the energy efficiency of the compressed air network successfully. Lower overall power usage has been achieved by implementing the improved control strategy.

CHAPTER 5. CONCLUSION



Figure 69: Mineworker on the job [76]

5.1 Summary

It has been found that compressed air network has been controlled manually according to predetermined set points. Due to the dynamic nature of compressed air networks, this resulted in inefficiencies. Compressors that was operated, over-supplied the compressed air network, which resulted in the network pressure being maintained at a higher pressure than required. If the control of supply of compressed air is improved, significant energy savings can be achieved.

A detailed investigation has therefore been conducted, in order to identify measures to optimise the control of a compressed air network. Both the demand and supply of compressed air have been characterised to fully understand the fundamentals in order to improve compressed air networks. With Eskom introducing the DSM programme, various projects have been implemented on the supply and demand side of compressed air networks. These DSM project was identified and fully discussed in Chapter 2.

It has been made clear in order to optimise the compressed air network, the demand and supply need to be integrated. The supply must therefore be controlled to accurately match the changing demand. This will improve the energy efficiency of compressed air network and the potential energy saving can then be realised.

Compressed air is widely used in Industries and therefore various control strategies to improve compressed air networks have been developed. The DCS controller is identified as a compressor control system that is able to integrate the demand and supply side of a compressed air network. The DCS controller is able to automatically control the supply of compressed air by evaluating the continuously changing requirements of the demand side.

However, in order to implement the DCS controller on a compressed air network certain infrastructure is required. A gold mining complex has therefore been identified with the required infrastructure already installed. The DCS controller has been implemented to determine if the controller is able to optimise the compressed air network.

The mine personnel had some concerns with automating compressor control and therefore defined operation constraints that have to be adhered to. Unfortunately, the simulation results obtained from the DCS controller have not obeyed the operational constraints set by the mine personnel. An improved control strategy has therefore been developed.

Communication to different equipment and field instrumentation has already been established by the implementation of the DCS controller. The required process data is received in real time and control commands could be relayed to equipment. Therefore, the improved control strategy uses the DCS controller as a backbone for the established communication links. Internal programmable tags within the GUI of the DCS controller was used to develop the new control strategy.

The new control strategy has determined compressor pressure set points. This has been achieved by characterising the demand side to adequately evaluate the requirements of the consumers. The effect of auto compression, flow loss, pressure drop and frictional loss have been considered to calculate an optimal required network pressure. The DCS controllers' predicted flow and pressure profiles have also been used to estimate future requirements. An accurate required supply flow and pressure set point are determined.

The supply side has also been characterised in order to schedule efficient compressor combinations to ensure the required supply flow and pressure set point is maintained. Start and stop priorities are allocated to compressors and certain conditions are set up in order to determine when it is required to stop or start a compressor. The improved control strategy is therefore able to control the compressed air supply pressure and flow according to the continuously changing demand for compressed air.

As part of the new control strategy, the inlet guide vanes of running compressors will be controlled when major disturbances on the demand side occur. The inlet guide vanes of compressors has been set to optimal positions for different scenarios. This ensured a stable network pressure, which has consequently resulted in an improved compressed air network efficiency.

Compressors blow-off has also been reduced by re-programming each compressors PLC. The control on PLC level, involves adjusting the inlet guide vanes of compressors that operated near blow-off conditions. The compressors will therefore not blow-off and as a result, the network pressure has increased. This has consequently led to stopping compressors earlier than before.

The improved control strategy has been commissioned in two phases. The first phase involves the soft commissioning phase, which entails manually controlling the compressed air network according to the proposed control outputs of the control strategy. The results obtained in the soft commissioning phase verifies the developed strategy. Therefore, the final commissioning phase has commenced. This involves implementing the control strategy to automatically control the compressed air network.

The control strategy has been successfully implemented. The necessary communication to relay control output commands have been established. The following control outputs can successfully be relayed to the equipment's PLCs:

- Control valves pressure set point;
- Compressors discharge pressure set point;
- Compressor's running status; and
- Compressor's guide vane angle set points.

The control strategy has improved the energy efficiency of the compressed air network significantly. An average evening peak saving of 3.3 MW has been achieved over a period of three months. This has validated the control strategy and proved that the control strategy can achieve sustainable savings.

5.2 Recommendations for future work

When the results after implementing the control strategy are considered, it can be said that the control strategy has been successfully implemented. The automatic control of compressed air supply accurately matches the demand for compressed air, which has resulted in significant energy savings.

Although the control strategy has optimised the compressed air network of Mining Complex A, further improvement is possible. Installing two smaller compressors to replace the two 15 MW Sulzer compressors at Shaft C would allow a closer supply-to-demand matching. This will eliminate the flow gap that is currently encountered when transitioning from different trimming compressors.

As discussed in section 3.3.2, the downstream pressure set points for the control valves at each consumer will be relayed from the DCS controller. The underground control valves at each mining shaft could also be controlled through the DCS controller. The optimal required pressure set point can then be determined by evaluating not only the major mining levels but also every mining level on the entire mining complex. This will result in complete integration of the compressed air network demand.

The control strategy can also be optimised. The characterising of compressors supply capacity is done manually at the moment. If the characterisation could be automated to update continuously, the time it will take to implement the control system on other compressed air network will also be reduced.

This study has proved that significant savings can be achieved on compressed air network, if the supply adequately matches the demand. The systematic approach used to develop the control strategy can be used to optimise other major energy consumers on mines. The systematic

approach followed in this study has involved characterising the demand and supply side. Cost saving strategies have then been identified and integrated in order to optimise the entire system.

This systematic approach can be used to optimise, for example the cooling and ventilation system used at deep level mines. The demand and supply for cooling and ventilation can theoretically be characterised. If the characterisation of the demand and supply correlates with actual conditions, the supply can be optimised in order to adequately match the demand. As mentioned in section 1.1, cooling and ventilation use approximately 28% of a mine's total electricity. By optimising the supply, significant energy savings can be achieved.

CHAPTER 6. BIBLIOGRAPHY

- [1] Line of Lode Association, “Mining Photos from the Past,” Lovell New Media, 2002. [Online]. Available: <http://www.oocities.org/bhsilvercity/photos.htm>. [Accessed 02 November 2016].
- [2] G. Tchetvertakov, “Global mining sector trending for change,” Finfeed, 13 November 2015. [Online]. Available: <http://finfeed.com/hot-topics/global-mining-sector-trending-for-change/20151113/>. [Accessed 16 September 2016].
- [3] N. Christos and J. Zhou, “Bull and bear markets in commodity prices and commodity stocks: Is there a relation?,” *Resources Policy*, vol. 43, pp. 61-81, 2015.
- [4] K. Iskyan, “The solution to low commodity prices,” Truewealth Publishing, 10 December 2015. [Online]. Available: <http://truewealthpublishing.asia/truewealth-asian-investment-daily/the-solution-to-low-commodity-prices/>. [Accessed 24 August 2016].
- [5] L. Stilwella, R. Minnittb and T. Monsonc, “An input–output analysis of the impact of mining on the South African economy,” Department of Mining Engineering, Sandton, South Africa, 2010.
- [6] Reuters, “Job cuts to escalate in South African mines as glabal economy slows,” EWN, 15 February 2016. [Online]. Available: <http://ewn.co.za/2016/02/15/Job-cuts-to-escalate-in-South-African-mines-as-global-economy-slows>. [Accessed 05 August 2016].
- [7] M. Rego, “Gold Miners Get A Boost From Lower Oil Prcies,” Seeking Alpha, 9 February 2015. [Online]. Available: <http://seekingalpha.com/article/2899746-gold-miners-get-a-boost-from-lower-oil-prices>. [Accessed 12 August 2016].
- [8] Eskom, “Eskom's integrated report,” Eskom, 31 March 2015. [Online]. Available: <http://www.eskom.co.za/IR2015/Documents/EskomIR2015single.pdf>. [Accessed 07 August 2016].
- [9] M. I. Howells, “The targeting of industrial energy audits for DSM planning,” *Energy in Southern Africa*, vol. 17, no. 1, pp. 58-69, 2006.
- [10] L. van der Zee, “Modelling of electricity cost risks and opportunities in the gold mining industry,” Ph.D Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2014.

- [11] U.S. Department of Energy, "Improving compressed air system performance: A sourcebook for industry," Efficiency and Renewable Energy Program, Washington, United States of America, 2003.
- [12] R. Saidur, N. Rahim and M. Hasanuzzaman, "A review on compressed-air energy use and energy saving," *Energy Reviews*, vol. 14, no. 4, pp. 1135-1153, 2010.
- [13] J. de la Vergne, "Hard Rock Miner's Handbook," Ontario: McIntosh Engineering, 2003.
- [14] H. Nesor, "Energy savings through the automatic control of underground compressed air demand," M.Eng Dissertation, School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom, South Africa, 2008.
- [15] J. W. Lodewyck, "Investigating the effects of different DSM strategies on a compressed air ring," M.Eng Dissertation, School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom, South Africa, 2007.
- [16] A. J. M. van Tonder, "Automation of compressor networks through a dynamic control system," Ph.D Thesis, School of Electrical, Electronic and Computer Engineering North-West University, Potchefstroom, South Africa, 2012.
- [17] P. A. de Villiers, R. P. Coetzee and L. J. Grobler, "Measurement and verification methodology for industrial compressed air load management on a mine," in *Proceedings of the Sixth Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 2009.
- [18] J. H. Marais, "An integrated approach to optimise energy consumption of mine," Ph.D Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2012.
- [19] J. C. Vosloo, "A new minimum cost model for water reticulation systems on a South African mine," Ph.D Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South, 2008.
- [20] A. Whillier, "Hydraulic rock drills and their effect on the underground environment," SAIMM conf, 1975.

- [21] B. . L. Capehart, “Compressed air systems,” *Encyclopedia of Energy Engineering and Technology*, vol. 2, no. 3, pp. 236-245, 2007.
- [22] R. N. Brown,, “Compressors: Selection and Sizing,” Gulf Professional Publishing, Houston, United States, 1997.
- [23] A. J. Schutte, M. Kleingeld and J. Vosloo, “Various procedures to reduce a mine's compressed air usage,” in *Proceedings of the Eighth Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 2011.
- [24] H. P. R. Joubert, G. D. Bolt and J. F. van Rensburg, “Energy savings on mining compressed air networks through dedicated process plant compressors,” in *Proceedings of the Ninth Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 2012.
- [25] Atlas Copco, “Secoroc YT29A Pusher Leg Rock Drill – Operator’s instructions,” 25 April 2013. [Online]. Available: <http://www.atlascopco.com/rockdrillingtools/news/rockdrills/>. [Accessed 12 August 2016].
- [26] Trident S.A., “LM57 AIR LOADER,” [Online]. Available: <http://www.tridentsa.co.za/LM57.html>. [Accessed 09 August 2016].
- [27] L. Padachi, “Energy efficiency through the integration of compressed air supply control with air network demand control,” in *Proceedings of the Sixth Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 2009.
- [28] R. Inglesi, “Aggregate electricity demand in South Africa: Conditional forecasts to 2030,” *Applicational Energy*, vol. 87, no. 1, pp. 197-204, Jan 2010.
- [29] E. Bonneville and A. Rialhe, “Demand side management for residential and commercial end-users,” *Efficiency & eco-design*, p. 2, May 2016.
- [30] Eskom, “Tariff & Charges Booklet 2014/15,” Eskom, 31 March 2015. [Online]. Available: <http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/TariffBrochureV9.pdf>. [Accessed 07 August 2016].

- [31] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Transactions on Industrial Informatics*, vol. 3, no. 7, pp. 381-388, 2011.
- [32] M. R. Muller and S. C. Schultz, "Wise rules for industrial efficiency: A tool kit for estimating energy savings and greenhouse gas emissions reductions," *Climate Wise*, July 1998.
- [33] AIRMaster, "AIRMaster compressed air system audit and analysis software version 1.4," *Analysis methodology manual for AIRMaster*, p. 32, 1997.
- [34] R. Christie, "Electricity, industry and class in South Africa," Macmillan : in association with St Antony's College, Albany, United State of America, 1984.
- [35] A. Bhatia, *Compressed Air Energy Efficiency*, Stony Point, NY: Continuing education and development inc, 2008.
- [36] P. Hanlon, *Compressor Handbook*, New York, NY: McGraw-Hill, 2001.
- [37] F. B. Horowitz, B. P. Gupta and B. G. Liptak, *Instrument Engineers' Handbook*, 4 ed., vol. 2, CRC Press, 1970, pp. 1763-1793.
- [38] F. Willems, W. P. M. H. Heemels, B. D. Jager and A. A. Stoorvogel, "Positive feedback stabilization of centrifugal compressor surge," *Automatica*, vol. 38, no. 2, pp. 311-318, Feb 2006.
- [39] M. van Niekerk, "The implementation of a dynamic air compressor selector system in mines," M.Eng Dissertation, School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [40] J. Wilson, A. Sheldon and D. Moines, "Matching antisurge control valve performance with integrated turbomachinery control systems," *Hydrocarbon processing*, pp. 55-58, Aug 2006.
- [41] R. Joubert, "Cost and time effective DSM on mine compressed air systems," M.Eng Dissertation, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2010.
- [42] L. Berkele, "Improving Compressed Air System Performance: A," US Department of Energy, 2nd ed., Washington DC, United States of America, 2004.

- [43] R. Mclin, "Approaching compressor control retrofits improving the compressor control algorithms," Instrumentation Symp. Process Ind, Houston, United States of America, 2012.
- [44] Moore Industries International, "Advanced compressor control & protection solutions," Moore Industrial Automation and Optimisation, Johannesburg, South Africa, 2016.
- [45] J. Venter, "Development of a dynamic centrifugal compressor selector for large compressed air networks in the mining industry," M.Eng Dissertation, School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom, South Africa, 2012.
- [46] S. van Heerden, "Developing a dynamic control system for mine compressed air networks," M.Eng Dissertation, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2016.
- [47] S. van Heerden, "A dynamic optimal control system for complex compressed air networks," Ph.D Thesis, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2015.
- [48] D. Kaya, P. Phelan, D. Chau and H. I. Sarac, "Energy conservation in compressed air systems," *International Journal of Energy Research*, vol. 26, no. 9, pp. 837-849, 2002.
- [49] W. Booysen, "Reducing energy consumption on RSA mines through compressor control," M.Eng Dissertation, School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa, 2009.
- [50] Rotork Controls Limited, "IQ Pro Range Electric actuators and control systems," [Online]. Available: <http://www.rotork.com/doc-dl/553>. [Accessed 09 August 2016].
- [51] DJF Consulting Limited, "Refuge stations/bays & safe havens," The Underground Coal Mining Safety Research Collaboration (UCMSRC), may, 2004.
- [52] Atlas Copco, "BBC 34W: Pusher leg rock drill (medium to hard rock)," [Online]. Available: <http://www.atlascopco.co.za/zaus/products/drill-rigs-and-rock-drills/1594742/1699850/>. [Accessed 09 August 2016].

- [53] D. Brake and G. Bates, "Criteria for the design of emergency refuge stations for an underground metal mine," *Journal of the Australasian Institute of Mining and Metallurgy*, vol. 304, no. 2, Dec, 1999.
- [54] D. Howett, "Compressed air: High pressure can equal lower cost," *Energy Engineering*, vol. 100, no. 4, pp. 6-9, 2003.
- [55] ATS 2000 (Pty), "Rigga – Mining series air hoist," ATS 2000, Johannesburg, South Africa, 2013.
- [56] MME Manufacturing CO. (Pty) Limited, "MME WAP series air winches," *ATS 2000*, vol. 27, no. 18, pp. 6-8, 2006.
- [57] H. N. Hickok, "Adjustable speed: A tool for saving energy losses in pumps, fans, blowers, and compressors," *IEEE Transactions on Industry Applications*, Vols. 1A-21, no. 1, pp. 123-136, 1985.
- [58] R. Joubert and L. Libenberg, "Cost and efficient DSM on mine compressed air systems," in *Proceedings of the Seventh Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 2010.
- [59] J. F. Wendt, J. D. Anderson, E. Dick, G. Degrez, R. Grundmann, J. Degroote and J. Vierendeels, *Computational Fluid Dynamics*, Berlin, Germany: Springer, 2009.
- [60] A. Garbers, M. Kleingeld and J. F. Van Rensburg, "Energy savings through auto compression and the air distribution control of a deep level gold mine," in *Proceedings of the Seventh Conference on the Industrial and Commercial Use of Energy*, Cape Town, South Africa, 2010.
- [61] R. Marshall, "Finding and fixing leaks," *Compressed Air Best Practices*, p. 30–34, May/June 2010.
- [62] U.S. Department of Energy, "Energy Tips - Minimize compressed air leaks," Industrial Technologies Program, Washington, United States of America, 2004.
- [63] A. Pregelj and M. Mozetic, "Leak detection methods and defining the sizes of leaks," *Application of Contemporary Nondestructive Testing in Engineering*, vol. 4, no. 2, pp. 3-8, 1991.
- [64] Y. A. Cengel and M. A. Boles, *Thermodynamics: An engineering approach*, Boston: MA: McGraw-Hill Higher Education, 2006.

- [65] R. T. Terrell, "Improving compressed air system efficiency: Knowing what you really need," in *Proceedings of the National Industrial Energy Conference*, Houston, United States of America, 1998.
- [66] Q. a. M. A. Hongbo, "Improving energy efficiency of compressed air system based on system audit," *Lawrence Berkeley National Laboratory*, vol. 6, no. 13, 2008.
- [67] J. I. Phillips, P. S. Heyns and G. Nelson, "Rock drills used in South African mines: a comparative study of noise and vibration levels," *National Institute for Occupational Health*, vol. 51, no. 3, pp. 305-310, 2007.
- [68] J. Snyman, "Integrating various energy saving initiatives on compressed air systems of typical South African gold mines," M.Eng Dissertation, School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom, South Africa, 2011.
- [69] A. S. Korpela, "Principles of Turbomachinery," John Wiley, Hoboken, United States of America, 2011.
- [70] D. Eaton, J. Rama and A. Macak, "Zero downtime: Five years of operation with new adjustable speed electric drive on critical non-spared compressors," in *Proceedings of the Petroleum and Chemical Industry Conference*, Dhahran, Saudi Arabia , 2006.
- [71] S. Hussain, "Compressed Air Basics, Part 11: Other Technologies," Air Compressor Works, 20 May 2014. [Online]. Available: <http://www.aircompressorworks.com/blog/index.php?mode=post&id=27>. [Accessed 15 September 2016].
- [72] G. Smith, "Centrifugal compressor," International, SPE, 2013.
- [73] P. Gallick, G. Phillippi and B. F. Williams, "What's correct for my application: A centrifugal or reciprocating compressor," in *Proceedings of the Thirty-Fifth Turbo Machinery Symposium*, Turbo Machinery Laboratory, Texas, United States of America, 2006.
- [74] J. Kijjarvi, Darcy friction factor formulae in turbulent pipe flow, Lunowa Fluid Mechanics, 2011.
- [75] D. R. Durgaiyah, Fluid Mechanics and Machinery, New Delhi, India: New Age International, 2002.

[76] J. Hodging, "Mining Industrial Photographer," James Callaway Production, [Online]. Available: <http://miningindustrialphotographer.com/mining/>. [Accessed 02 November 2016].