Developing a dynamic control system for mine compressed air networks

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Abstract

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Mines in general, make use of compressed air systems for daily operational activities. Compressed air on mines is traditionally distributed in two typical fashions. Firstly, direct pipe feed systems for single shafts or compressed air ring networks where multiple shafts are supplied with compressed air from an integral system. These compressed air networks make use of number compressors feeding the ring from various locations in the network. While mines have sophisticated control systems to control these compressors they are not dynamic.

Compressors are selected on static priorities for a chosen time period of the day. While this is acceptable for some days it is not always the ideal solution. The compressed air demand of the ring is dynamic and it is difficult to estimate the future need of the system. The Dynamic Compressor Selector (DCS) is described as a solution to this problem.

DCS is a computer based control system featuring a Graphical User Interface (GUI). The aim of DCS is to dynamically calculate a control pressure set-point, given the demand for compressed air as well as choose the optimal compressors to supply the given compressed air. This will reduce the power requirement of the compressed air ring as well as reduce compressor cycling.

DCS was implemented and tested on a single mine compressed air system. Achieved results were 1.8 MW in electricity savings as well as the added benefit of reduced cycling. This saving results in a cost saving of R3.7 million per annum. The problems and shortfalls of the system are also discussed as well as possible future directions for moving forward.

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List of symbols, abbreviations and terms

A	Area
BRICS	Brazil, Russia, India, China and South Africa
csv	Comma separated value
D	Diameter
DA	Data Acquisition
DCS	Dynamic Compressor Selector
EMS	Energy Management System
f	Friction factor
g	Gravitational acceleration
GUI	Graphical User Interface
kg/s	Kilogram per second
L	Length
M	Mass flow
m	Metre
MC	Hiprom Master Controller
OLE	Object Linking and Embedding
OPC	Open Platform Communication
OPC DA	OPC Data Access
ρ	Fluid density
P	Pressure
Pa	Pascal
PLC	Programmable Logic Controller

Q	Volume flow
R	Gas constant
Re	Reynolds number
REMS	Real-time Energy Management System
REMS-OAN	REMS- Optimised Air Networks
SCADA	Supervisory Control And Data Acquisition
SP	Set-Point
T	Temperature
µ	Viscosity
v	Fluid velocity
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
W	Watt

1. Introduction

1.1. Background

South Africa is not only part of the BRICS (Brazil, Russia, India, China and South Africa) nations, but is also a newly industrialised country with influence in both regional and global affairs. The South African economy is heavily reliant upon mining and other industries. The effect of this can be seen in the energy usage when compared to other countries since South Africa uses considerably more energy per capita [1].

Initially South Africa produced relatively inexpensive electricity compared to the rest of the world, which has led to undesirable behaviour patterns [2] concerning electricity usage. This applies to all electricity users, both residential and industry. After the electricity shortages of 2007-2008 many of these bad habits have been identified and changed. As a result of this and the sharp increase in the electricity price, the growth rate of electricity usage has a healthy decrease.

South Africa has large coal reserves. Due to the abundance of coal, most of the power stations are fossil fuelled with almost all being coal powered. More than 70% [3] of South Africa's electricity is produced by coal and thus it has a very high CO_2 emissions per capita rating as well as being the sixth largest consumer [4] of coal in the world. Figure 1 shows a comparison of South Africa to the world and other nations.

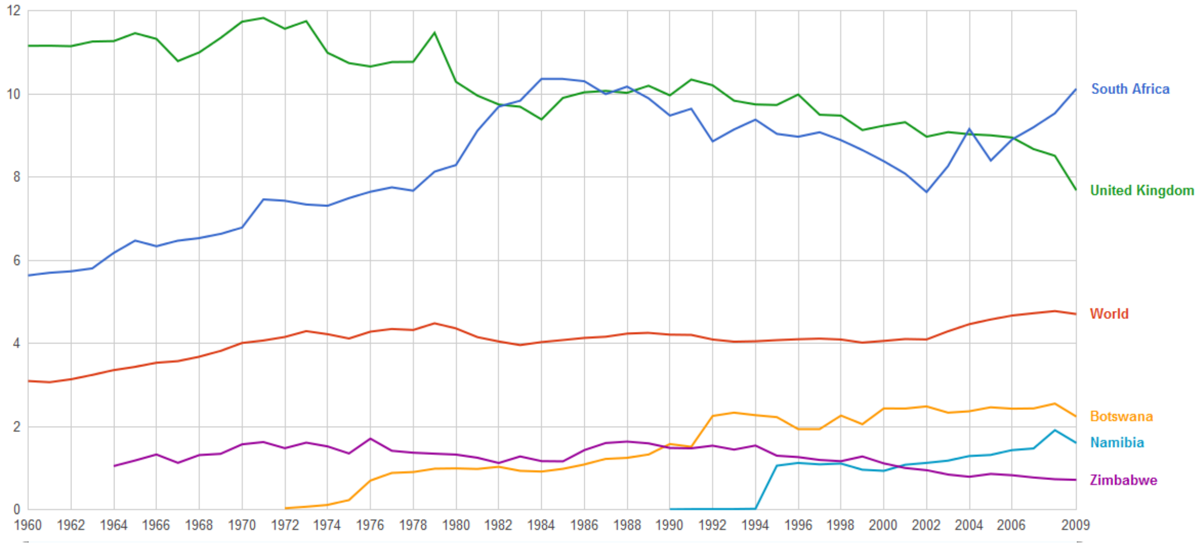

Figure 1: CO_2 per capita (adapted from [5])

This type of power generation comes at a cost to the environment with CO_2 being a major cause of global warming. According to the Guardian [6] 2012 was the ninth hottest year on record as well as being the hottest year ever on record in the United States [7]. Global warming is a concern for every one and it is in everyone's best interest to reduce contributors to this phenomenon.

Compressors on mines consumes a large percentage of the total electricity used in mines while, according to Cameron [8], electricity cost is responsible for 75% of the total lifecycle cost. The reason for this is partially related to insufficient utilisation patterns where mines will operate compressors at maximum capacity throughout the day [9], even though the production shift is only 3-4 hours of the day. By reducing the output pressure of the compressors, energy consumption can also be reduced.

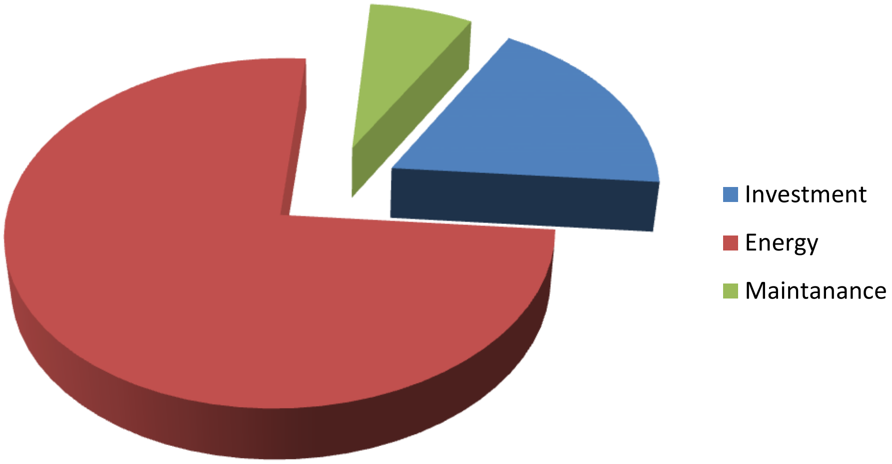

Figure 2: Compressor life time cost (adapted from [8])

To try and reduce the energy usage and costs of compressors, DSM (Demand Side Management) programmes are being implemented. DSM is where the demand of electricity is matched to the supply and is not only limited to compressors. In most cases DSM is used to reduce electricity usage while it can also be used to smooth out the energy demand by reducing peaks and increasing valleys.

It has been shown that by reducing the output pressure and effectively selecting compressors [10] the energy cost and usage can be decreased. The aim of the Dynamic Compressor Selector (DCS) is to reduce energy usage by dynamically selecting compressors and running the selected compressors at specific set-points without influencing production.

1.2. Turbo machines and their use in mining

1.2.1. Turbo machines

Turbo machines are the most important prime movers[1] in existence. According to Korpela [11] turbo machines are devices that exchange energy with a fluid using continuously flowing fluid and rotating blades. Turbo machines are used in power generation by forcing rising steam through the blades. They are also used on the other side of the spectrum where electrical energy is used to move a fluid to generate either movement or potential mechanical energy.

Fluids and gases are both classified as fluids [12]. In a positive displacement machine the interaction between the moving part and the fluid involves a change in volume or translation of the fluid or both [13]. Only some compressors are turbo machines which convert electrical energy to mechanical energy. Turbo machines consist of the following main components [11]: rotor, guide blade, shaft, housing, and a diffuser.

Rotor (impeller or runner): This is the rotating element of the turbo machine. Here the energy transfer occurs between the fluid and the mechanical rotating part due to the exchange of momentum.

Guide blade (stationery, fixed element or nozzle): This is the part of the turbo machine responsible for managing the flow into the rotor. This part is not available in all turbo machines.

Shaft: This is the central element on which the rotor is mounted. It usually resembles a constant diameter pipe.

Housing (casing or volute): The housing of a turbo machine constricts the flow of the fluid so that it only flows into a given space or direction. This is not used in all turbo machines. A volute is a spiral passage used for the collection of fluids in compressors and pumps. Compressors for example, use the volute to guide air into the diffuser, while air turbines do not use volutes at all.

Diffuser (draft tube): A passage that converts kinetic energy into static pressure head. A draft tube is a diffuser placed at the outlet of a hydraulic turbine.

Compressors are either positive displacement machines or turbo machines. This research document will focus more on turbo machine compressors as discussed below in 1.2.2.

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[1] **Prime Mover** - A machine that transforms energy from/to thermal, electrical or pressure to/from mechanical

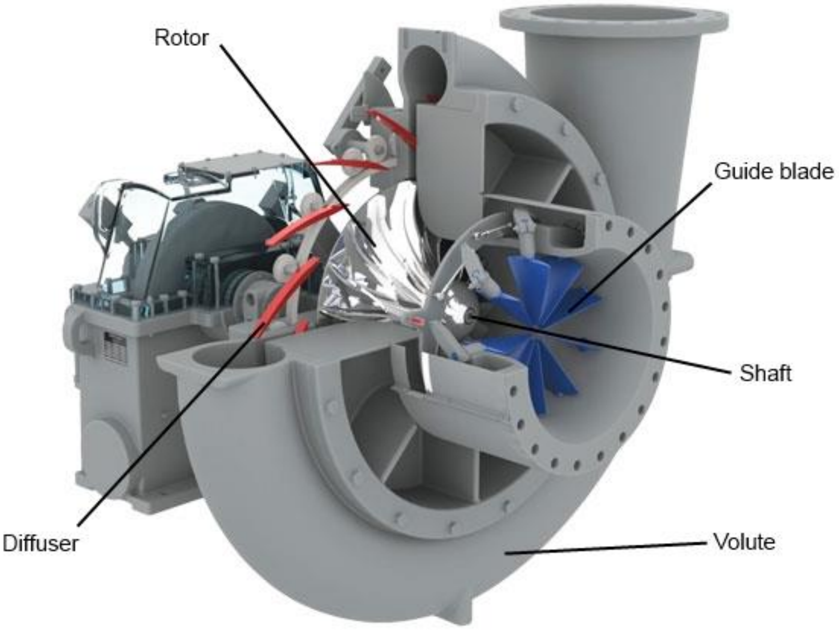

Figure 3: Typical diagram of a turbo machine (adapted from [14])

1.2.2. Usage

Compressors are typically used in two different layouts in mining: localised or in a ring. Localised compressors are located at each mine plant or shaft. Each user has its own compressor supply. In a ring the compressors are sometimes split into more than one compressor supply location but they are still all connected in one large network. Localised compressors are usually more efficient in supplying air to the user since less pipe losses occur than in ring compressors.

Compressed air rings are more reliable and robust in supplying compressed air and require less compressor locations and electricity supply infrastructure. The additional capacity of a ring has the benefit that a compressor can easily be shut down for maintenance or energy saving purposes and the compressed air users will still be supplied with sufficient compressed air from the pipeline.

An example of a mine compressor electricity baseline can be seen in Figure 4. This baseline contains peak usage periods and normal usage periods. Figure 4 indicates the peak usage from 08:00 to 14:00. During this shift [15] the holes for the explosives are drilled underground. This is usually done with air power drills. The reduction in consumption after the peak is where blasting occurs, after which the cleaning shift starts which will again require compressed air.

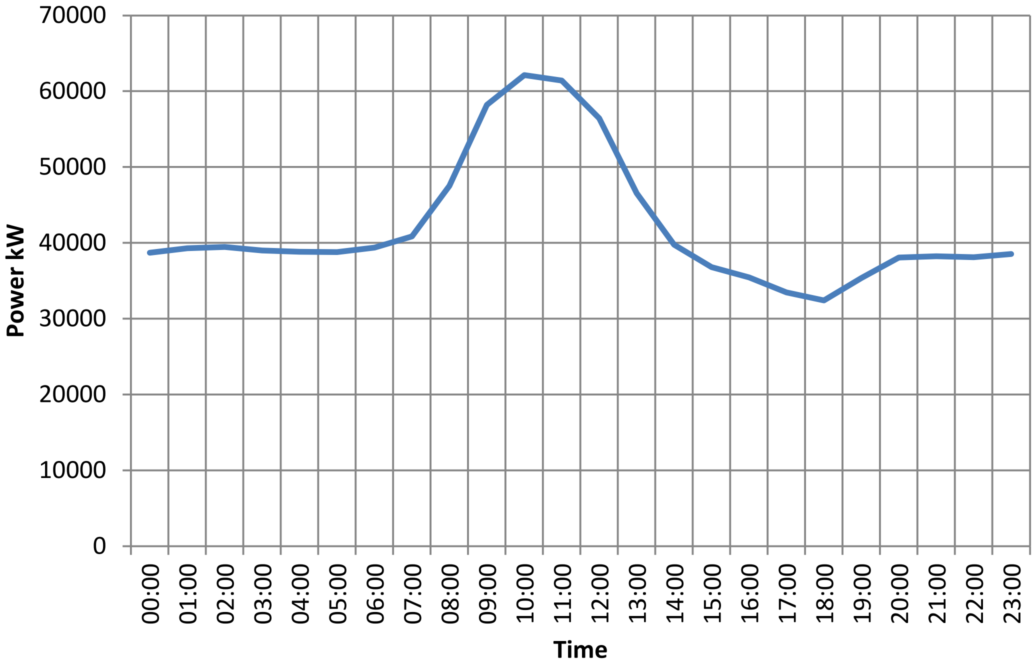

Figure 4: Typical mine weekday compressor electricity baseline

South African mining regulations [16] stipulate that there must always be a positive pressure in the network feeding the refuge bays. This regulation forces a minimum pressure on the air network during off-peak times. This minimum pressure ensures that there is a constant positive air pressure in refuge bays which will keep toxic gases out and ensure the air is breathable in the refuge bay.

To help with maintaining proper compressed air pressure throughout the network, valves are used [17]. These valves limit the pressure at users who require less compressed air pressure. This is done so that the pressure at users who require a higher compressed air pressure can be increased, without over supplying the low demand users. These valves limit the flow to certain sections of the network, consequently isolating high pressure regions from low pressure regions.

Mines use compressed air for various purposes [18]. The main end-users of compressed air in mines include the following, all of which have specific pressure requirements [19]:

- pneumatic rock drills
- pneumatic loaders
- pneumatic cylinders
- ventilation and cooling
- processing plants

- **Pneumatic Rock Drills**

Pneumatic rock drills are used by mines to drill single holes in the rock face. Explosives are then placed in these holes to blast and break open the rock face.

- **Pneumatic loaders**

Pneumatic loaders are machines which load rock and other materials into other equipment (e.g. mine cars). There are usually carriage ways to transport rock out of the shaft.

- **Pneumatic cylinders**

Pneumatic cylinders are used to create motorised force. These cylinders are used to open doors and chutes throughout the mine. They are also used to switch tracks on the rail network in the mine.

- **Ventilation and cooling**

Safety regulations state that there must be a constant positive pressure down in the mine and especially refuge in bays. Sometimes open-ended pipes are also used to create cooling and ventilation.

- **Processing plants**

Processing plants process the rock mined to extract the required minerals. The compressed air used by these plants is supplied by the same air network servicing the shafts. Processing plants use compressed air mostly for agitation and instrumentation.

The abovementioned end-users of compressed air use air at different times, different pressures, different flows and for different usage patterns. This makes management of compressed air systems particularly challenging since all end-users' needs have to be met. If the wrong pressure is applied to an end-user, the equipment could become damaged. If too little flow is supplied the equipment will not function properly and miners will down their tools and not work that shift resulting in large losses due to lost mining time.

As a solution to this very dynamic usage pattern and to counteract these potential losses mines usually over-supply [20] their compressed air network and allow compressors to blow off air if the pressure in the system becomes too high. Successful air network control should result in the needs of each end-user being met without over supplying.

1.2.3. Main compressor types

Compressors can be divided into two main categories: intermittent and continuous [21].

Intermittent compressors (Positive displacement machines): These compressors are cyclic in nature. A specific quantity of air is taken in and compressed before being released into the air network.

Continuous compressors: These compressors deliver a continuous flow of air. The air is compressed while it is moving through the compressor. The flow is never interrupted, hence the name: continuous compressors. Continuous compressors are divided into dynamic and ejector compressors. Figure 5 [21] shows a diagram used for classification of compressors. From this diagram the classification of a specific compressor can be identified.

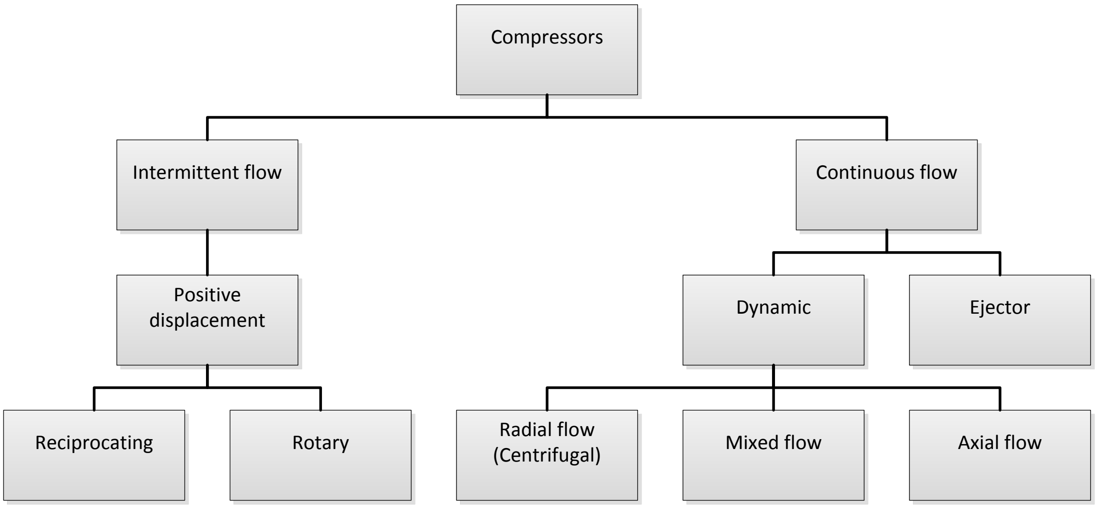

Figure 5: Compressors (adapted from [21])

The type of compressor chosen for a specific application depends on many factors including but not limited to the required flow and pressure. Typical application ranges can be seen in Figure 6 [21] .

Dynamic Compressors (Turbo machines): These compressors transfer energy to the air via a moving set of blades. They are divided into sub-categories depending on their direction of flow through the compressor.

Centrifugal compressed are most commonly used in the mining industry [18], although axial, reciprocating and mixed-flow compressed can also be found.

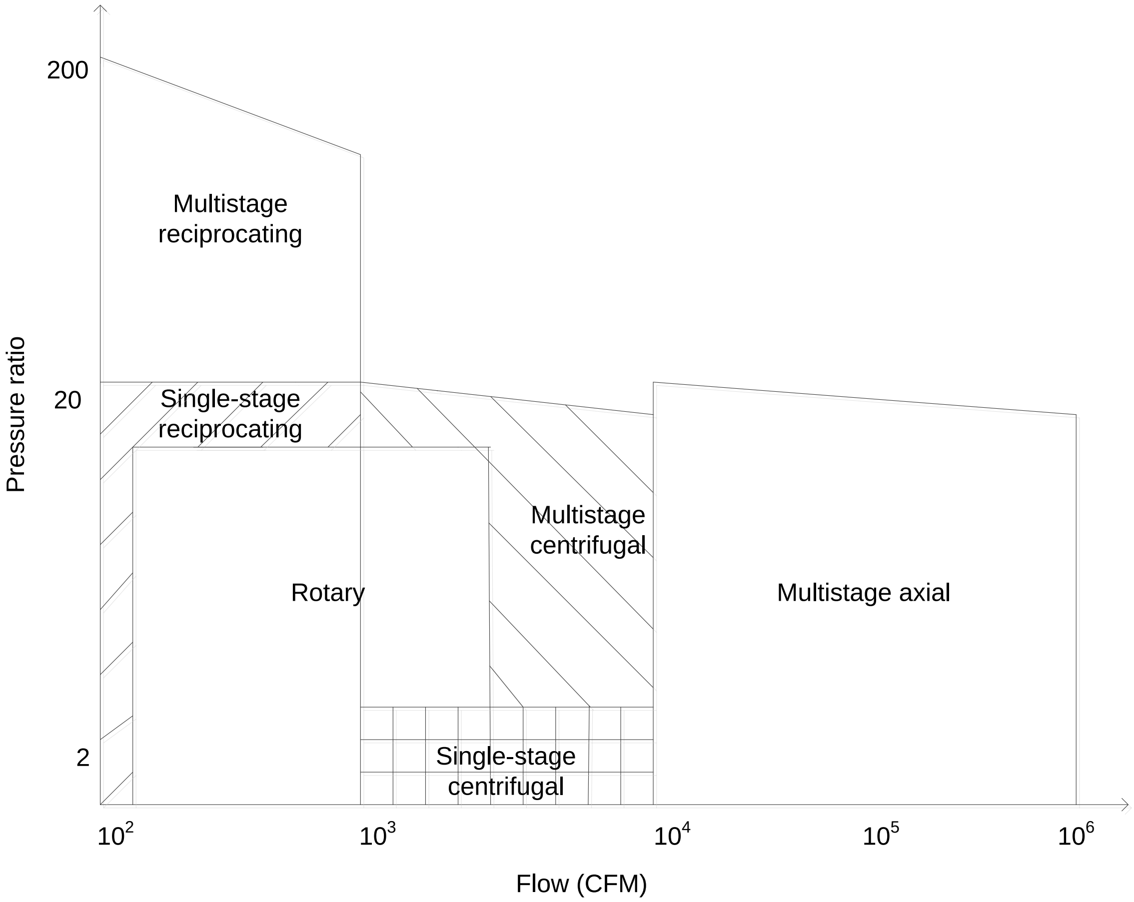

Figure 6: Application ranges (adapted from [21])

1.2.4. Centrifugal compressors

Centrifugal compressors are used because of their simplicity, low vibration and large capacity [21]. Centrifugal compressors were initially not as efficient as reciprocating compressors [21]. At the time when most centrifugal compressors were selected electricity was still relatively cheap and this cost was not really taken into consideration. However later developments in centrifugal compressors made these machines reliable and more efficient.

Centrifugal compressors are dynamic machines because they have a continuous flow of fluid which receives energy from the rotating impellers. The energy is changed into pressure by the impellers and stator. The fluid (air) moves over the impeller and gains pressure as well as velocity as the impeller pushes the fluid outward. As the fluid moves through the diffuser it will lose velocity and gain pressure [22].

In a multistage compressor, the diffuser will run into a return channel which will channel the fluid into the inlet of the next stage. The last stage in any compressor contains a discharge volute which collects fluid from the diffuser and conveys the fluid into the discharge nozzle.

Most centrifugal compressors use electrical motors to drive the shaft that drives the impeller. Electricity is used because of its relative efficiency when compared to fossil fuel motors [23] as well as the availability of electricity at mines. Many centrifugal compressors use constant speed motors. Newer, more efficient compressors feature VSDs (Variable Speed Drive) which enable the compressor to run at different speeds and broaden its operating range.

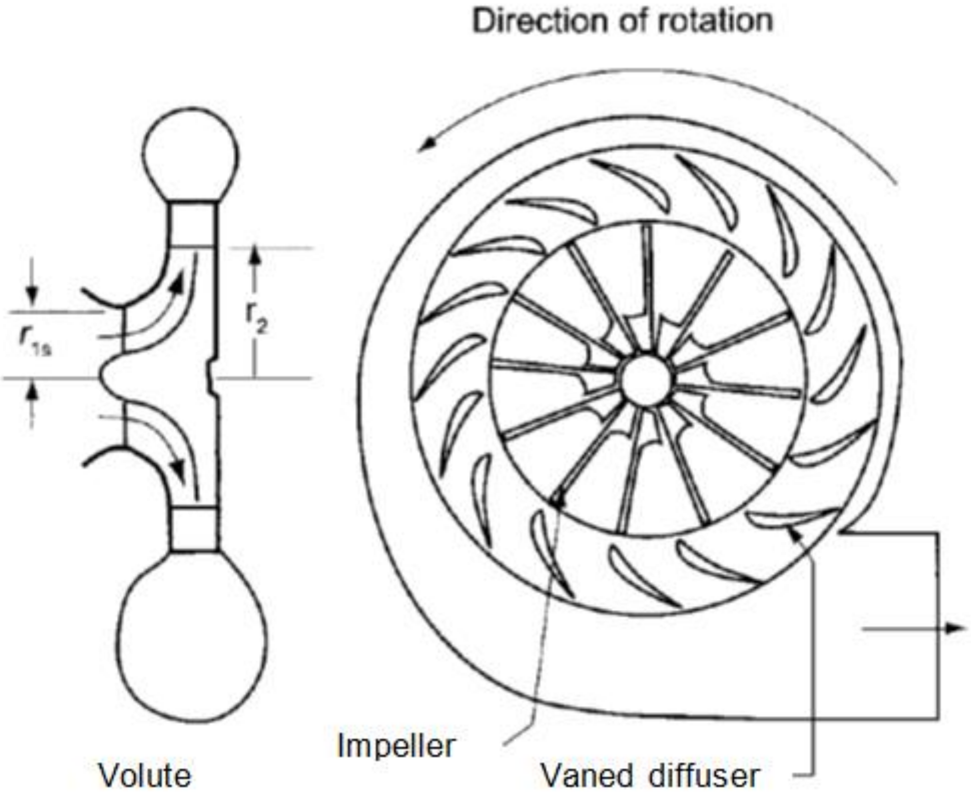

Figure 7: Single-stage centrifugal (adapted from [11])

Centrifugal compressors can be configured in both single and multistage layouts. These stages employ a single impeller diffuser pair, as can be seen in Figure 7. Figure 8 displays a multistage centrifugal compressor. A single-stage compressor has one impeller and one diffuser whereas a multistage compressor has multiple impeller diffuser pairs.

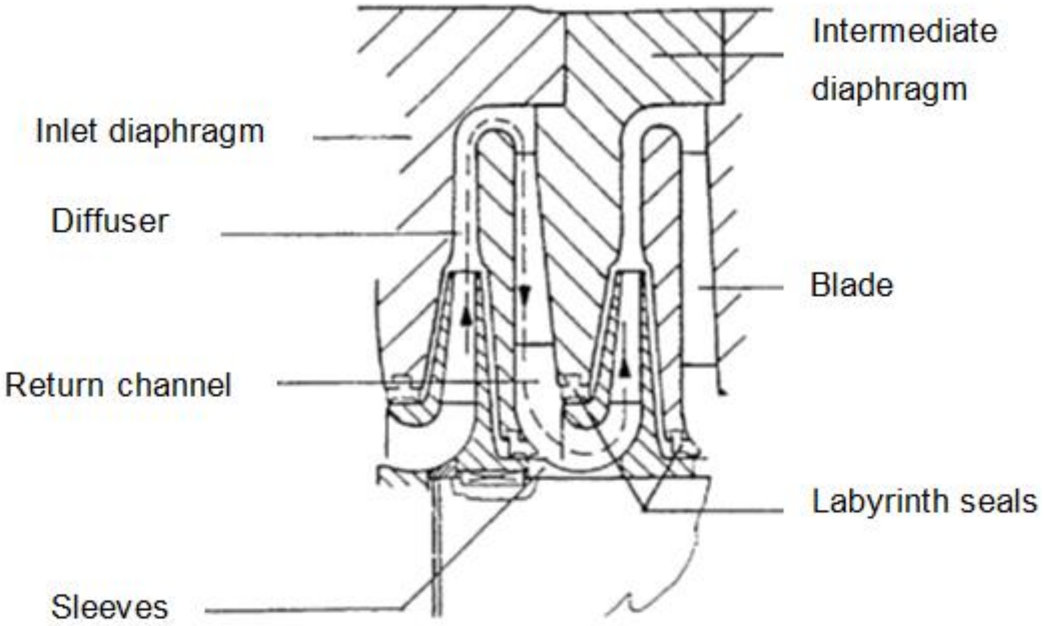

Figure 8: Multi-stage centrifugal compressor (adapted from [24])

In a multistage compressor the air will move from the previous stage's diffuser into the next stage's impeller to be further compressed. The per-stage performance of single-stage compressors is higher than those of multi stage compressors. However multistage compressors offer a better compression ratio than single-stage compressors as was shown in Figure 6.

1.2.5. Compressor system

Apart from the compressor, a compressor system also requires the following components:

- compressor driver
- lubrication system
- instrumentation

Compressor drivers are the elements that drive the shaft of the compressor. The three main driver types are: fossil fuel, steam and electrical. The electrical drive is most widely used due to the relative availability and continuity of the supply of electricity. Many of these drives can supply variable speeds to the compressor.

Compressor systems use oil for lubrication, shaft sealing and temperature control. When the compressor is started in cold temperatures the oil is heated to reach operating temperature. Instrumentation is used to control and monitor the compressor.

1.3. Compressor performance

1.3.1. Characteristics

Figure 9 [25] describes what happens to the flow and the pressure ratio between the inlet and outlet of a compressor running at a constant speed by opening the exit valve. Point A on the graph represents the pressure ratio when the valve is fully closed. As this valve is slowly opened the pressure rises as the flow increases. At point B the efficiency is at a maximum. Beyond this point, increasing the flow will cause the pressure ratio to drop.

At point E when the valve is fully opened the pressure ratio will be zero but the flow will be at its maximum and all the power will be absorbed in order to overcome internal frictional resistance. In practice the area between point A and B is highly unstable due to the phenomenon known as surging. Point B is obtainable in practice.

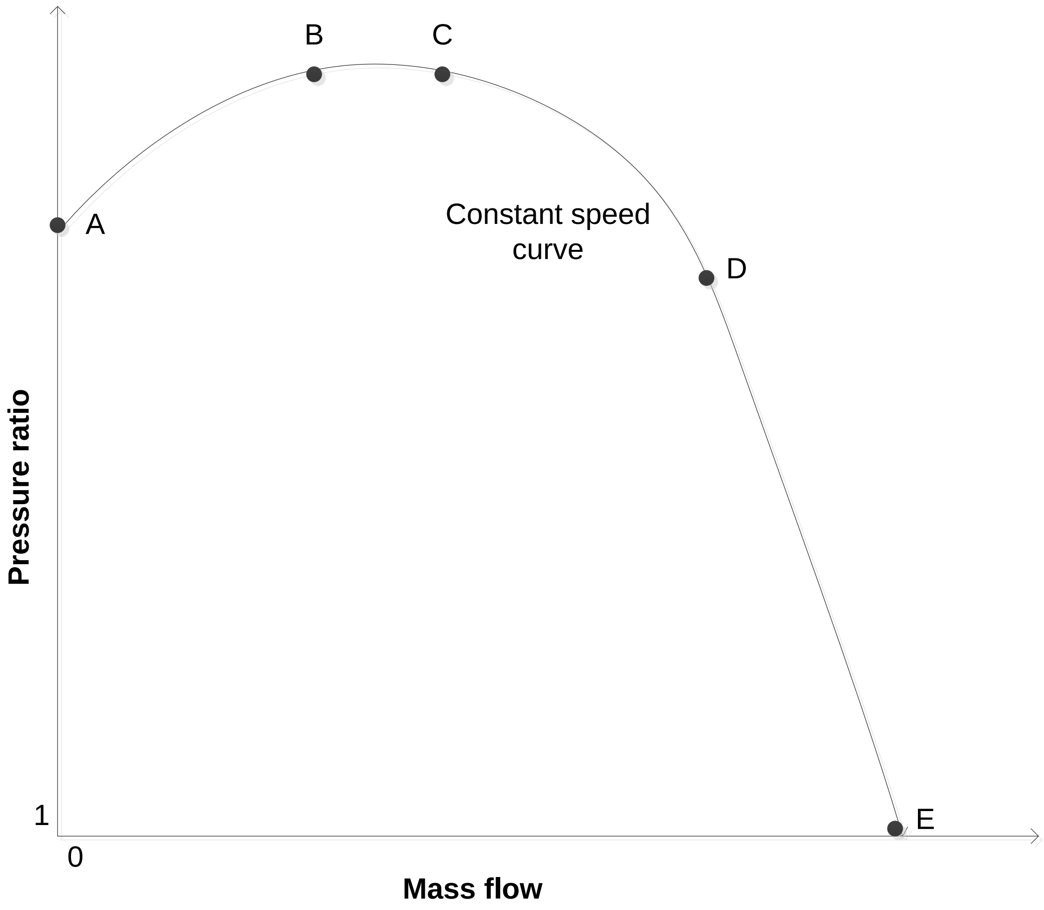

Figure 9: Compressor pressure ratio vs. flow (adapted from [25])

1.3.2. Surge

Surge [26-28] is the phenomenon which causes instability in the entire system. It occurs in low flow regions and is associated with one or more installed stages. This usually causes loud noises and violent vibrations which could cause severe damage.

Point A to B in Figure 9 falls in the region that will result in surging. From this point, if the mass flow decreases the pressure will decrease. If the downstream pressure does not decrease fast enough the air flow will reverse direction and flow into the compressor. The downstream pressure will drop as a result of the negative flow and the compressor pressure will be lifted to above the downstream pressure again. This will cause a cycle where the flow repeatedly flows in and out of the compressor.

1.3.3. Stall

Stalling [24, 29] occurs when there is non-uniformity in the flow of the fluid through the vanes. In Figure 10, blade B causes the fluid to be deflected in such a way that blade C receives the fluid at a reduced angle of incidence and blade A at an increased incidence. As result of this blade A will stall, resulting in a reduction of incidence to blade B enabling the flow in the blade B to recover. This stall will pass through all the blades along the impeller in the opposite direction to the movement of the impeller and will induce vibrations.

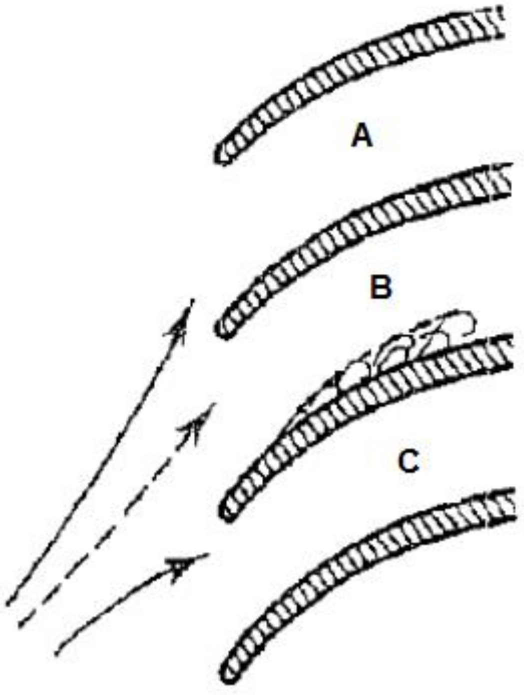

Figure 10: Compressor blade stall (adapted from [25])

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1.3.4. Choke

Choking [22, 29] is a phenomenon that causes abrupt decreases in performance of a stage. This happens when the fluid reaches sonic conditions. The occurrence of this phenomenon depends on the geometry, operating conditions of the stage and thermodynamic properties of the fluid. In Figure 9 the point E is the maximum obtainable mass flow. Choking occurs at this point.

1.3.5. Compressor map

Compressor performance can be illustrated by characteristic curves [30]. These combine all the limits discussed above into one graph. An example of a characteristic curve can be seen in Figure 11. Although Figure 11 displays a compressor map from a car turbocharger, a car turbocharger is still classified as a centrifugal compressor. All these compressor curves together are called the compressor map.

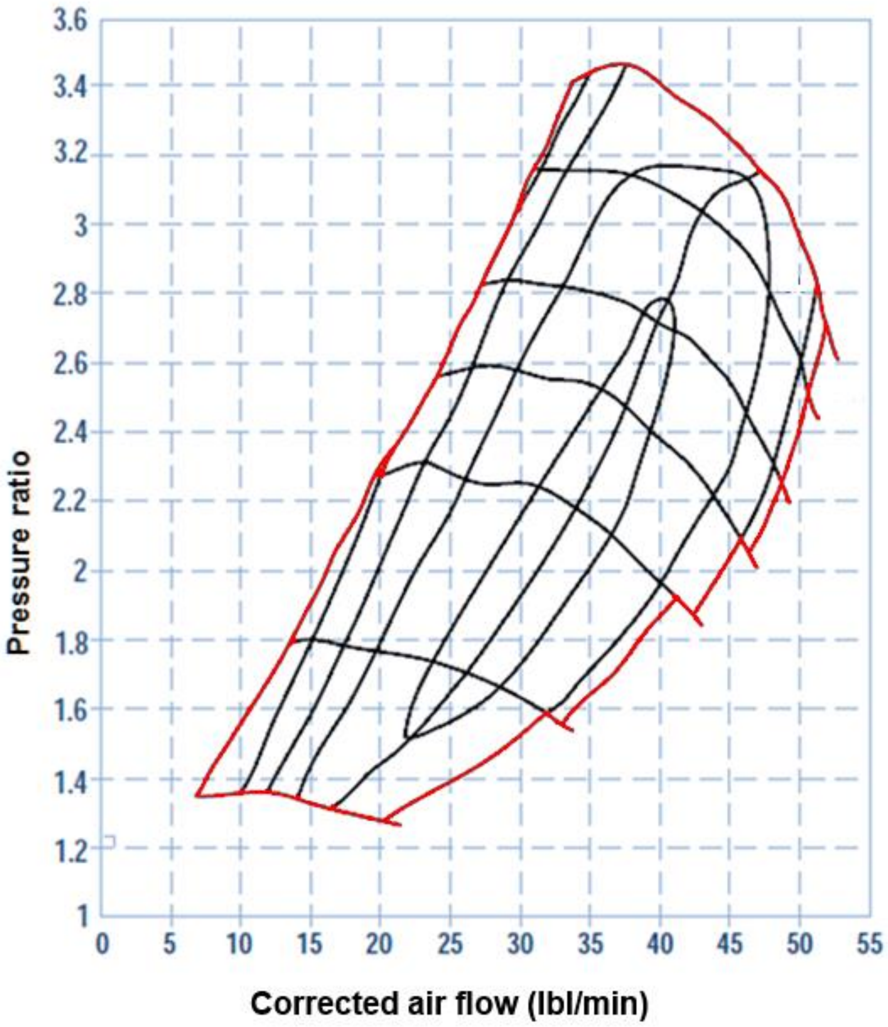


Figure 11: Compressor map (adapted from [31])

This map indicates the four lines that limit the compressors operating flow and pressure, which can only deliver flow and pressure between these limits. These four lines are indicated in red. The top and bottom limits are due to the rotational speed of the motor. Near horizontal lines indicate the rotation speed of the compressor. The vertical left and right limits are due to surging and choking respectively.

These limits are the following: maximum speed, minimum speed, surge limit and choke limit. From Figure 11 it can be seen exactly which limit lies where. The minimum and maximum speeds are only applicable if the rotational speed of the impeller can be changed. The set-points must be within this map and is adjusted on the map by a control element. This can be either a control valve, guide vane or a rotational governor [26].

1.4. Control strategies

1.4.1. Introduction

Compressor control strategies can be divided into two distinct types, demand and supply strategies. Demand side control focuses on the control of all elements that use compressed air. An example of demand side control is controlling the pressure to a mining shaft via a control valve. This valve will reduce the air going to the shaft. Supply side focuses on the control for the supply of compressed air.

Supply side compressor control can be divided into network control and integrated compressor control. Network control is obtained by selecting which compressors are to start and when to start them. Integrated compressor control is the method by which each individual compressor is operated. Integrated compressor control must control each compressor individually. One of the most important aspects of integrated compressor control is to avoid damage to the compressor.

1.4.2. Integrated Compressor control

The following are important objectives of the integrated controller [26]:

- Performance: the compressor must be able to run at the set-point. This can be accomplished via a discharge control valve, guide vane control, VSD, etc.;
- Surge protection: this protects the compressors from damaging surges without sacrificing efficiency or capacity;
- Limiting control: maintaining any limiting processing variables such as drive motor current;
- Event sequencing: controlling the start-up, shutdown and purging of the compressor.

1.4.3. Discharge control valve

This is the most rudimentary method of controlling the output of a compressor. The valve will control the amount of air going into the compressed air network and will discharge air into the atmosphere. This method of controlling is not widely used because of the energy wastage by venting compressed air into the atmosphere.

Section 1.3.1 describes how to control the compressor output with a discharge valve, also known as a blow off valve or a bleed valve. Figure 11 shows the compressor output flow at a given flow.

1.4.4. Guide vane control

Inlet guide vane control adjusts the angle of the air entering the impeller, thus changing the velocity of the gas relative to the impeller. This modifies the compressor characteristic curve by changing the velocity of the gas through the impeller. As the velocity of the air increases relative to the impeller, less energy will be transferred into the fluid [27]. This causes a drop in exit velocity. On centrifugal compressors the implementation is limited as they can only be employed on the first stage of multistage centrifugal compressors

Guide vanes change the efficiency of the compressor by altering the velocity of the gas relative to the impeller. At full guide vanes the compressor will run at maximum efficiency but will also use the most energy. As the guide vanes change the velocity of the gas relative to the impeller the efficiency will be lower, but the total energy usage will also drop.

1.4.5. Variable speed drive

Vsd's also known as a Variable frequency drives (VFD), are used to control the rotation speed of the motors which turn the impellers. Since the rotation speed of the impeller is proportional to the pressure, a reduction in speed will result in a reduction of the delivered pressure.

A reduction in the speed of the impeller will result in a change of the efficiency characteristics of the compressor. Compressors are most efficient at full rotational speed, but a reduction in the rotational speed will result in a reduction of the energy usage. VSDs are rarely used on mine compressors due to their long payback periods.

1.4.6. Inlet throttle valve

Inlet throttle control works by reducing the inlet air to the compressor via a valve. Care must be taken when using inlet throttle valve control since unrestricted flow can cause a surge. When the inlet throttle valve is opened the flow through the compressor will be increased which will also in turn reduce the pressure. If the valve is closed the exact opposite will occur, namely the flow will decrease and the pressure will rise.

1.4.7. Network control

Network control is applied when a compressor needs to start up or one needs to shut down. If the pressure requirement is raised above the current maximum delivery, more compressors need to start to be able to sustain the pressure. If the pressure requirement drops sufficiently, a compressor may be shut down. This will allow a reduction in the use of electricity.

This controller is not as important as the integrated controller since a compressor cannot run without an integrated controller. This means that a network can be supplied with compressed air without a network controller. A network controller assists the compressed air network to run efficiently and without compressor cycling.

Compressor cycling occurs when compressors are started and stopped unnecessarily within a short timespan [32]. This can be caused by a spike in the network demand or by starting the incorrect compressor. The red circled areas in Figure 12 show periods where cycling had occurred more than once. Many controllers are reliant on preset priorities for compressors and these priorities can be incorrect.

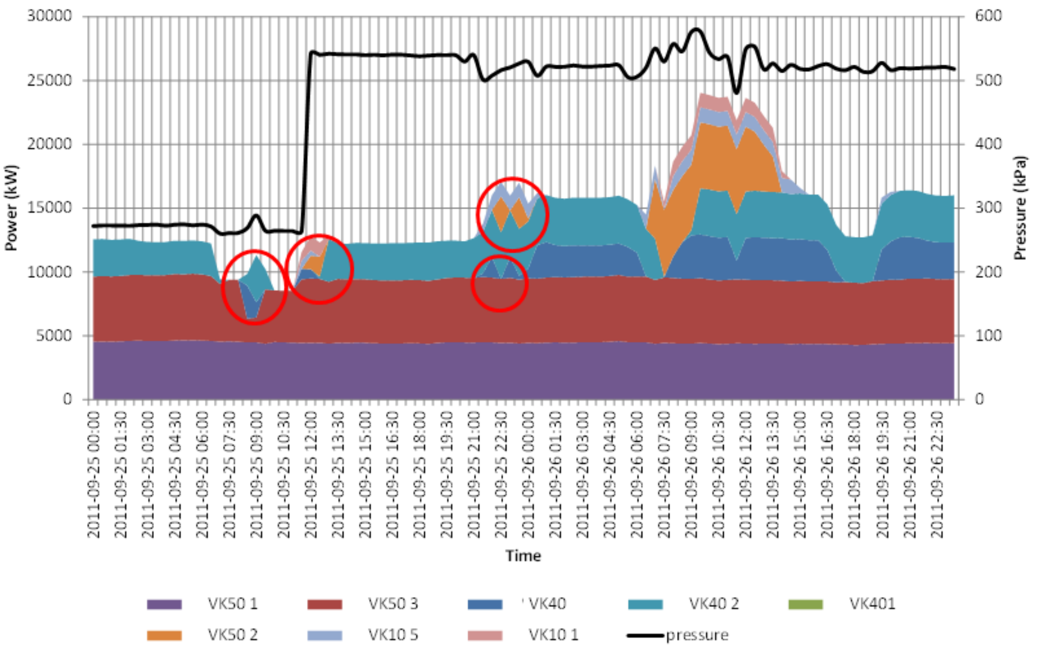


Figure 12: Power profiles of cycling compressors

Cycling can be overcome by loading/unloading of compressors. Loading/unloading uses a discharge control valve to remove the compressor from the network. When a compressor is unloaded from the network the compressor will still run but all air will be blown into the atmosphere and not into the network.

While in its unloaded state the compressor will use less energy [33] than in its loaded state because of the reduced load on the compressor. By keeping the compressor running the compressor will not have to start again, helping to reduce maintenance costs.

1.4.8. Current control systems

When network control is required, there are many different controllers available for air compressors. This section examines commercially available compressor controllers and compares these to the proposed DCS.

Table 1: Compressor controllers

Name of controller	**Incorporated valve control**	**Automated control**	**Manual override functionality**	**Manual priorities**	**Automated priority handling**	**Number of compressors controllable**	**Integrated control**	**Historic data availability**	**Monitoring**	**Dynamic set-points**
EMS	-	X	X	X	-	∞	-	X	X	-
REMS-OAN	X	X	X	X	-	∞.	-	X	X	-
PL 4000	-	X	-	-	X	∞	-	X	X	-
Airtelligence provis 2.0	-	X	-	-	X	16	-	X	X	-
Hiprom controller	-	X	X	X	-	∞	X	-	X	-
DCS	X	X	X	X	X	∞	-	X	X	X

Legend: X contains the mentioned feature, - feature not available in controller, ∞ infinite number

- **Energy Management System (EMS)**

EMS [18] is a software control application which automatically manages the number of compressors running while maintaining the current air pressure set-point. The program will start up another compressor if the pressure at the compressor house drops below the set-point. The opposite is also true, where a compressor will be shut down if the pressure at the compressor house rises above the pressure set-point.

The control features historic data which is logged at 2 minute intervals. The data logged by the controller includes: Controller mode (automatic or manual), number of compressors running, compressors power usage etc. All these log files are saved as csv (comma separated value) files for easy processing when generating reports [34].

- **Real-time Energy Management System – Optimised air networks (REMS-OAN)**

REMS-OAN [35] has evolved from EMS, building upon the concept of running the minimum number of compressors. To achieve this goal, it includes the ability to manage the valves supplying mining levels and shafts, which will allow only the required flow to each level and shaft, with the controller adapting to the changing demand.

- **PL 4000**

The PL 4000 [36] is a controller developed by Pneu-Logic. This controller automatically manages all compressors in a network, but does not feature a manual override to allow an individual compressor to be started, or to allow its priority to be changed manually. The PL 4000 is viewed by industry users as a black box system.

- **Airtelligence provis 2.0**

Airtelligence provis 2.0 [37] was developed by BOGE America, Inc. This compressor controller has much the same feature list as the PL 4000 and it is also a black box system. The main difference between the two controllers is that Airtelligence provis 2.0 can only manage 16 compressors and 24 additional accessories such as fans, dryers etc.

- **Hiprom controller**

The Hiprom controller was developed specifically for platinum mining by Hiprom [38]. The controller has much the same features as the EMS controller. This controller is currently used by Lonmin. The controller does not feature historic data like the EMS controller.

1.5. Control via dynamic selection

1.5.1. Introduction

Most current compressor controllers have a fixed priority list for starting compressors and require user input to change this list. These fixed lists may work well with a fixed usage pattern. While mines have fixed times for drilling, blasting etc., the usage patterns at those times are never exactly the same because of the dynamic nature of the usage pattern on the mines. To circumvent this, a dynamic list needs to be created.

While some controllers do feature dynamic priorities, they do not feature dynamic set-points. DCS is the only controller that incorporates dynamic set-points as well as automated dynamic compressor priorities. It also includes all previous features of REMS-OAN and of EMS to create a comprehensive software compressor controller.

The DCS will simulate the entire network to identify all pressure and flow changes in the network. This will ensure that pressure drops in the system will lead to the start-up of two compressors simultaneously, which will lead to one of them shutting down again. This will allow changes in the system to be anticipated and the effect of these changes minimised.

To simplify the simulation, it only covers the above ground network, including the area from the compressor houses to the mining shafts. This excludes the individual underground levels of each shaft as these are all seen as a mining shaft from the controller’s perspective. Each mining shaft is separated from the main network with a valve. These valves ensure that only the required pressure is provided for each shaft. For simplification the following assumptions [38] are made:

- The compressed air network is currently in a steady state;
- The flow is one-dimensional, isothermal and incompressible;
- The roughness of pipes is the same throughout the system;
- Historically logged data is correct;
- Losses due to air leaks are negligible;
- The surface air pressure network is at the same height above sea level.

1.5.2. Calculations

Viscosity (μ)

The viscosity of a fluid is the resistance to relative motion of the fluid [39]. According to Venter [38] the average viscosity of air at 316K in the pressure range of 300 kPa to 700 kPa is 3.0134 x 10^{-5} kg/m-s while, the maximum and minimum only varies by 0.1% from each other.

Fluid density (ρ)

The fluid density of a fluid can be calculated as follows:

$$\rho = \frac{P}{RT} \qquad \textit{Equation 1-1}$$

ρ : Fluid density [kg/m^3] .
R : Gas constant [J deg^{-1} kg^{-1}].
T : Temperature [K].
P : Pressure [Pa].

Reynolds number

The Reynolds number [40] of a fluid is used to determine whether the flow is laminar or turbulent, whereas the Reynolds number itself is dimensionless. Because of the high mass flow rate at which the air travels in the compressed air network the flow will always be turbulent.

$$Re = \frac{\rho V D}{\mu} \qquad \textit{Equation 1-2}$$

Re: Reynolds number.
V : Fluid velocity [m/s].
D : Pipe diameter [m].
μ : Viscosity [kg/(sec*m)].

Bernoulli’s theorem

Bernoulli’s theorem [41] can be used in flow calculations if the flow is frictionless and incompressible.

$$\frac{\rho v^2}{2} + \rho g z + P = constant \qquad \text{Equation 1-3}$$

v : Fluid velocity [m/s].
p : Pipe diameter [m].
g : Gravitational acceleration [m/s^2].
z : Measured height [m].

This can be adapted to be applied to two points in a cavity

$$\frac{\rho v_1^2}{2} + \rho_1 g z_1 + P_1 = \frac{\rho v_2^2}{2} + \rho_2 g z_2 + P_2 \qquad \text{Equation 1-4}$$

If the change in altitude is, as assumed, to be constant throughout the entire network, Bernoulli’s theorem can be adapted to.

$$\frac{\rho v_1^2}{2} + P_1 = \frac{\rho v_2^2}{2} + P_2 \qquad \text{Equation 1-5}$$

Bernoulli’s theorem can be adapted to include frictional losses as follows.

$$\frac{\rho v_1^2}{2} + P_1 = \frac{\rho v_2^2}{2} + P_2 + P_{loss} \qquad \text{Equation 1-6}$$

P_{loss} : Cumulative frictional losses between P_1 and P_2

Mass flow

Mass flow can be calculated as follows:

$$m = \rho v A \qquad \text{Equation 1-7}$$

m : Mass flow [kg/s].
v :Average pipe velocity [m/s].
A :Area of the pipe [m^2].

Because

$$Q = vA \qquad \text{Equation 1-8}$$

Q : Volume flow [m^3/s].

The formula of mass flow can be rewritten as

$$m = \rho Q \qquad \text{Equation 1-9}$$

Velocity (V)

Bernoulli's equation for frictional flow can be written as:

$$P_0 = P_1 + \frac{\rho v^2}{2} \qquad \text{Equation 1-10}$$

If Bernoulli's equation is solved for average velocity:

$$v = \sqrt{\frac{2(P_0 + P_1)}{\rho}} \qquad \text{Equation 1-11}$$

Friction factor (f)

One of the major losses of pressure in a pipe is friction caused by the walls of the pipe. The losses can be computed as follows:

$$\Delta P_{friction} = f \frac{L}{D} \frac{\rho v^2}{2} \qquad \text{Equation 1-12}$$

f : Friction factor.

L : Length [m].

The friction factor can be computed as follows:

$$\frac{1}{\sqrt{f}} = -2 * \log(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}) \qquad \text{Equation 1-13}$$

ε : Pipe roughness [µm].

The roughness of a pipe will depend on the material used and the condition of the material. Commercial steel for example has a roughness of 0.045mm or 45µm

According to Venter [38] the conditions at mines will allow for the Swamee and Jain approximation. This will change the formula for f as follows:

$$f = \frac{0.25}{[\log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)]^2} \qquad \textit{Equation 1-14}$$

Pressure losses

The pressure difference caused by geometry changes in the pipes can be calculated as follows:

$$\Delta P_{geometry} = K_L \frac{\rho v^2}{2} \qquad \textit{Equation 1-15}$$

K_L : Value for geometry losses in the pipe.

By combining Equation 1-12 and Equation 1-15 the total pressure loss can be calculated as follows:

$$\Delta P_{total} = \Delta P_{friction} + \Delta P_{geometry} = (f\frac{L}{D} + K_L)\frac{\rho v^2}{2} \qquad \textit{Equation 1-16}$$

Pressure

If the pressure at one end of the pipe and mass flow are known, the Bernoulli's theorem can be used to calculate the pressure at the other end of the pipe.

$$P = P_n - \left[\left(\frac{v^2}{2}\right) * \rho\left(f\frac{L}{D} + k\right)\right] \qquad \textit{Equation 1-17}$$

Where v was calculated as

$$v = \frac{m}{\rho A} \qquad \textit{Equation 1-18}$$

Determining supply pressure

By making an assumption that an end-user has a resistance to flow, Bernoulli's equation can be rewritten as:

$$\mathrm{P}_{\text{end user}} - \mathrm{P}_{\text{atm}} = \mathrm{S}_{\text{resistance}} \frac{\rho_{\text{enduser and atm}} \mathrm{v}^2}{2} \qquad \textit{Equation 1-19}$$

$S_{resistance}$: End-user resistance to flow.

By using the resistance S of the end-user the end-user can be replaced by the atmospheric pressure. By eliminating the end-user the new velocity to atmospheric pressure can be calculated as follows:

$$\mathrm{v}' = \sqrt{\frac{2(\mathrm{P}'_{\text{node}} - \mathrm{P}_{\text{atm}})}{\left(\mathrm{f}\frac{\mathrm{L}}{\mathrm{D}} + \mathrm{K} + \mathrm{S}\right)\rho_{\text{node and atm}}}} \qquad \textit{Equation 1-20}$$

From here the pressure of the end-user can be calculated as follows:

$$\mathrm{P'}_{\text{shaft}} = \mathrm{P'}_{\text{node}} - \left(\mathrm{f}\frac{\mathrm{L}}{\mathrm{D}} + \mathrm{K}\right)\frac{\rho_{\text{node and enduser}}(\mathrm{v}')^2}{2} \qquad \textit{Equation 1-21}$$

By adjusting the supply pressure, the new end-user pressure can be calculated. The supply pressure can be adjusted until the end-user pressure equals to the required end-user pressure. Following this method the correct supply pressure can be calculated to supply the end-users.

1.5.3. Simulation

According to Venter [38] it will be easier to use a numerical iterative approach than a Hardy-Cross method or Electric-Hydraulic analogy. According to Muson, Young, Okiishi and Huebsch [42] as a rule of thumb, a 10% accuracy is the best that can be expected in these calculations because of assumptions in the formulas. The network will be divided into nodes. Each node consists of an intersection and only 3 or 4 pipes.

For simplification each pipe will be considered separate from the other. Consider the simple network in Figure 13. In this network P_1 represents a compressor house while P_2 and P_3 each represent a shaft. P_t will represent the centre of the intersection of the three pipes. The pressure at P_t will not be known and must be assumed as the average pressure of the three end points of the three pipes, P_1, P_2 and P_3.

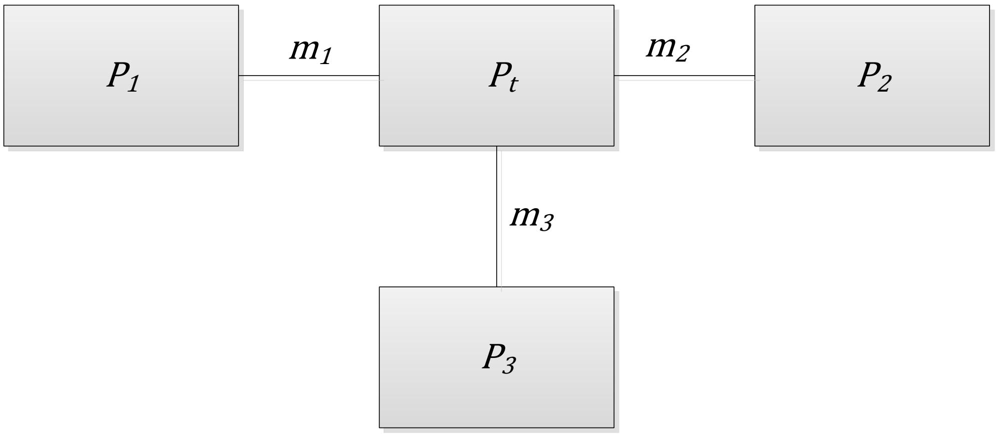


Figure 13: Simplified air network

Because P_t now has a pressure, each pipe has a beginning and end pressure, this means that flow calculations can be carried out on each pipe. The pressure of P_t will be iterated until the mass flow balances out. Assuming leaks are negligible, the total flow into each node will equal the total flow out of the node. This translates to the following equation:

$$m_1 + m_2 + m_3 = 0 \qquad \text{Equation 1-22}$$

m_x : mass flow of pipe x

The order of the calculations for each:

- Calculate fluid density;
- Calculate Reynolds number;
- Calculate friction coefficient;
- Calculate velocity;
- Calculate mass flow.

One deviation to this is done when the pipe is connected to a surface valve leading into a mining shaft. To allow for valve control all the pressure sensors are installed after the valves. This means that when the controller reads the pressure and the valve is not fully open the pressure will be inaccurately read as very low.

If one of the pipes is connected to a shaft the order of calculations for that pipe is as follows:

- Calculate fluid density;
- Calculate Reynolds number;
- Calculate friction coefficient;
- Calculate velocity;
- Calculate pressure.

When calculations begin, the end pressure of these pipes is assumed to be the read values of the pressure meters after the valves. Using Equation 1-21 the pressure can be calculated using the mass flow through the valve.

When using a larger network with more than one node in it, the simulation will take one node at a time and solve the pipes of that node. The simulation will iterate through all the nodes until the outflow from one node is the same as the incoming flow of the next node in the network. In Figure 14 the $m_3=m_4$ must be met.

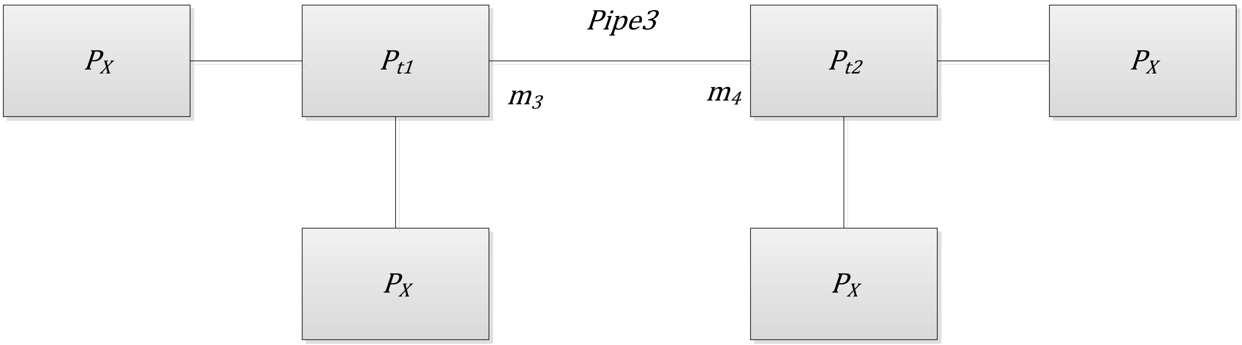


Figure 14: Air network

The flow m_3 is the flow in $pipe3$ as seen by node P_{t1} while the flow m_4 is the flow in $pipe3$ as seen by P_{t2}. The nodes must be iterated through because the pressure of each node will affect the pressure of the next node and because the pressures of the border nodes are inputs to the centre node.

1.6. Need for this study

With the cost of electricity rising at much higher than inflation each year to mainly match the financing needs of Eskom (South Africa's major electricity provider), the input costs of doing business is rising each year. New carbon tax laws being introduced to try and limit the amount of CO_2 released into the atmosphere will also increase the cost of doing business. Each business needs to investigate means to reduce the input cost of doing business. As mines are energy intensive users, electricity is a major input cost that has to be addressed.

This study addresses the need to reduce the cost of mining production by reducing the compressors' electricity usage. For this to be successful the mine cannot afford to lose production. By reducing the use of electricity, the carbon footprint is also reduced which improves the company's public image by being seen as less harsh on the environment. An added benefit to this will be to reduce the strain on Eskom's already small reserve margin [43].

This dissertation addresses the issue of mining compressors operating constantly, as well as cycling compressors. The combination of these two factors consumes unnecessary energy and causes additional CO_2 emissions. The reduction of cycling in compressors will also reduce the wear on them, and thereby reducing maintenance costs.

1.7. Overview of this study

This document discusses the development of a compressor controller system aimed at a reduction of compressor cycling and reducing electrical energy consumption. It focuses on the dynamic selection of compressors to operate the optimum number of compressors as well as the best fit compressors.

The following chapters are contained in this document:

Chapter 2: Design

This chapter discusses the design of the compressor controller. The requirements will be laid down as well as the detailed design. The detailed functionality of each component will also be discussed.

Chapter 3: Results

The results of each requirement will be listed in this chapter. Part of the results will be a case study detailing the results obtained by implementing the controller at a mine.

Chapter 4: Conclusion and future research

This chapter will contain the conclusion as well as ideas and recommendations for future research on this subject.

2. Control system design

2.1. Foreword

This chapter focuses on the design and development process for a dynamic compressor selector controller. This controller will implement the control strategy discussed in 1.7. The requirements for DCS, as well as the features that the REMS design will add will be discussed below.

2.2. Design requirements

2.2.1. Introduction

The requirements for DCS are discussed below. The critical requirements are top level user requirements while the input and output are detailed requirements that are necessary for the program to work.

2.2.2. Critical requirements

The following are the critical requirements:

- Component based

  This is required to ensure that any compressed air network can be built by the user. By making it component based, a network can be constructed and adapted to any circumstance by simply introducing the right component into the project.

- Prioritise compressors dynamically

  Compressors must be dynamically selected by viewing the current flow. The flow ranges of all compressors at a certain pressure range are required and depending on its flow the compressors should be prioritised so that the optimal compressor for the situation is operated.

- Calculate compressor pressure set-point dynamically

  The compressor pressure set-point must be as low as possible. As the required flow is dynamic in nature, compressor set-points are overestimated to ensure that shafts do not lose production due to a shortage of compressed air. To ensure the lowest possible set-point, DCS should dynamically calculate the pressure set-point.

- Start and stop compressors automatically

  Operating compressors should be kept to a minimum and only the required number of compressors should be left running. The compressors should be started, stopped, unloaded and loaded as required. This should ensure that unnecessary extra energy is not consumed by compressors that should not be Operating.

- Simulate an air network

  It should be able to simulate the compressed air network to allow the program to know the flow and pressure at any point in the network, at that time. This will also allow the controller to make an assumption as to what the flow will be in the future.

- Estimate the future state of an air network

  It should be able to estimate the future state of the network given a list of the future set-point pressures. This will ensure that, when the compressor controller schedules a compressor to start, it starts one that can supply the required flow for the future and therefor reduce cycling.

- Gather data from a Supervisory Control And Data Acquisition (SCADA) system

  The program should feature a way to connect to the SCADA system of the mine. It is used as a central location to store all data from all systems on the mine. All mining components are also controlled from the SCADA. To be able to collect information as well as send out control information, a connection to the SCADA will be necessary.

- Log all data

  All data that comes in from the SCADA should be logged, as well as all data from the decisions and simulations of the program. This will allow users to review decisions made and results obtained from the program while reducing the effort to create daily reports of energy used and saved.

- User access control

  The program should feature user access control that will enable different levels of access control for different users. This will stop certain users to change the program settings or the component settings or layout, and will ensure security against possible sabotage as well as prevent users from accidentally changing the settings or the component layout.

- Feature an Open Platform Communication (OPC) connection

  Most of the connections to and from the SCADA use an OPC connection. Until recently this referred to Object Linking and Embedding (OLE) for platform control. OPC is the standard way to connect to a SCADA system and thus should be implemented as the communication standard to adhere to current standard and principles.

- Graphical User Interface (GUI) to display feedback

  The program should feature some GUI to be able to display feedback to the user. This will allow the user to be able to easily set up and edit a layout of components as well as settings. The user will also easily be able to monitor the status of the program and the decisions the program makes. This will allow the user to interfere if the program encounters a problem or if the program reports a fault.

2.2.3. Input requirements

This section will describe what input requirements are required for the program to be able to run efficiently. It will be divided into each of the different components. The input requirements can be divided into the following four sub-requirements:

- Compressors;
- Layout;
- Simulations;
- OPC.

Compressors

The input requirements for the compressors will encompass all the required information and control tags from the SCADA that are required to operate the compressor. The following control tags from the SCADA, which will allow the program to control each compressor are required:

- Start tag;
- Stop tag;
- Load tag;
- Unload tag;
- Priority;
- Weight.

Start, stop, load and unload tags are used to indicate to the SCADA that it should start, stop, load or unload that compressor. Priority tags are used by the compressor to indicate its assigned priority. Lastly weight tags are used by the controller itself to help with assigning compressor priorities.

To assist the controller, the compressors also require feedback tags. These tags show the current state of the compressor and allow the controller to acquire feedback from its actions. The tags required are as follows:

- Running;
- Loaded;
- Available;
- Priority.

The controller also requires the running ranges for each compressor it is meant to control. This will allow it to make decisions as to which compressor is the most optimal unit. The compressor map of each compressor will show exactly what the running ranges for the compressor are.

Layout

The whole compressed air network layout should be available to the controller to simulate the network. The layout is the position of the compressor houses, the shafts, pipes as well as all other major air users on the layout. The network according to the controller will end at the shaft entrance valve, which will be seen as an air user. The compressed air network below ground etc. will not be simulated by the program.

Because pipes are made from different materials and with different diameters these properties are also required. The roughness factor [44] will be required and this will depend on the material used in the manufacturing of the pipe and friction of the interior of the pipe. The k-loss factor [45] will also be required, which depends on the amount of bends and the type of bends in each pipe.

Simulations

To be able to simulate the whole network, calculate the set-points and estimate future flow values, the program requires the following input variables:

- Pressure at compression source;
- Flow at end-users;
- Current user pressure set-points;
- Future user pressure set-points;
- Atmospheric pressure;
- Compressor outlet temperature.

The pressure at the compression source and flow at the end-users are used as starting points for the simulation. Because pressure meters are required for level flow control on each shaft the pressure meters themselves are installed after the shaft valves. Due to the fact that the pressure meters are installed downstream of the valves the pressure readings are unusable for the simulator since according to the simulator the network ends at the valve.

The pressure readings will only be useful to the simulator if the valves are fully opened. To circumvent this, the simulator reads the flow through the valve because the flow before and after the valve will be the same. This flow is then used to calculate the pressure before the valve.

The end-user set-points are used to calculate the set-points for the compressors. This pressure will be used as operating pressure at the compressor houses. The future set-points will be used as an estimation to calculate the future flow requirement of the network. The exact supply flow for the network will be impossible to calculate due to the dynamic nature of the air demand.

This future estimated flow of the compressed air network will be used by the compressor controller to receive an indication of the future required flow, and will be used by the compressor controller when selecting a compressor. To circumvent cycling the compressor controller uses the higher of the current and future flow when calculating the optimal compressor control.

Most air pressure gauges and meters read what is called gauge pressure. This pressure is the pressure above ambient or atmospheric pressure. For accurate calculations and estimations the total pressure must be used by the simulations. The total pressure can simply be calculated as follows:

$$P_{total} = P_{Gauge} + P_{Atmospheric} \qquad \textit{Equation 2-1}$$

OPC

All mining equipment usually gives out data on an OPC connection to the SCADA which in turn also sends instructions to the components via the OPC connection. All this data can be accessed and changed from an OPC Data Access (DA) server. To be able to access equipment data and control components, the program must be able to access the OPC DA server.

2.2.4. Output requirements

The output requirements for the program are to give data outputs to the SCADA as well as visual outputs for the users in the form of a GUI. The outputs can be divided into the three sub categories as follows:

- SCADA;
- Logging;
- GUI.

SCADA

The program must be able to send data to the SCADA via an OPC DA connection. This connection will enable the program to control components or give instructions to other controllers or components.

Logging

All acquired data and control information must be logged into csv format to allow for easy logging and storage into files. This logged data will be used for debugging and policing purposes to ensure that the program operates optimally and when a fault occurs, the problem can be seen more easily. To help with this, the data will be used to generate reports for end-users [34].

GUI

The GUI of the program will allow users to create and watch layouts to control a specific mine air compressor network. The GUI must enable operators to quickly assess the status of the whole compressed air network at the mine. To be able to accomplish this, the program must allow them to see all relevant data concerning the compressed air network.

Examples of this are the following:

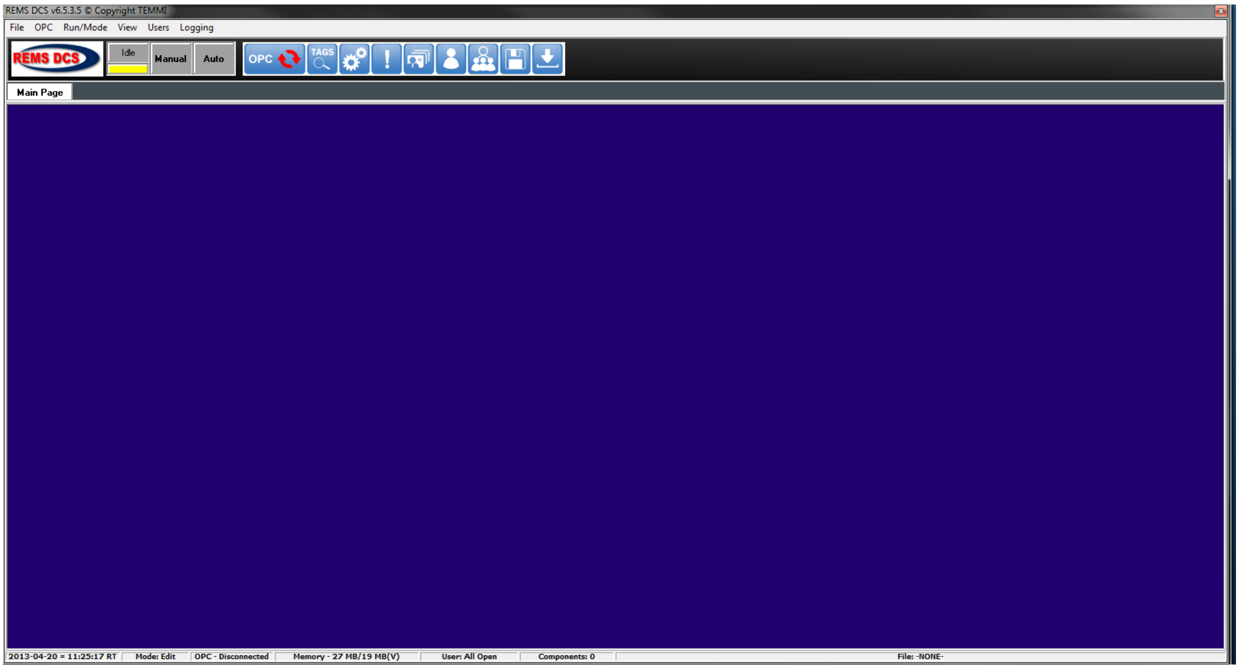
- Real-time pressure of all end-users;
- Real-time pressure at the compressor houses;
- Real-time flow of all end-users;
- Real-time flow supplied by every compressor house;
- Current compressors running and their running statuses.

All this information will help the operator to be more efficient at operating the compressed air network as well help him confirm that the program is running as intended.

2.3. Real-time energy management system

2.3.1. Intro

REMS is a system design which allows users to save time by concentrating on the design of specific platforms. By using the REMS design, the specific controller automatically fulfils many of the requirements. Figure 15 gives an example of how the basic REMS design looks before any components are created for it.



2013-04-20 = 11:25:17 RT | Mode: Edit | OPC - Disconnected | Memory - 27 MB/19 MB(V) | User: All Open | Components: 0 | File: -NONE-

Figure 15: DCS platform

2.3.2. Advantages

Components

REMS design works by creating components for every necessary mining sub-system that will be used by the program. This allows the system to be easily scalable to every specific mine. These components can be placed anywhere and linked to other components as necessary. To help spread out the components, they can be placed on different pages to allow easier viewing by the user.

Logging

The REMS design includes a few components with added functionality which will possibly help any system. One of these tools is the Master logger. The Master logger will log data from any added component and write the data into a .csv file for easy storage. The Master logger will go through each component and update its log file every 2 minutes.

Another logging component added into the design is the trend tool. This component allows the user to add one or more OPC tags which it will then draw onto a graph to display on screen. The value of this tag will also be logged in a .csv file. All of these logging components or other components that log data, log it into a folder named: “HVACI/PlatformData”.

The REMS design stipulates that a copy of all should be data logged into a folder named “Spooler/Data”. The data moved to this folder will only be the current day’s data. This Spooler folder allows other support programmes to email only that day’s data and not data from the time system started to log data.

The REMS design will also force a user defined site ID that should be unique to each system on site. In the Spooler/Data folder, each day gets its own folder which is named as follows: “[SITE ID]-date”. This will give the support program the unique ID so that a remote server can identify each site’s data.

User access control

The REMS design includes user access control. This user access control features four different user groups with each having a different access level. The groups are as follows:

- Viewer;
- Operator;
- Supervisor;
- Administrator.

Table 2 gives a brief overview of the access rights of each of the user groups. When a username and password are added to the program the user must specify a control access group. The user can set a time limit at which, if at all, the user must be logged out. If no user is logged in, the program will assume viewer privilege rights.

Table 2: User access control

Action	Viewer	Operator	Supervisor	Administrator
Connect/Reconnect OPC	Yes	Yes	Yes	Yes
Log in	Yes	Yes	Yes	Yes
Switch modes(auto/manual)	No	Yes	Yes	Yes
Save	No	Yes	Yes	Yes
Backup	No	Yes	Yes	Yes
Change component settings	No	No	Yes	Yes
User manager	No	No	No	Yes
Contacts	No	No	No	Yes
Alarms	No	No	No	Yes
Options	No	No	No	Yes
Tags	No	No	No	Yes
OPC options	No	No	No	Yes
Idle/Edit	No	No	No	Yes

OPC and tags

The OPC component used by the REMS design is DOPC, made by Kassl[2]. This component is integrated into the REMS design so that all OPC tags can be accessed by all components. Included into the design is a watchdog timer which will periodically increase the value of a tag. If this remains static, the design calls for the automatic reconnection of the OPC.

The tag browser allows the user to view all tags on the SCADA through an OPC DA connection. To assist in making the program more scalable the tag browser can add internal tags. These tags appear to be OPC tags but they are only visible within the program. These tags can be a simple memory tag which holds a value like a normal OPC tag, to more advanced tags that allows the user to create a script in the tag to accomplish a task.

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[2] Kassl GmbH is a German software development company.

The list of internal tags is as follows:

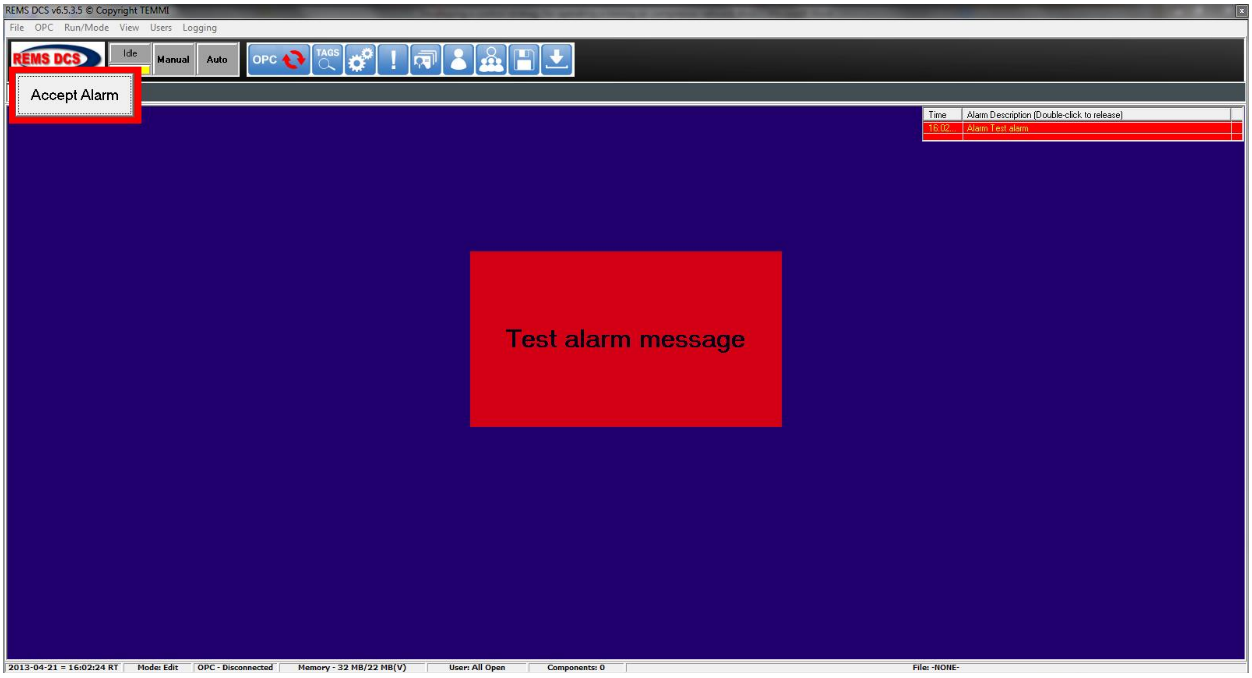
- Additive;
- Subtractive;
- Multiplicative;
- Division;
- Maximum;
- Minimum;
- Boolean switch;
- If then else;
- Set value;
- Condition list;
- Dam selection;
- 24-hour profile (Boolean and double);
- Stable value;
- Programmable;
- Memory;
- Change checker.

Many of these tags represent a function that returns the value. An example of this will be the maximum tag, which holds a list of tags and returns the value of the tag with the highest value.

Alarms

The built-in-alarms in the REMS design allows the user to alert himself or other users if certain conditions are present. The alarms can be triggered by a timed event or if a tag value reaches a condition where it is larger, smaller, equal etc. to a certain value. When the user combines the different tags available to the user, the user can make alarms trigger from different scenarios.

When an alarm triggers, the program notifies the current user via an on screen GUI event as indicated in Figure 16. The alarms can also generate SMS and email messages. These messages are sent via an external program and are created for the specific user linked to the alarm.



Time	Alarm Description (Double-click to release)
16:02...	Alarm Test alarm

Test alarm message

2013-04-21 = 16:02:24 RT | Mode: Edit | OPC - Disconnected | Memory - 32 MB/22 MB(V) | User: All Open | Components: 0 | File: -NONE-

Figure 16: REMS alarm

Operating modes

REMS design calls for four different modes: Edit, Idle, Manual and Auto. Each mode changes the way the components interact and function. Edit mode allows the user to change the layout of components and the component settings. Idle mode disables editing, but still has no automatic controlling, except for the OPC tags update. Auto mode allows the program to control everything automatically. Manual mode is the same as auto mode except that no values are written out to the SCADA.

Rigidity

To make the system more resilient to problems, the design includes a few extra features with the most basic one being a “save file”. Save files allow the system to be closed and opened again without having to rebuild the whole platform. These save files save the operating mode, the users, the component and component settings.

The system will automatically backup all its component .dll files as well as the save file. When the system is installed it will create a shortcut in the start-up folder to start itself up automatically when Windows logs in. The user access stops the program from being closed by unauthorised users. All these features make sure that REMS design will keep a system working or will start working after it stopped.

2.3.3. Disadvantages

The existing REMS design has only two major disadvantages, i.e. OPC is very deeply imbedded into the design and the design was created in Delphi 6. Both of these are major issues but they can both be circumvented as discussed below.

OPC

The communication component used for OPC is deeply imbedded into the REMS design and not via a communications class first. This means that only OPC can be used to communicate with the SCADA, and if another protocol needs to be implemented the whole system needs to be redesigned. This can be circumvented by using a local OPC DA server. This local OPC DA server will connect to the SCADA via the required protocol but will give the system an OPC connection to acquire data from and write data to it.

Delphi 6[3]

Delphi 6 was first released to the public in 2001 and is currently 12 years old. The problem with using Delphi 6 is that it was created before Windows 7. Most mines use servers that run either Windows server 2003 or Windows server 2008. To make the system run correctly it must be installed and run as administrator. This means that the system requires extra effort to run successfully, which would not have been required had the design been written in a newer language or IDE (Integrated Development Environment).

2.3.4. Structure

The class structure of the REMS design that relate to the components can be seen in *Figure 17*. The design only uses a base class TIconDLLInterface. Each individual component has its own IconDLLInterface which inherits from the base class TIconDLLInterface.

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[3] Released by Borland for the first time in 1995 for win 3.1, it evolved from Turbo Pascal.

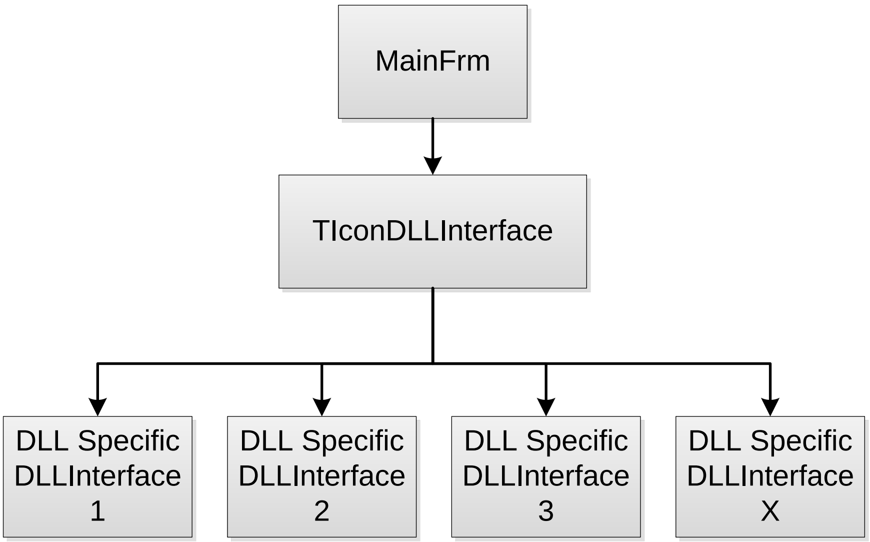


Figure 17: REMS component inheritance

The component structure can be seen in Figure 18 below. The specific component DLL uses the component. The component inherits from the TComponentInterface class which in turn inherits from TDLLMainAncestor.

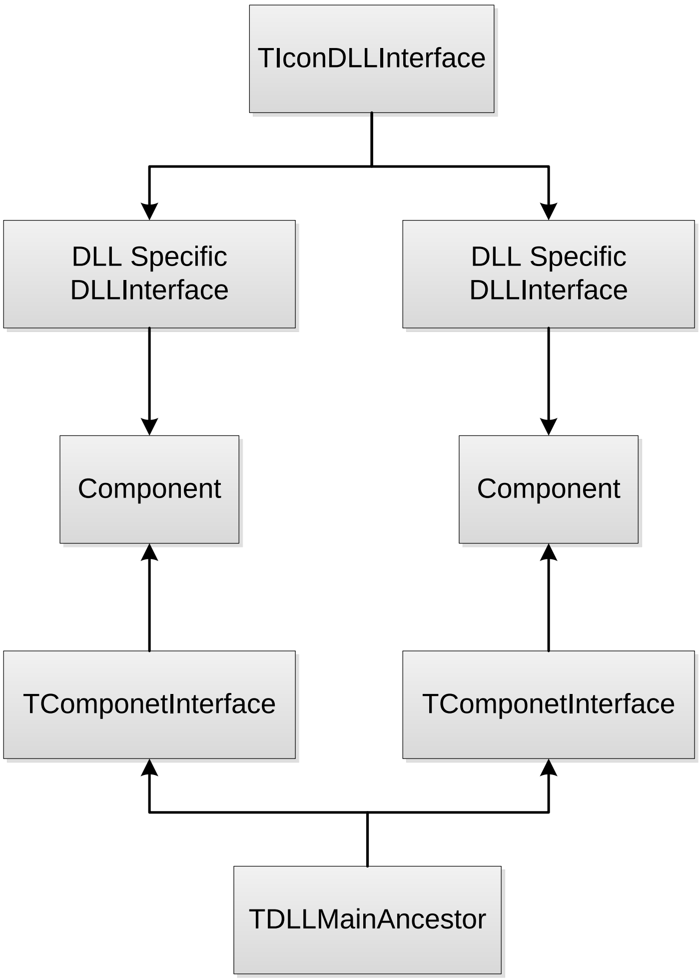


Figure 18: Component inheritance

2.4. Dynamic compressor selector

The DCS platform will be composed of the following components:

- Air Node;
- Air Pipe;
- Air Simulator;
- Set-Point Controller;
- Compressor;
- Dynamic Compressor Controller.

The Air Node encompasses the functions of: compressor house, end point user and junction. The Air Node can be set into one of the three modes and is used to represent the main points on the compressed air network. The compressor house mode represents a compressor house on the air network while the end-user represents all valves before an air user, for example a mining shaft or a processing plant. The junction represents any junction 3 or 4 way in the air network.

The Air Pipe represents a pipe that will connect two nodes to each other. In the Air Pipe the user can define the properties of the section of pipe between the two nodes. The properties include the following: length, diameter, friction and k-loss. By using the Air Pipes and Air Nodes simultaneously any compressor air network can be reproduced in the dynamic compressor selector platform.

The Air Simulator component is used to simulate the air network. This component will use the method described in section 1.5 to calculate all the pressures and flows throughout the network that cannot be read. This data will be used by the Set-Point Controller as well as the compressor controller. The Air Simulator will not only calculate the current values but also set-point values and future values.

The Set-Point Controller is used by the DCS platform for the calculation of compressor house set-points. The Set-Point Controller uses the data calculated by the Air Simulator and then uses the same method as the Air Simulator to calculate the set-points of the compressor house. It will keep adjusting the set-point until all end-users have enough pressure at the valves to satisfy their needs.

The Compressor Component simulates a compressor. This component is only a data entry to hold all relevant information about the compressor. Each component will link directly to each physical compressor. The Compressor Component will also show the user whether the compressor is off, on or unloaded.

The Dynamic Compressor Controller controls the compressors. It has the ability to start, stop, load and unload a compressor depending on the compressor house set-point and the actual delivery pressure. The priorities of the compressors are also calculated by this. The data for the calculations is received from the Compressor Component. The compressor controller is based on the controller which was developed by du Plessis [18].

The Dynamic Compressor Controller only serves as a network controller. It will be assumed that each compressor already features an integrated compressor controller. The DCS platform will supply a running set-point to each compressor as well as optimum compressors that should run at that time. Without the integrated compressor controller for each compressor DCS will not function successfully.

The correlation between the components can be seen in Figure 19. The Air Node gathers data from the Air Pipes, including connected nodes and pipe properties. The Air Simulator obtains the network layout from the Air Nodes and stores all the calculated results in the nodes for redistribution. The Set-Point Controller gets the data from the Air Nodes and rewrites the calculated results into the Air Nodes again.

The compressors get their set-points from the Air Nodes, via the results that were stored there by the Set-Point Controller. The Dynamic Compressor Controller gathers all relevant information from the compressors. The controller also gathers data from the Air Node as to the status of the network. This will be used by the controller in its decisions.

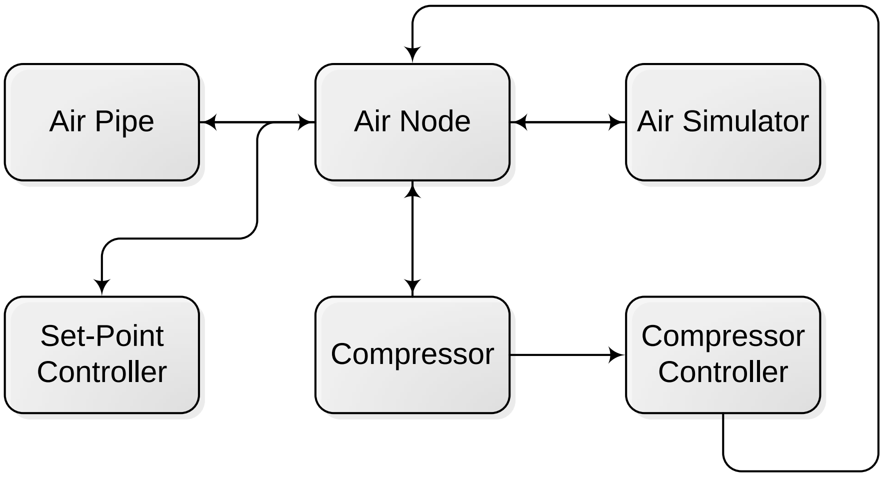


Figure 19: DCS components relation

2.5. Components

2.5.1. Air Node

The Air Node is a central part of the compressed air network simulation. This component represents all end points, supply points and intersections. The Air Node only acts as a storage unit for data. The node keeps references to the pipes connected to it to enable other components to obtain references of these pipes. With the aid of references, the other component can get the references to the nodes connected to that pipe which will allow the component to access the entire network.

The node component will have to establish which pipes are connected to it automatically since the user does not input which pipes are connected to it. The Air Node accomplishes this by gathering references to all Air Pipe components from the system. The Air Node iterates through the pipes and compares the nodes connected to that pipe to itself. This allows the Air Node to determine which pipes are connected to it.

One limitation placed on the Air Node component when it is a normal Air Node and representing a junction in the network, is that only four pipes can connect to it. When the user connects more than 4 pipes to the Air Node it will only use the first four. This can be seen in the edit form and from the Air Simulator and Set-Point Controller components. This limitation is set because networks with junctions featuring more than four connecting pipes are very seldom used.

GUI

The GUI of the Air Node is divided into two parts, the icon and the edit form. The icons which can be seen in Figure 20 below represent the 3 Air Node types. Sea-green represents a normal Air Node that represents a junction. Light blue represents a supply Air Node which in turn represents a compressed air source. The orange icon represents a demand Air Node which represents an end-user.

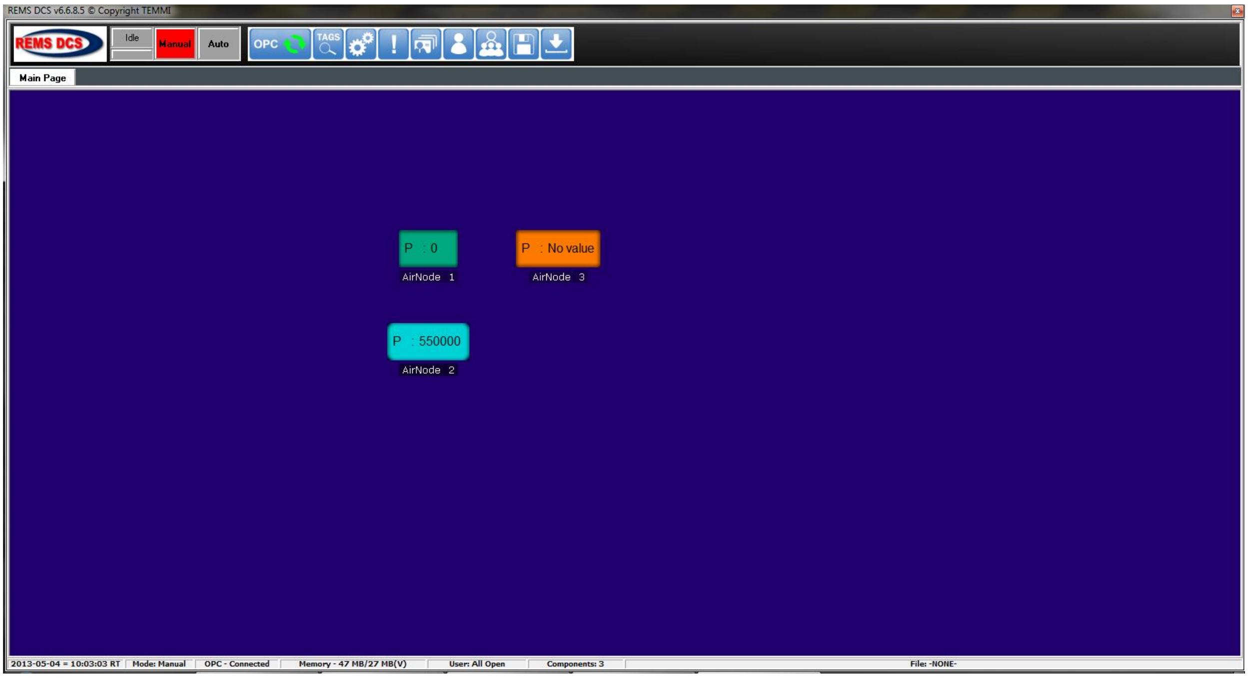
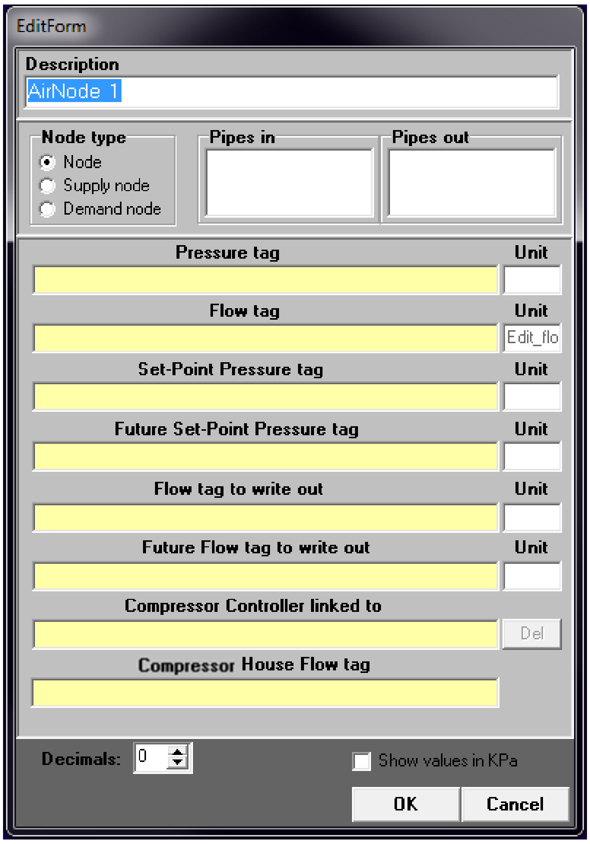


Figure 20: DCS Air Node

The icon displays the pressure of the of the air network at that point. In Figure 20 AirNode 2 displays a pressure of 550,000 Pa or 550 kPa. A pressure reading acquired from a tag will be displayed on a supply Air Node. Normal Air Nodes and demand Air Nodes only acquire their readings from calculated results by the Air Simulator. In Figure 20 the width of all three Air Nodes differs because the component automatically scales its width depending on the number of digits of the pressure reading.

Figure 21 shows the edit form of the Air Node. This allows the user to edit the options of the Air Node. The description field allows the user to set a custom name to the component. The two boxes in the top display the pipes connected to the user. The differences between in- and out pipes are just used to distinguish between direction of flow since the Air Simulator uses polarity to indicate direction. At the bottom of the edit form the user can change the number of decimal places the icon may display before rounding the pressure, as well as the display in kPa or normal Pa.

All other input options in the edit form are OPC tags. When the Air Node is a normal Air Node all the OPC tags are not used. The pressure tag is used by the supply node to indicate supply pressure, while on the demand node the pressure tag is used as an indication of the pressure. The flow tag is only used by the demand node; this flow is used by the Air Simulator to calculate the pressure of the node.



Description: AirNode 1

Node type
● Node
○ Supply node
○ Demand node

Flow tag Unit: Edit_flo

Decimals: 0

☐ Show values in KPa

Figure 21: Air node edit form

The set-point and future set-point pressure is used by both the supply and demand nodes as indications to the required pressure and what the pressure will be in the future. The flow tag to write out and the future flow tag to write out allow the Air Node to write the value of the flow and future flow out to OPC tags. The compressor controller linked to and compressor house flow tags are used by the air node when in supply mode. These allow the user to link the supply Air Node to a compressor controller.

2.5.2. Air Pipe

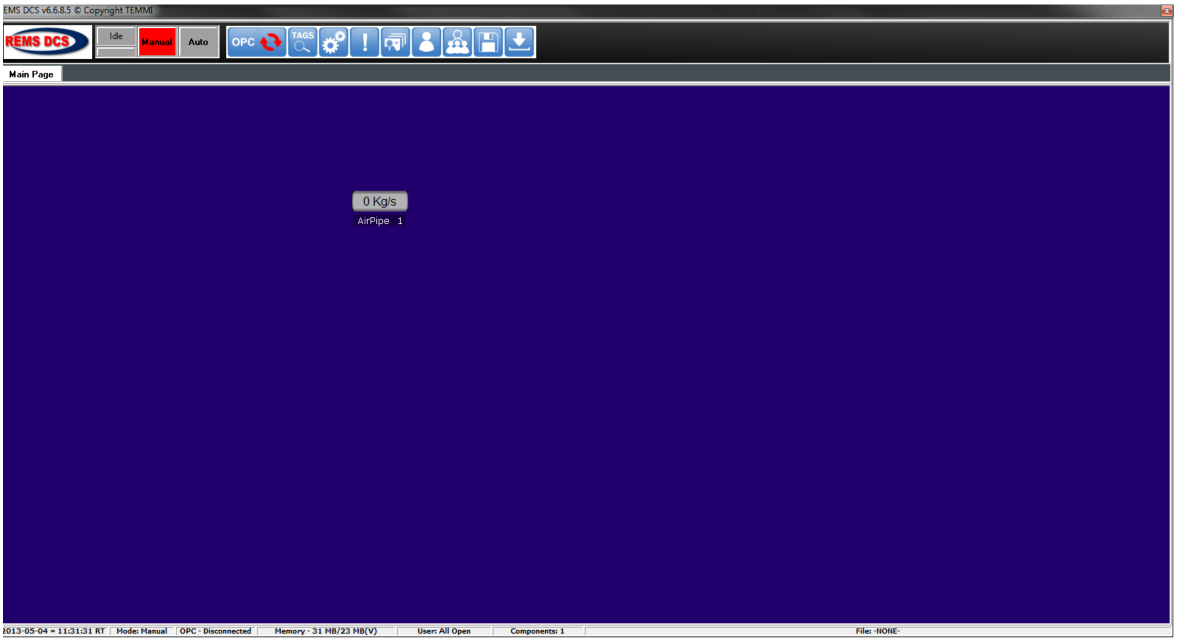
The Air Pipe is the component representing the pipes that form the compressed air network. The Air Pipe connects different nodes to each other to form the network in DCS. Much like the Air Node component the Air Pipe component also only serves as a storage unit. The Air Pipe component stores all data from a specific section of pipe as well as references to the two nodes that each pipe connects to. Unlike the Air Node component the references are obtained through a GUI and not automatically.

A pipe can only connect to two nodes. If a pipe branches out to form two pipes, such a branch forms a junction which can be represented by an Air Node component. By combining pipes with nodes all networks can be created in DCS. The only limitation is networks with junctions featuring more than four connecting pipes. The pipe component will also periodically check to see if the node it connects to still exists. If not, the Air Pipe component will remove the reference to that Air Node.

GUI

The GUI of the Air Pipe is divided into three parts: the icon, view form and edit form. The icon, which can be seen in Figure 22, represents the Air Pipe component. This icon displays the mass flow through that pipe in kg/s. Like the Air Node component, the width of the component automatically adjusts to the number of digits of the mass flow. Because the REMS design already includes a pipe component that allows the user to draw pipes that connect components visually, the Air Pipe does not have to connect them visually and the end result can be seen in Figure 23.

The view form which can be seen below in Figure 24 is a way for users without access rights to see some of the settings of the component. The view form of the Air Pipe component shows the length, diameter, k-loss, roughness and the connecting nodes. This appears on a double click on the icon when the system is in manual or auto mode.



2013-05-04 = 11:31:31 RT | Mode: Manual | OPC - Disconnected | Memory - 31 MB/23 MB(V) | User: All Open | Components: 1 | File: -NONE-

Figure 22: DCS Air Pipe

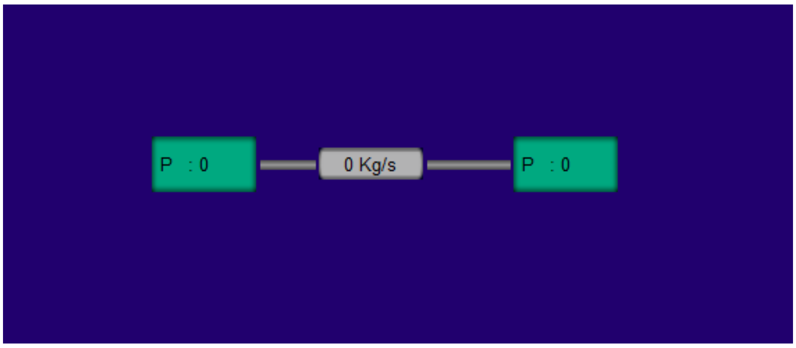


Figure 23: REMS pipe component

Pipe

Length : 0
Diameter : 0
K Loss 0
Roughness 45

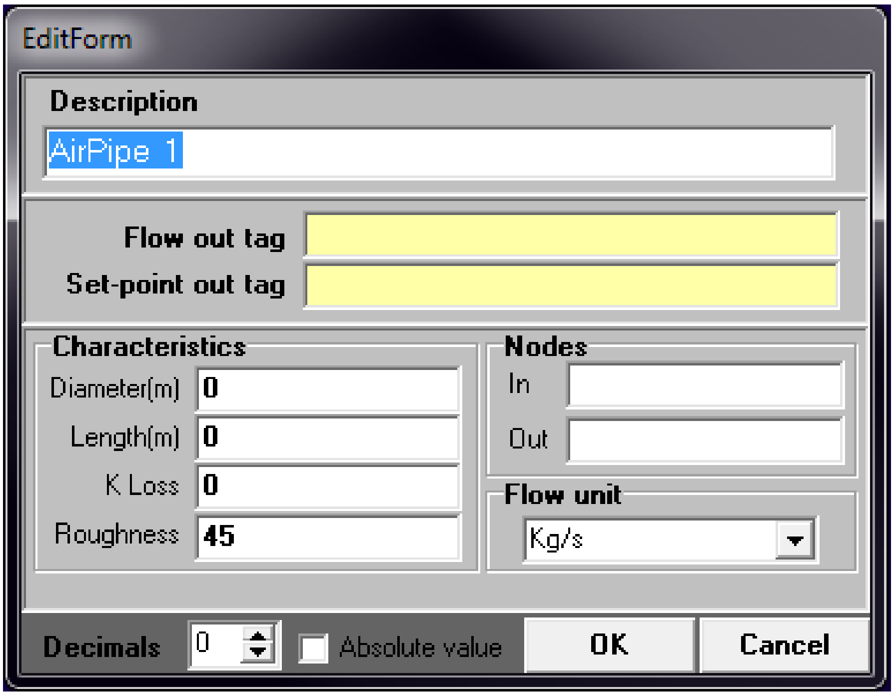
Nodes

Node in :
Node out :

Figure 24: Air Pipe view form

The edit form of the Air Pipe component can be seen in Figure 25. The options start at the description which allows the user to change the name of the Air Pipe. The flow out tag and set-point out tag are used by the component to write the current mass flow and set-point mass flow out to OPC tags.

The characteristics group allows the user to define the properties of each pipe. This includes the following options: diameter, length, k-loss and roughness. The diameter and length are in metres. The Nodes window allows the user to select which node the pipe connects to. The menu can be seen in Figure 26 and this is opened by double clicking on the in- and out fields.



Description: AirPipe 1

Diameter(m): 0

Length(m): 0

K Loss: 0

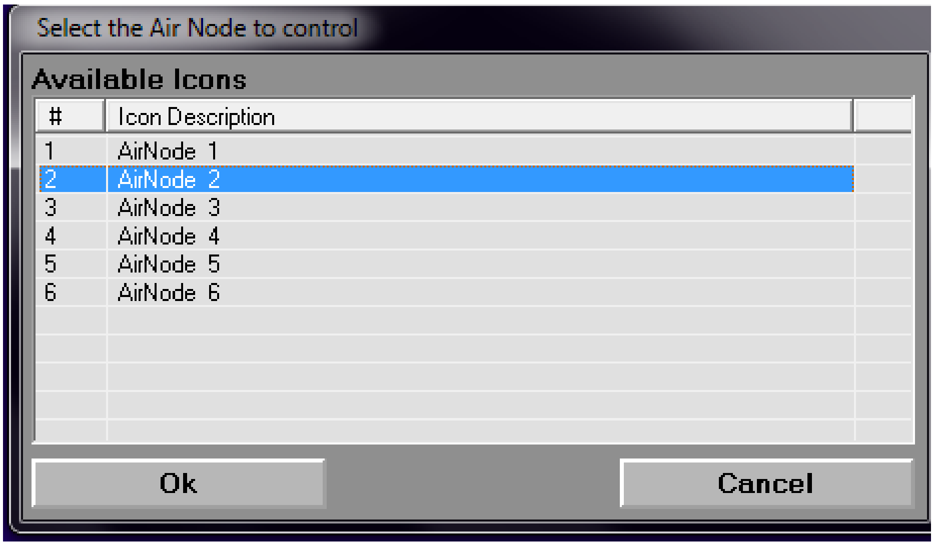
Roughness: 45

Flow unit: Kg/s

Decimals: 0

☐ Absolute value

Figure 25: Air Pipe edit form



#	Icon Description
1	AirNode 1
2	AirNode 2
3	AirNode 3
4	AirNode 4
5	AirNode 5
6	AirNode 6

Figure 26: Air Pipe node selection

2.5.3. Air Simulator

The Air Simulator is the component that simulates the whole network. This component gathers all the data required for its calculations from the Air Node and Air Pipe components. The Air Simulator then calculates all the missing pressure and flow values for the nodes and the pipes as discussed in 1.5.1. These values will be calculated in a separate thread from the GUI and written to the Air Nodes and Air Pipes.

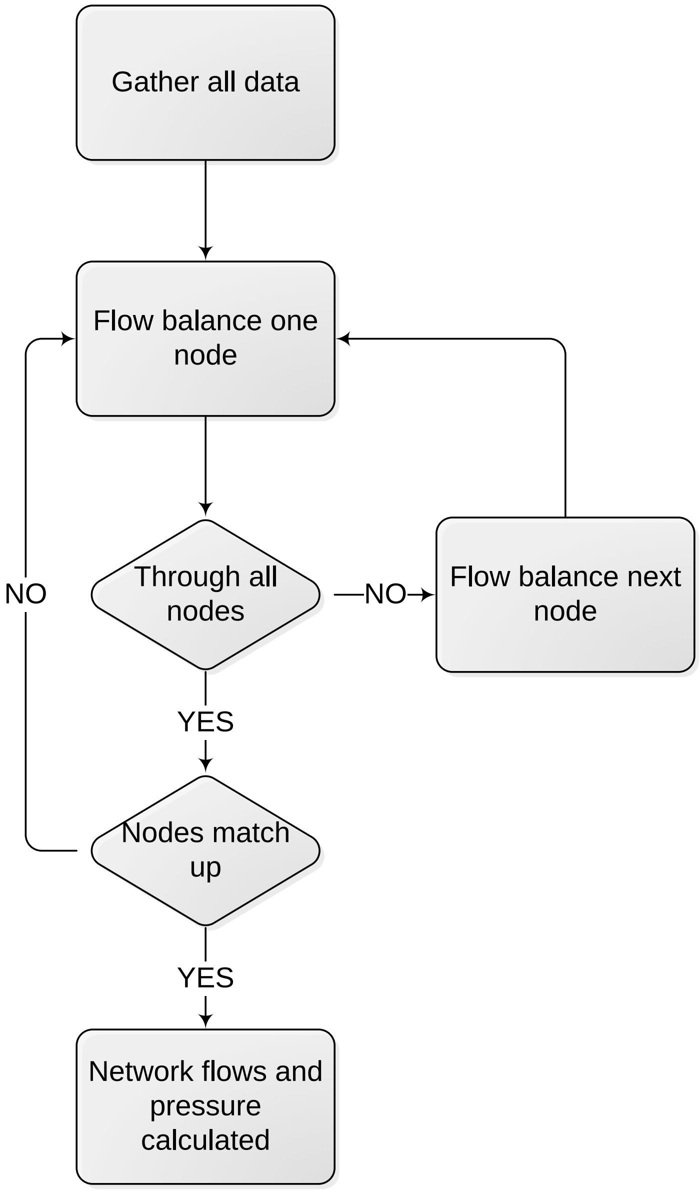


Figure 27: Air Simulator process

Figure 27 shows the process block of the Air Simulator component. The Air Simulator starts by making a copy of all the data and then it follows the process block in Figure 28 until the flow is balanced in the node. It repeats the flow balance for each node. If the rate of change between two nodes drops below 1, the whole network is simulated. If this is not the case, then the Air Simulator starts over by repeating the process.

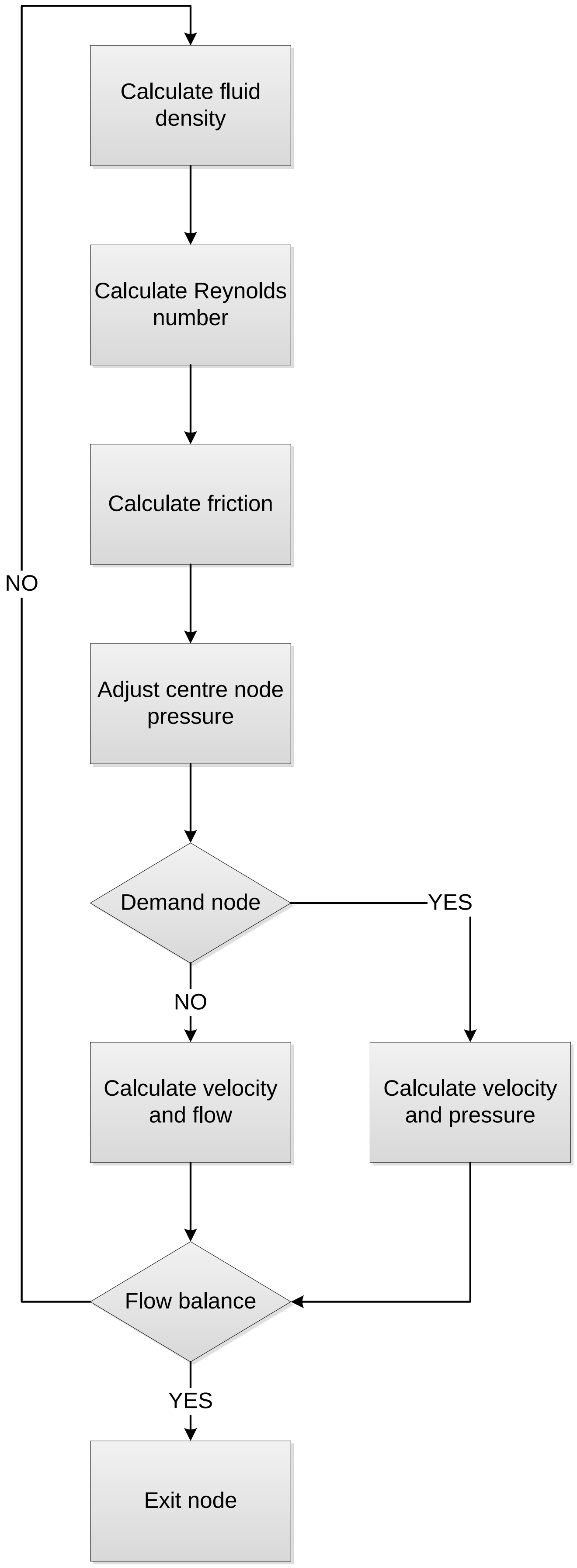


Figure 28: Air Simulator calculation process

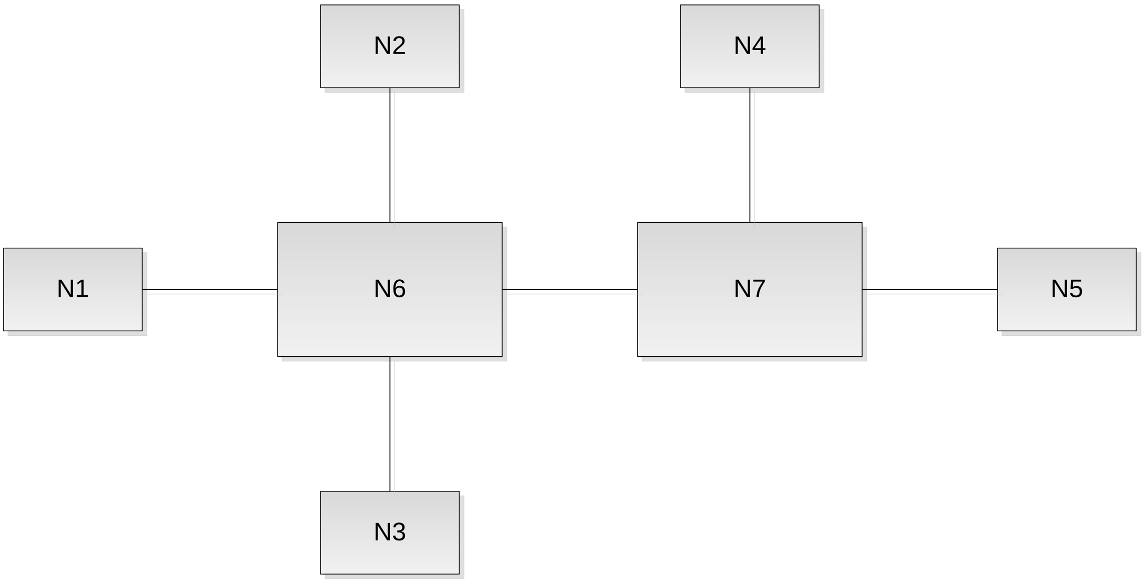


Figure 29: Network example

The Air Simulator will break up the network into nodes for simulating. It will only use the Air Nodes that represent junctions. If the Air Simulator simulated the network in Figure 29, it would break up the network in two smaller networks. N6 and N7 are Air Nodes representing junctions in the network while N1 to N5 are either air supply points or air end-users. These two smaller networks can be seen in Figure 30. By using this approach, the Air Simulator can simulate very large and complex networks.

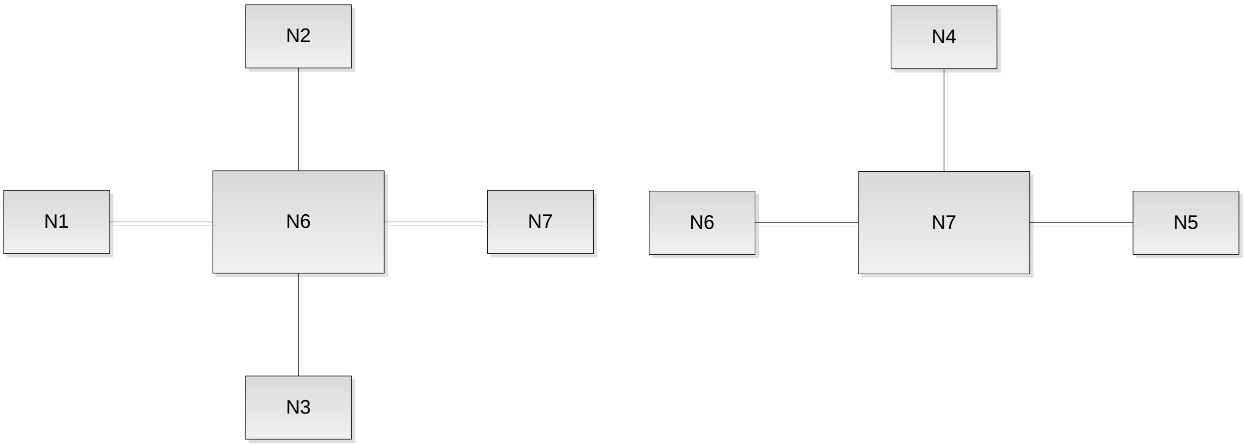


Figure 30: Network example breakup

The Air Simulator calculates the network three separate times, each with different values. The values used for each of the calculations are: current values, set-point values and future values. The set-point and future networks differ from the current network in that they only use pressure as starting points for the calculations while the current network uses pressure as well as flow for the initial values of the network.

The Air Simulator component handles these three different networks separately. Each of these networks will follow the same procedure when calculating the values. As the calculations are done on a separate thread, the component makes a copy of the data before it starts processing. This prevents the case where two components try to access the same data at the same time. The REMS design stops this by only allowing one component at a time to run its run function.

During this run time the Air Simulator component will check to make sure it is not already calculating. If it is not running it will make a local copy of the data before it starts the thread to start the calculations. The thread will start to calculate the current values. If tags are present for the set-point network it will be calculated next and, if tags are present for the future network, it will be calculated last.

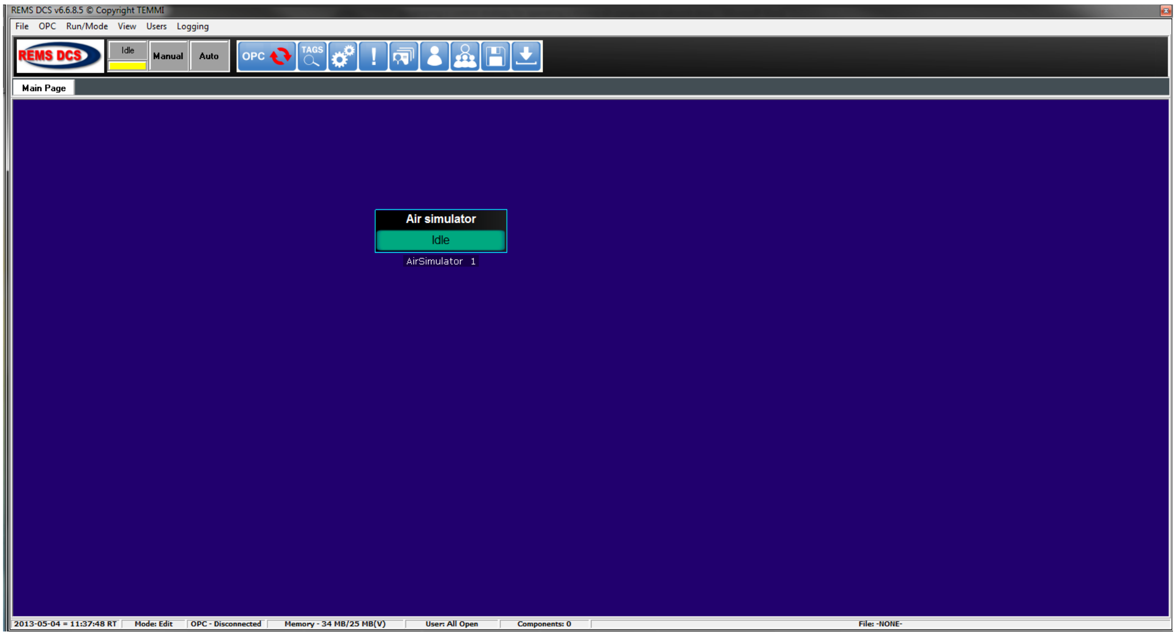
When the Air Simulator is calculating the current values network it will use the flow of the end-users to calculate the upstream pressure of the end-users. The downstream pressure is used as a starting point. As it is impossible to know what the flow will be in the future and because of the dynamic nature of the usage of compressed air, the set-point and future values network will not use the flow to calculate the pressure and will instead just use the set-point and future set-point values for the end-users.

During calculations the Air Simulator component only works with the normal nodes and not the supply and demand nodes. It forms small networks as depicted in Figure 13 where there is a central node with three or four border nodes. It solves each of these in turn and keeps resolving each one until the rate of change between the flows of two adjacent pairs are less than 1.

To help with the preservation of resources the user is limited to only one Air Simulator component. This has no negative impact since one component can calculate more than one network. To ensure that the Air Simulator can calculate more accurately, it requires a weather station component with ambient temperature and ambient pressure OPC tags. This will ensure that the Air Simulator can use accurate temperature and air pressure when calculating.

GUI

The GUI of the Air Simulator component is divided into an icon and an edit form. The icon of the Air Simulator component can be seen in Figure 31. The icon displays “idle” when the thread is currently not processing. The text on the icon will switch to “calculating…” when the thread is busy calculating the values since this can take a while. The icon will also be displayed if the Air Simulator component encountered an error.

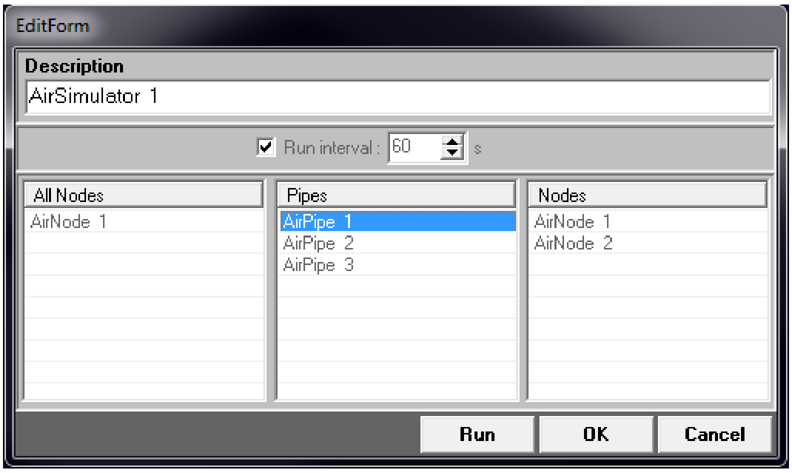


2013-05-04 = 11:37:48 RT | Mode: Edit | OPC - Disconnected | Memory - 34 MB/25 MB(V) | User: All Open | Components: 0 | File: -NONE-

Figure 31: DCS Air Simulator

Figure 32 shows the edit form for the Air Simulator. The Air Simulator does not have any options except for the idle time. This idle time is the lapse of time since the last calculation of the values. As it is not necessary to calculate all the values in real-time and continuously, the timer preserves resources for the computer by only allowing a calculation after a period of time specified by the user.

The bottom three boxes are used for debugging purposes by the user. This allows the user to check up on his created air network to ensure everything is connected as he intended it to be connected. If the user selects a node, the Air Simulator component will display all pipes connected to that node. If one of those pipes is selected, the Air Simulator will display the two nodes connected to that pipe. In the first box the component will only display the Air Nodes that are of the type normal node. An example of the edit form can be seen in Figure 32.



Description
AirSimulator 1

☑ Run interval : 60 s

All Nodes	Pipes	Nodes
AirNode 1	AirPipe 1	AirNode 1
	AirPipe 2	AirNode 2
	AirPipe 3	

Figure 32: Air Simulator edit form

2.5.4. Set-Point Controller

The Set-Point Controller component is responsible for the calculation of the compressor house pressure set-points. These set-points are determined for compressed air supply locations and not on individual compressors. The Set-Point Controller tries to calculate the minimum set-points that will supply the minimum required air pressure to all end-users to ensure that no equipment is damaged and the lowest possible pressure is delivered [46].

The Set-Point Controller component uses the calculated results of the Air Simulator component in its calculations which means that the Set-Point Controller cannot be used without the Air Simulator component. Like the Air Simulator component the Set-Point Controller can only be added once to each project since they will adjust all set-points on a network, whether they are connected or not.

The Set-Point Controller uses the same basis for its calculations as the Air Simulator, resulting in similar calculations. The difference is that while the Air Simulator component tries to calculate the pressure and flow of the nodes, the Set-Point Controller tries to calculate the minimum supply pressure, given the required demand pressure at the demand nodes.

It accomplishes this by calculating the resistance of each end-user. This resistance will not change with pressure and will always be the same. This can be calculated by Equation 1-19. As the pressure for each demand node is unknown, it uses the resistance to flow as well as the atmospheric pressure, as the end point pressure. This allows it to simulate all the flows of the network which in turn will allow it to calculate the pressure of each node and compare that pressure to the set-point of that node.

The Set-Point Controller only calculates a new set-point pressure if the current pressure and the set-point pressure of an end-user differ by 5kPa. The process block for the Set-Point Controller can be seen in Figure 33. It is very similar to the process of the Air Simulator except that it calculates the resistance as well as the pressure of the end-users from the new supply users.

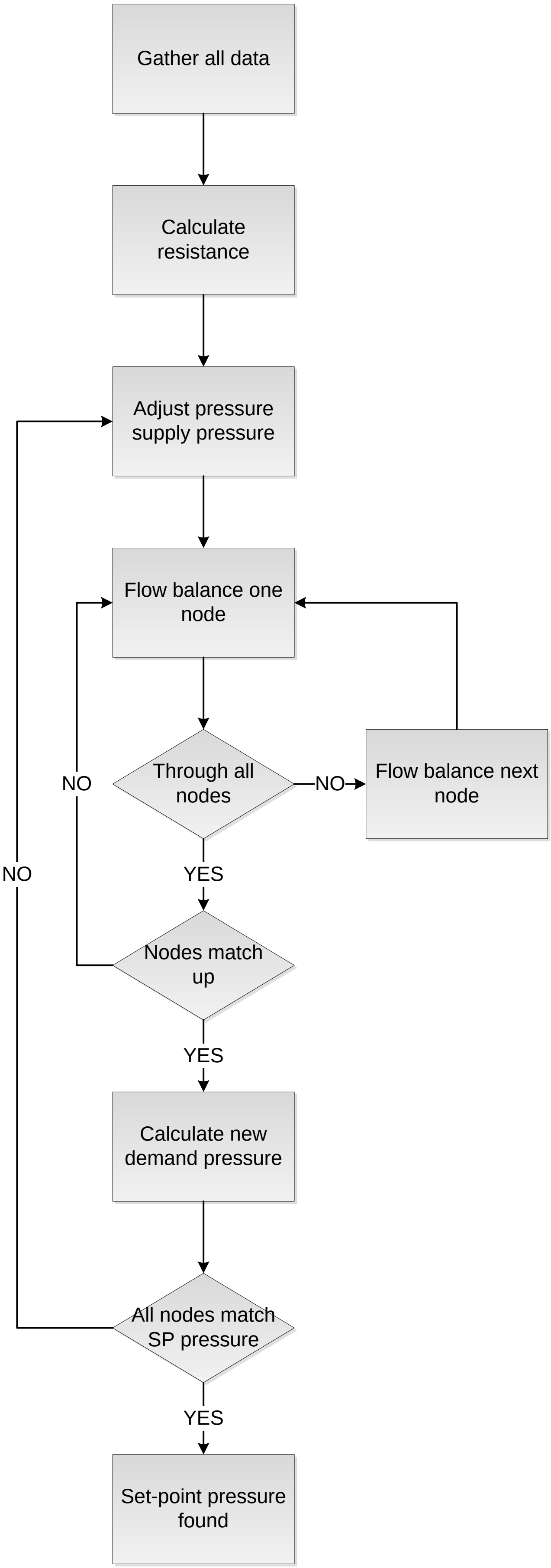
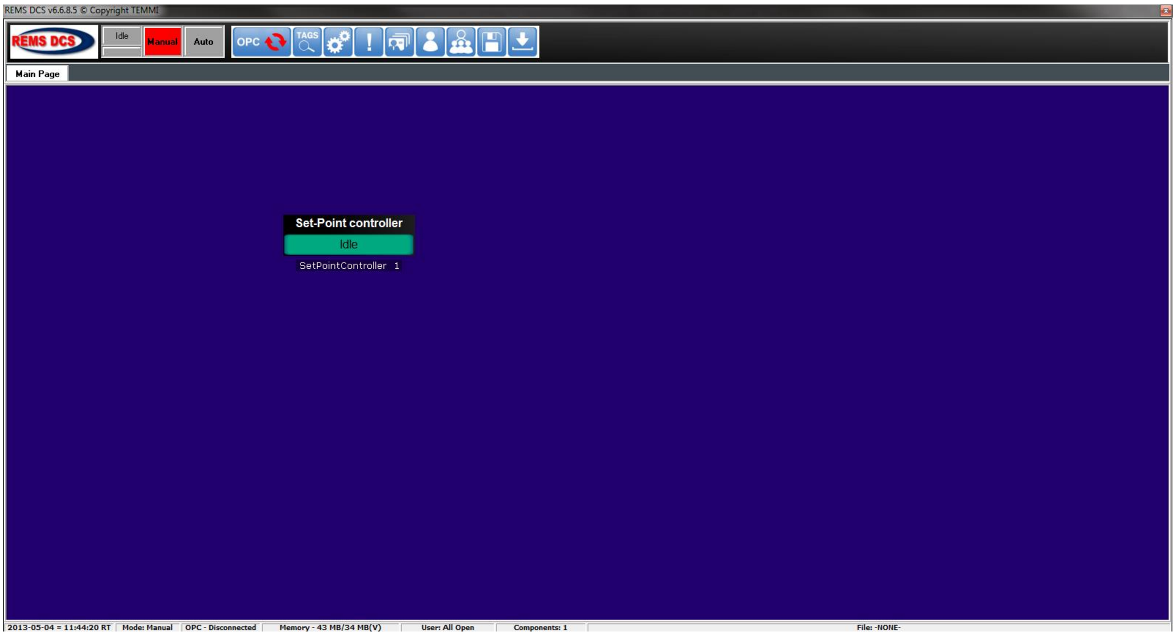


Figure 33: Set-Point Controller process

Like the Air Simulator component the Set-Point Controller component will also do all calculations in a separate thread to keep the GUI fully responsive to user input. The method of solving is the exact same as the air pressure component but it only replaces the set-point pressure value of the supply nodes. To help improve accuracy it can also read OPC tags for ambient temperature and atmospheric pressure.

GUI

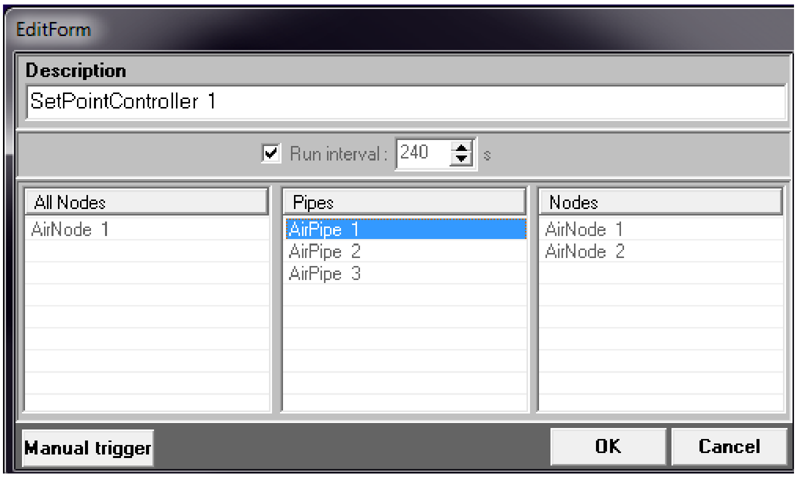
The GUI for the Set-Point Controller component is divided into two: the icon and the edit form. The icon can be seen in Figure 34. This icon displays the status of the set-point controller. It displays *idle* when it is not calculating, *calculating* when it is calculating and *updating* when it is updating values to the nodes and OPC tags. If it encounters a problem, the icon will also display the error.



2013-05-04 = 11:44:20 RT | Mode: Manual | OPC - Disconnected | Memory - 43 MB/34 MB(V) | User: All Open | Components: 1 | File: -NONE-

Figure 34: DCS Set-Point controller

The edit form of the component can be seen in Figure 35. The edit form is very similar to the Air Simulator component. It offers the user the opportunity to change the name, edit the run interval and enable the component. It also features the debug windows to ensure that the network is seen correctly from the component’s view. This debug feature works exactly the same as in the Air Simulator component. The manual trigger button allows the user to start the calculations immediately without waiting for the timer to run out.



Description: SetPointController 1

☑ Run interval : 240 s

All Nodes: AirNode 1

Pipes: AirPipe 1 (selected), AirPipe 2, AirPipe 3

Nodes: AirNode 1, AirNode 2

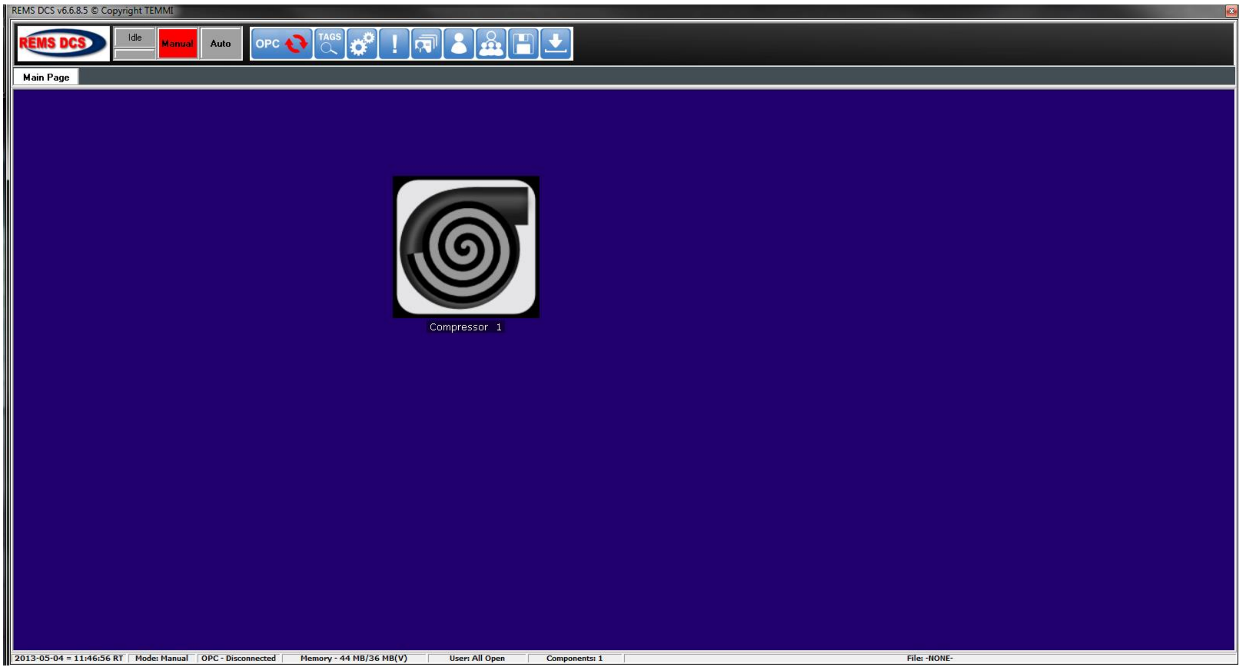
Figure 35: Set-Point Controller edit form

2.5.5. Compressor

The Compressor Component is merely a virtualisation of a compressor. This component will only act as a bridge to the SCADA. It will get status values from the SCADA and give instructions back to the SCADA. This will all be done via OPC tags. The Compressor Component will also hold all relevant information about the compressor. These can then all be acquired from the Compressor Component by other components.

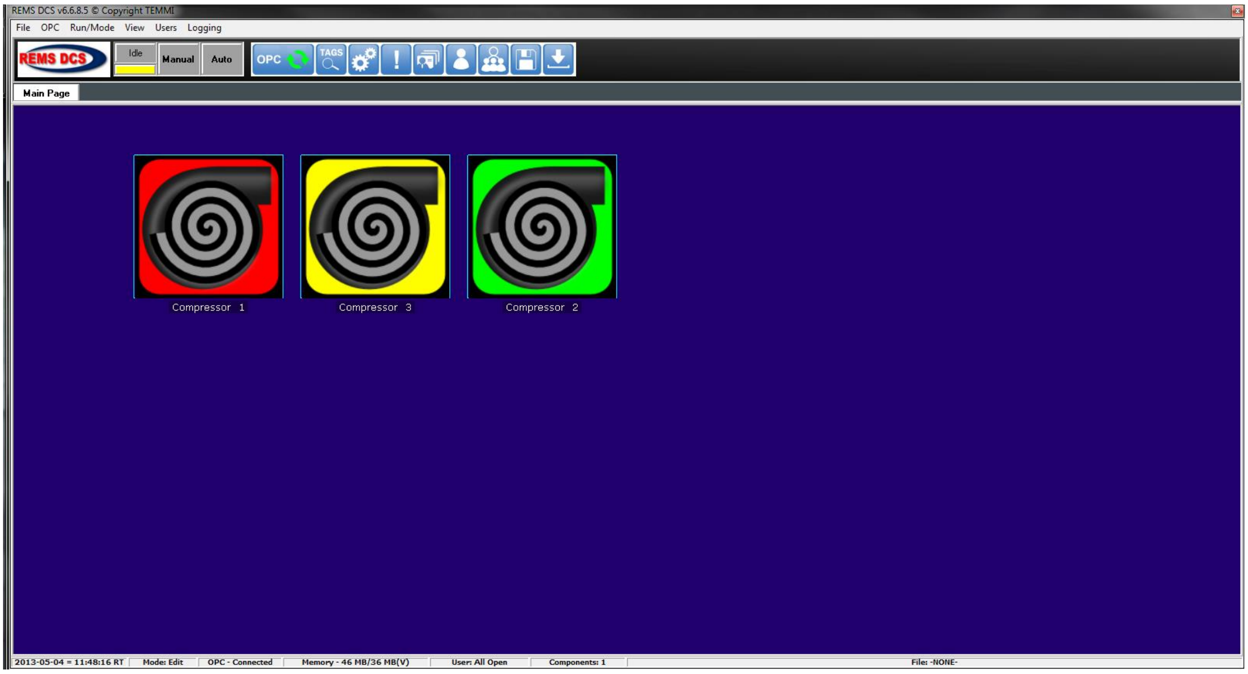
GUI

The GUI for the compressor is divided into three: icon, view form and edit form. The basic icon can be seen in Figure 36. This icon is displayed if no connection to the SCADA is available. If a connection is available to the SCADA, the icon changes to red, yellow or green. This can be seen in Figure 37. If the icon is red: the compressor is not running. If the icon is yellow the compressor is running but not loaded. If the icon is green the compressor is running and loaded.



2013-05-04 = 11:46:56 RT | Mode: Manual | OPC - Disconnected | Memory - 44 MB/36 MB(V) | User: All Open | Components: 1 | File: -NONE-

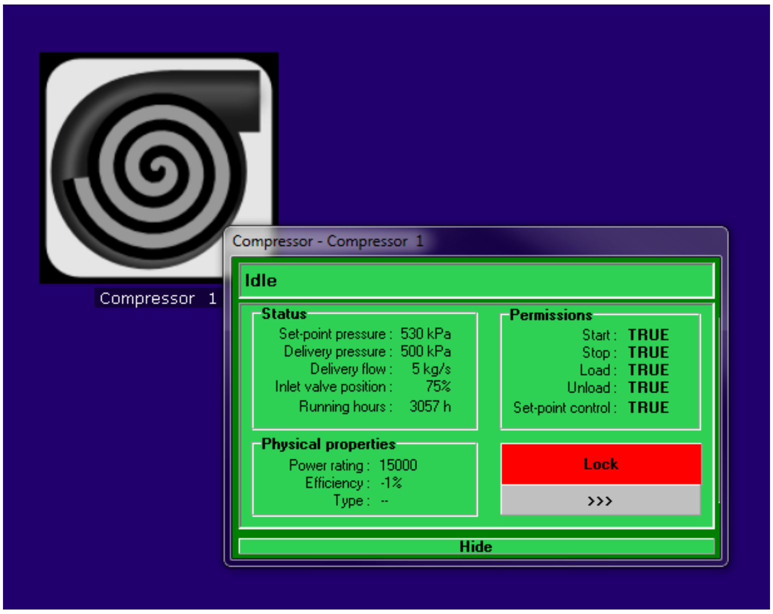
Figure 36: DCS compressor



2013-05-04 = 11:48:16 RT | Mode: Edit | OPC - Connected | Memory - 46 MB/36 MB(V) | User: All Open | Components: 1 | File: -NONE-

Figure 37: Compressor status

The view form for the Compressor Component will show the status, permissions and physical properties of the compressor. This page can be viewed by any user group. If the user has sufficient rights, the user can lock the compressor which draws a cross across the compressor. If a compressor is locked out, the compressor is unavailable to the other components. This means its status cannot be changed by other components. The basic view form can be seen in Figure 38.



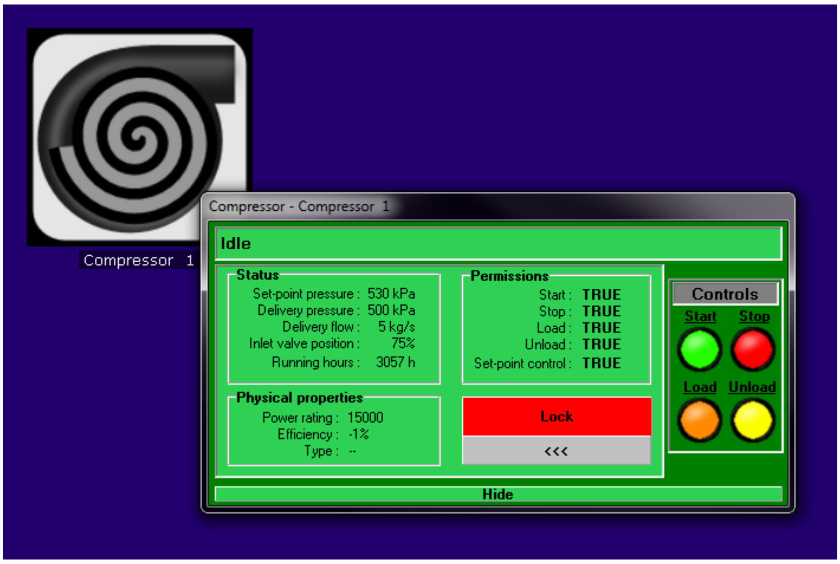
Set-point pressure : 530 kPa
Delivery pressure : 500 kPa
Delivery flow : 5 kg/s
Inlet valve position : 75%
Running hours : 3057 h

Start : TRUE
Stop : TRUE
Load : TRUE
Unload : TRUE
Set-point control : TRUE

Power rating : 15000
Efficiency : -1%
Type : --

Figure 38: Compressor view form

If the user has the required privileges he can open the advance menu by selecting the >>> button. The advance menu can be seen in Figure 39. From this menu the user can start, stop, load and unload the specific compressor linked to the Compressor Component. This can be done in manual or auto mode. The system will write the data through to the SCADA for this request even if it is in manual mode, where writing to OPC tags is usually disabled.



Set-point pressure : 530 kPa
Delivery pressure : 500 kPa
Delivery flow : 5 kg/s
Inlet valve position : 75%
Running hours : 3057 h

Start : TRUE
Stop : TRUE
Load : TRUE
Unload : TRUE
Set-point control : TRUE

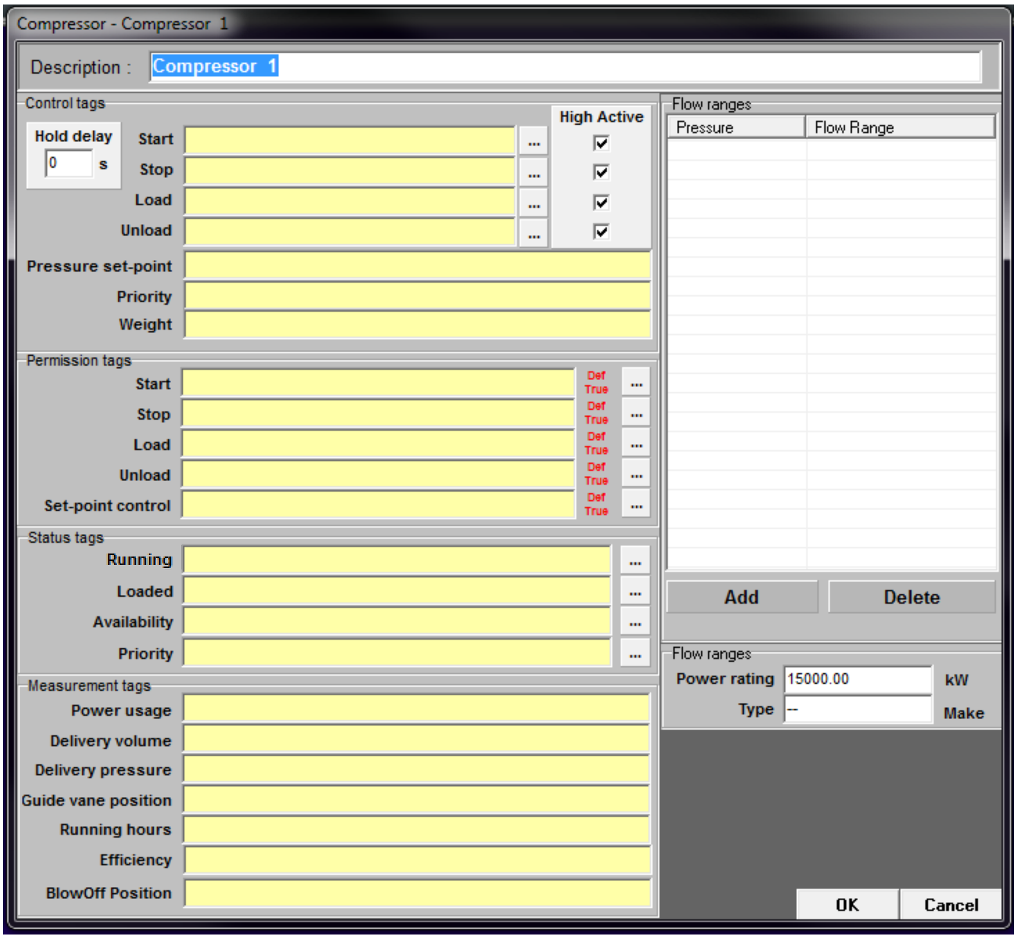
Power rating : 15000
Efficiency : -1%
Type : --

Figure 39: Compressor view form advance

The edit form of the Compressor Component allows the user to change the properties of the compressor and link them to actual OPC tags. The edit form of the Compressor Component can be seen in Figure 40. This edit form is divided into six sections: control tags, permission tags, status tags, measurement tags, flow ranges and properties. The high active tick boxes make 1 or high true; however, if this is unticked, high or 1 will be false.

The control tags section is used to link the component with OPC tags for controlling the compressor. The start, stop, load and unload tags will go high if the compressor must go into that state. The pressure set-point tag will be used to give an individual compressor a pressure set-point. The priority is used when starting or stopping a compressor to stop or start the optimum compressor. The weight tag is used by the Compressor Controller Component when deciding between two compressors which are equal in size.

The permission tags section is used by the Compressor Component to gather its permissions. These permissions are: start, stop, load, unload and set-point control. If these permissions are false then the compressor knows it cannot change the control tag related to that compressor. To make it easier for the user, these tags all have a default value of 1 or true. If no tag is present then the compressor assumes the value is 1 or true.



Description : Compressor 1

Hold delay: 0 s

High Active: Start ☑ Stop ☑ Load ☑ Unload ☑

Power rating: 15000.00 kW

Type: --

Figure 40: Compressor edit form

The status tags are used to get feedback from the Compressor Component to the user. These tags are: running, loaded, availability and priority. The running tag is used to ascertain whether the compressor is running, while the loaded tag is used to ascertain whether the compressor is loaded. The availability tag is used to see if the compressor is available to start. The priority indicates the current priority of the compressor.

The measurement tags are used to give feedback to the user for logging purposes. These tags are: power usage, delivery volume, delivery pressure, guide vane position, running hours, efficiency and blow off position. These properties are also used for logging purposes. The power rating and type can also be entered manually by the user.

The flow ranges section of the compressor is used to acquire the compressor performance map. Estimations are used to make it easier to input the map. The user must enter a flow range for a specific pressure since the compressor can only deliver a specific flow range at a specific pressure. This is used by the compressor controller component when selecting a compressor.

2.5.6. Dynamic Compressor Controller

The Dynamic Compressor Controller is the component responsible for controlling the compressors. It selects the priorities of the compressors as well as the start, stop, loading and unloading compressors. The controller can also be used to create priorities for the compressors. Each compressor controller component is linked to a set of specific compressors which are chosen by the user. The compressor controller component can only control one group. If there is a need to control more groups, additional controllers have to be used.

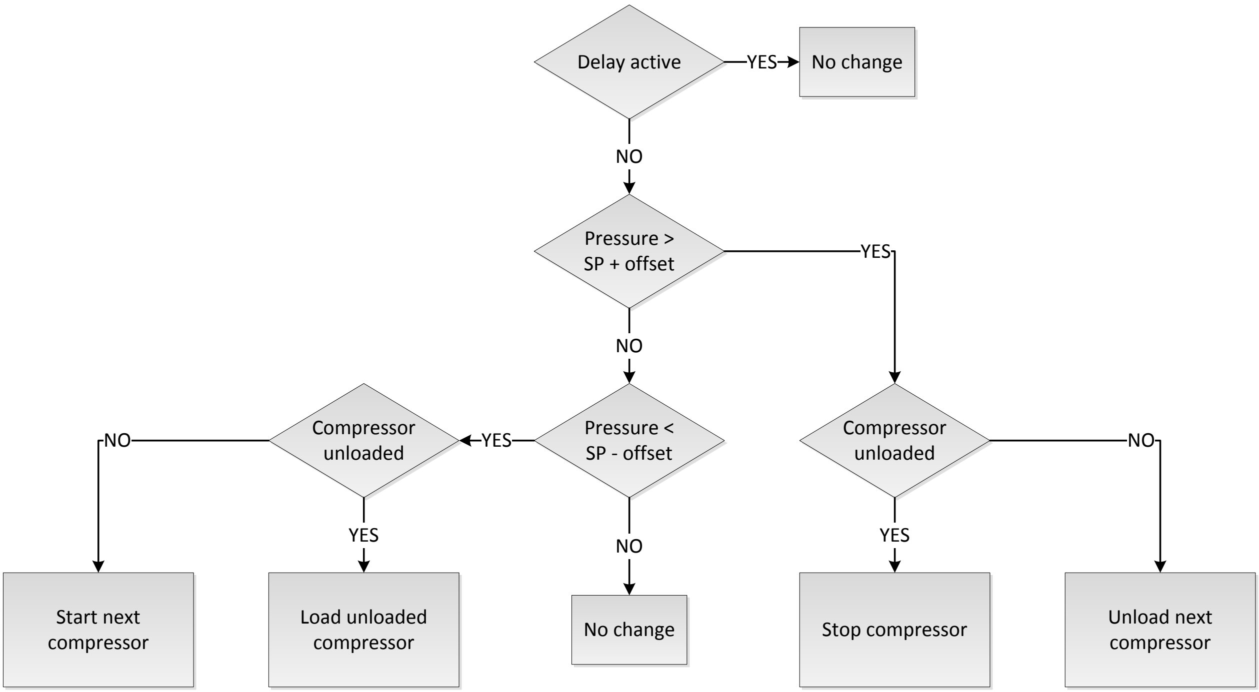


Figure 41: Compressor controller control philosophy

Figure 41 shows the compressor controller control philosophy. This is how the compressor controller decides what action to take depending on the delay and the actual current pressure. The delay timer is customisable by the user and is there to stop cycling of compressors. By default this timer is set to 30 minutes which limits compressor controller action to a maximum of once every 30 minutes. This time delay gives the network time to stabilise after a change.

The controller compares the actual pressure to the set-point (SP) pressure. If the two differ more than the offset, the compressor controller will take action dependent on the pressure being smaller or greater than the SP and the offset combined. To further reduce compressor cycling, the controller will first try to unload or load an already started compressor. An unloaded compressor consumes less power [47] than a loaded compressor which already results in reducing electricity consumption. If a compressor is required it will first load all unloaded compressors since they are already running.

The compressor priorities range from one to the maximum number of compressors. The compressor with priority one is the compressor with the highest priority, while the compressor with the highest number is the compressor with the lowest priority. When a compressor must be selected to start, the selected compressor will be the compressor with the lowest number for a priority that is not already running. When a compressor must be unloaded or started, the compressor with the highest number among the running compressors will be selected.

Because static priorities can negatively impact the selection of compressors the compressor controller component can dynamically change the priorities of the compressors. To do this the compressor controller takes into account the current required flow and the future required flow estimate to determine which will be the optimal compressors. To help reduce cycling, compressors already running get preference from the controller.

Figure 42 shows how the controller calculates the priorities of the compressors, the compressors are divided into three groups by the compressor controller component: baseload, running and off. Base-load compressors are chosen by the user. These compressors are always kept on and must therefore always be given the highest possible priority. The compressor controller is not allowed to shut down these compressors and thus, when calculating priorities, these compressors are given the lowest number first.

The next compressors to be taken into account are the running compressors. The compressor controller obtains the necessary data of all running compressors to calculate their combined maximum[4] and minimum[5] flows. The compressor controller then compares it to the required flow. The compressor controller's required flow will be either the required flow or the estimated future required flow, whichever is the highest.

If it is possible to remove the minimum supplied flow, from one of the current running compressors from the current total running minimum flow, then the compressor controller will move the compressors to the off list. The current required flow will then be adjusted to the current on list of compressors to reflect the removed compressor. This can be done more than once to remove more than one compressor.

If the required flow is more than the current supplied flow then the compressor controller will add a new compressor. This selection of the new compressor will be done on the average[6] supplied flow. The compressor controller uses the average and not the maximum because that adds headroom for flow change which in turn will reduce cycling by the lessening the need to change around compressors.

The compressor controller chooses the smallest possible compressor on an average flow that will make the supplied flow larger than the required flow. If no single compressor can be found to satisfy this need, the compressor controller will add the largest possible compressor. If the maximum supplied flow is still less than the required flow, another compressor will be selected to be added to the on list.

The compressor controller will then process the three lists and assign priorities to them. It will start at priority 1 and keep on increasing that by one when assigning priorities, in the following order: base-load, on and then off. This will ensure that the baseload compressors will always have the lowest priorities, followed by the optimal compressors.

The off list is ordered from small to large since it is more likely that an additional small increment of flow will be required rather than a large flow. Small compressors are also the better option because they use less energy when started and start quicker. This flow calculation runs completely independent of the controller part and only creates priorities for the compressors. This will allow the compressor controller to be used in locations where another controller is already being used to control the start and stop of compressors.

---

[4] The maximum flow is the maximum flow the compressor can supply at the current pressure according to the performance map, this data is supplied by the compressor component.

[5] The minimum flow is the minimum flow the compressor can supply at the current pressure according to the performance map, this data is supplied by the compressor component.

[6] The average supplied flow is the average between the minimum supplied flow and the maximum supplied flow.

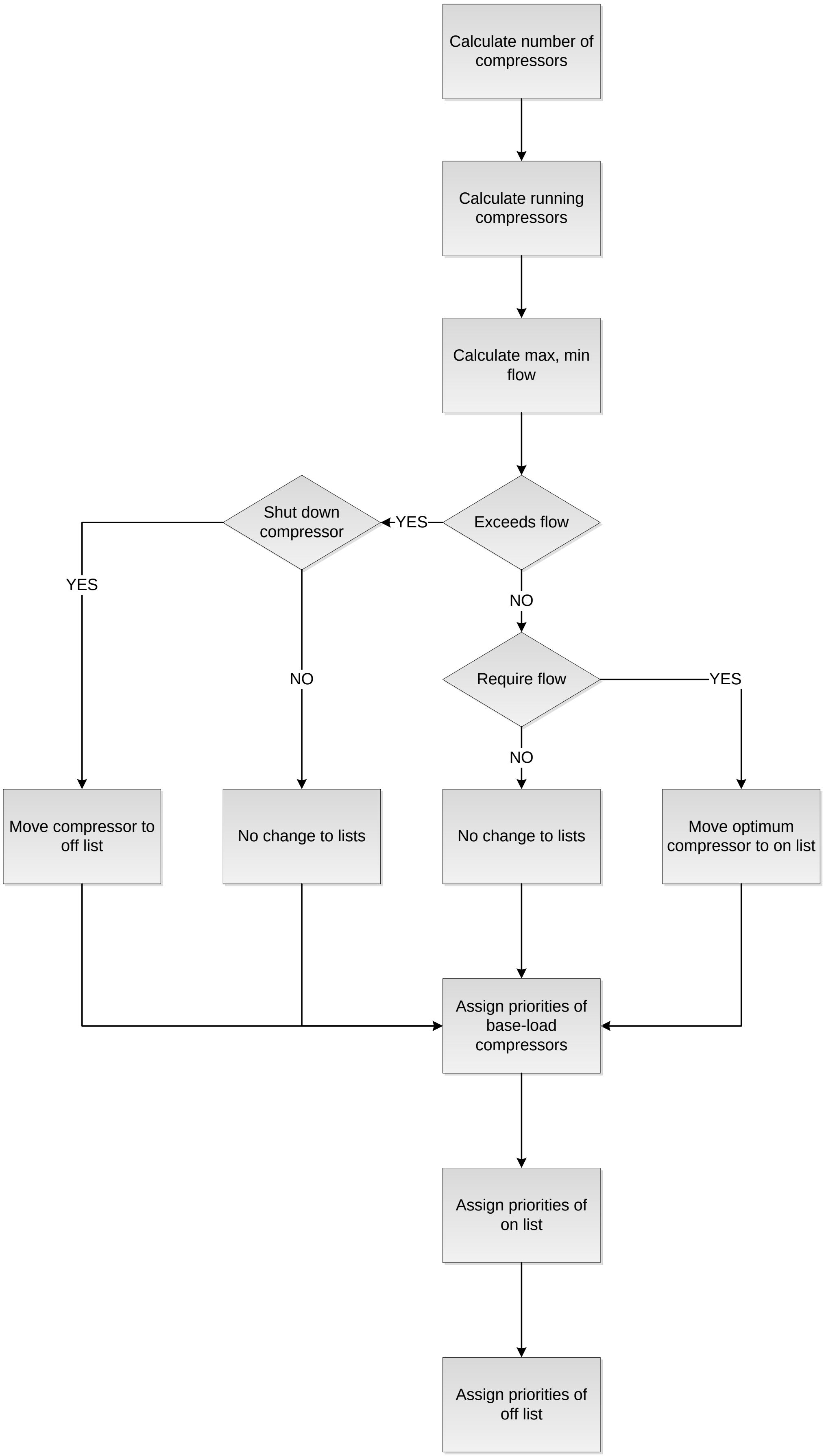
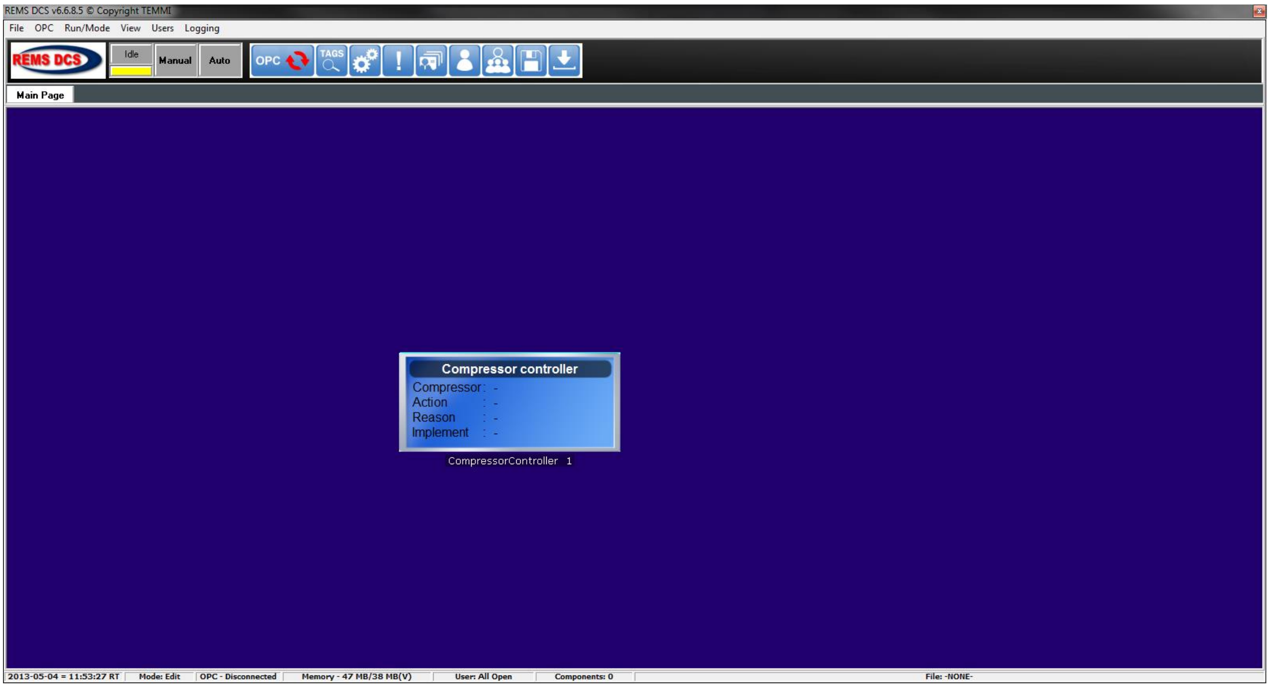


Figure 42: Compressor controller flow calculations

GUI

The compressor controller component's GUI is divided into three: the icon, view form and edit form. The icon of the compressor controller can be seen in Figure 43 and displays the action the compressor is implementing as well as the action it wants to implement and the countdown to that action. This allows the user to see what the controller is currently doing and what it wants to do in the future. This also allows an operator to stop it if the proposed action is undesirable.

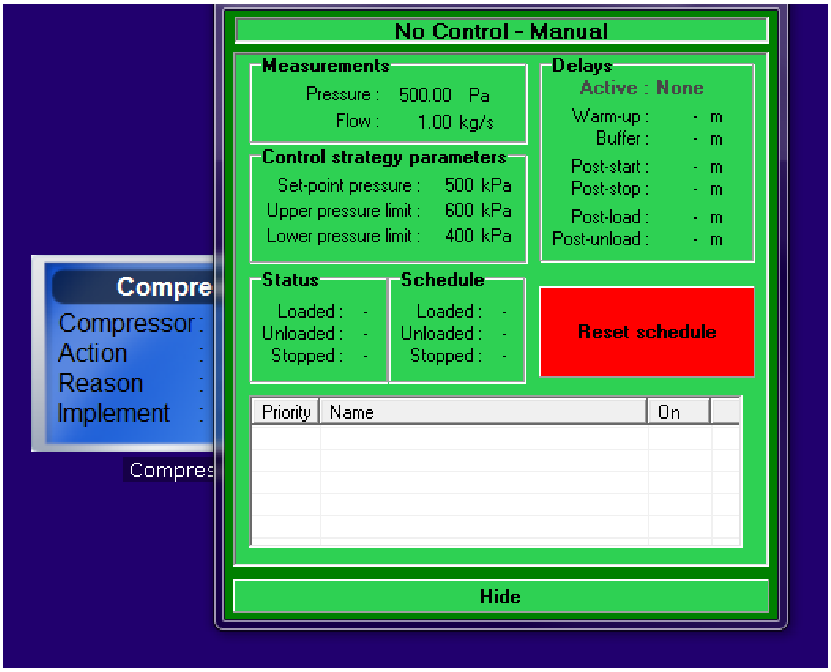


Compressor controller
Compressor : -
Action : -
Reason : -
Implement : -

2013-05-04 = 11:53:27 RT | Mode: Edit | OPC - Disconnected | Memory - 47 MB/38 MB(V) | User: All Open | Components: 0 | File: -NONE-

Figure 43: DCS compressor controller

The view form of the compressor controller can be seen in Figure 44. The view form allows all users to view the current properties of the controller and displays the measurements, control parameters, status, schedule and delays. The reset button on the view form allows the user to reset the schedule and restart everything. The list on the bottom displays the priorities of the current attached compressors. The list will update when the user opens the view form. The right side column will show on which list the compressor resides. An example of a populated list can be seen in Figure 45.



No Control - Manual

Measurements
Pressure : 500.00 Pa
Flow : 1.00 kg/s

Control strategy parameters
Set-point pressure : 500 kPa
Upper pressure limit : 600 kPa
Lower pressure limit : 400 kPa

Delays
Active : None
Warm-up : - m
Buffer : - m
Post-start : - m
Post-stop : - m
Post-load : - m
Post-unload : - m

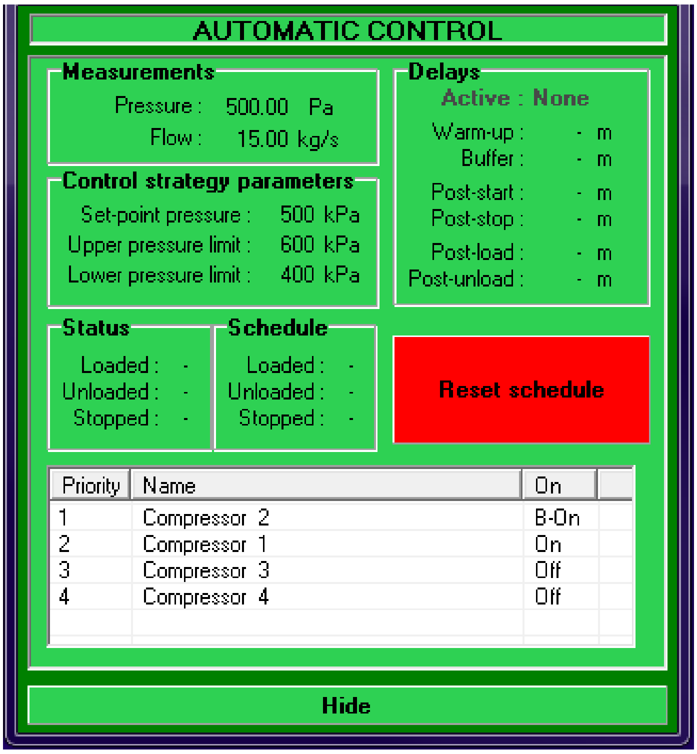
Status
Loaded : -
Unloaded : -
Stopped : -

Schedule
Loaded : -
Unloaded : -
Stopped : -

Priority	Name	On

Compre
Compressor :
Action :
Reason :
Implement :

Figure 44: Compressor controller view form



AUTOMATIC CONTROL

Measurements
Pressure : 500.00 Pa
Flow : 15.00 kg/s

Control strategy parameters
Set-point pressure : 500 kPa
Upper pressure limit : 600 kPa
Lower pressure limit : 400 kPa

Delays
Active : None
Warm-up : - m
Buffer : - m
Post-start : - m
Post-stop : - m
Post-load : - m
Post-unload : - m

Status
Loaded : -
Unloaded : -
Stopped : -

Schedule
Loaded : -
Unloaded : -
Stopped : -

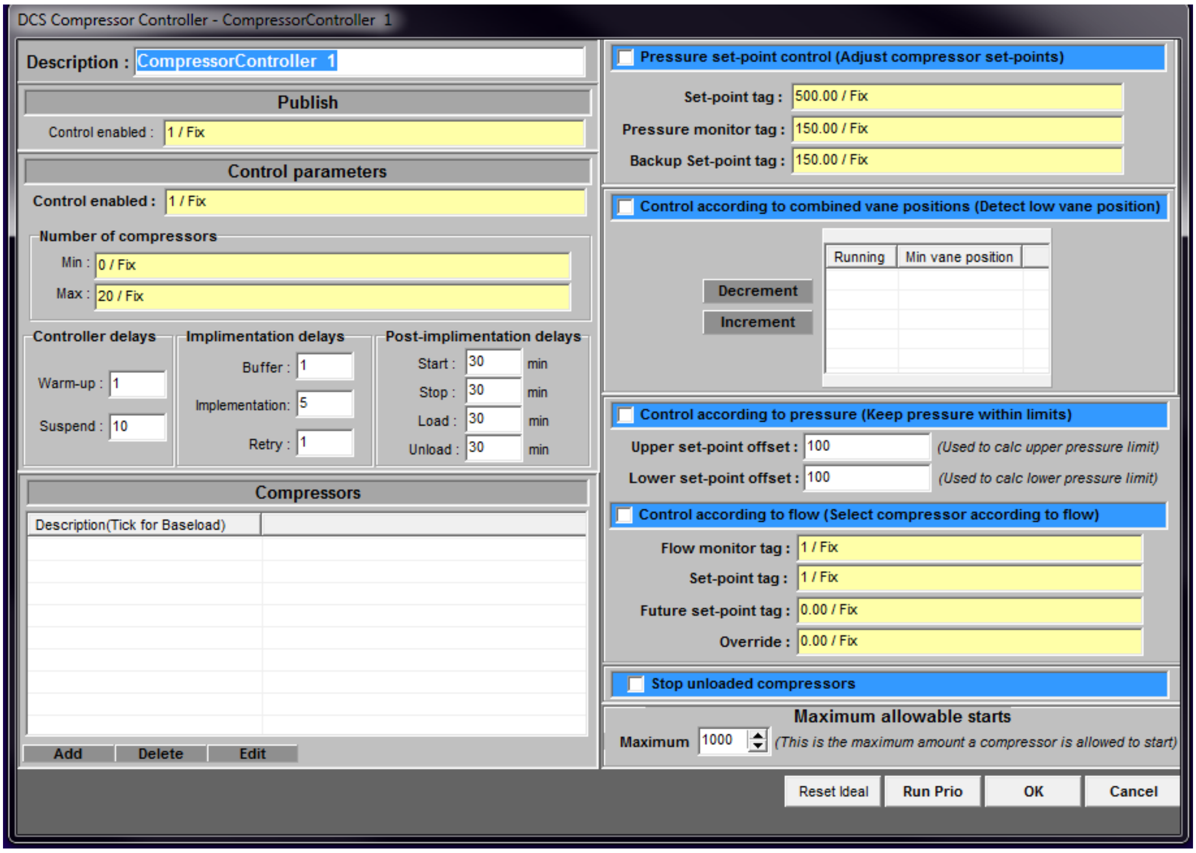
Priority	Name	On
1	Compressor 2	B-On
2	Compressor 1	On
3	Compressor 3	Off
4	Compressor 4	Off

Figure 45: Compressor controller priority list

The compressor edit form can be seen in Figure 46. This form allows the user to edit all properties and settings of the compressor controller component. The edit form is divided into three major sections: control parameters, compressors and control. The description allows the user to change the name of the compressor controller while control enables and disables the controller.

The control parameters allow the user to change the parameters of the controller. These include the following: minimum number of compressors, maximum number of compressors and all the delays. The parameter settings control the way the compressor controller controls all compressors added to it. The number of compressors is the maximum and minimum number allowed running at a time.

The compressors section allows the user to add and remove compressors to the controller. A compressor must be added to enable the controller to control it. The edit button allows the user to edit the properties of the selected compressor. If the add button is used, a list appears that allows users to select compressors to add. Compressors added will be displayed in the list with a tick box next to it to allow the user to make it a baseload compressor.



Description : CompressorController 1

Control enabled : 1 / Fix

Control enabled : 1 / Fix

Number of compressors

Min : 0 / Fix

Max : 20 / Fix

Controller delays

Warm-up : 1

Suspend : 10

Implimentation delays

Buffer : 1

Implementation: 5

Retry : 1

Post-implimentation delays

Start : 30 min

Stop : 30 min

Load : 30 min

Unload : 30 min

☐ Pressure set-point control (Adjust compressor set-points)

Set-point tag : 500.00 / Fix

Pressure monitor tag : 150.00 / Fix

Backup Set-point tag : 150.00 / Fix

☐ Control according to combined vane positions (Detect low vane position)

☐ Control according to pressure (Keep pressure within limits)

Upper set-point offset : 100 *(Used to calc upper pressure limit)*

Lower set-point offset : 100 *(Used to calc lower pressure limit)*

☐ Control according to flow (Select compressor according to flow)

Flow monitor tag : 1 / Fix

Set-point tag : 1 / Fix

Future set-point tag : 0.00 / Fix

Override : 0.00 / Fix

☐ Stop unloaded compressors

Maximum allowable starts

Maximum 1000 *(This is the maximum amount a compressor is allowed to start)*

Figure 46: Compressor controller edit form

The following sections will allow the user to specify what the controller should use to control the compressors. The sections are: set-point control, guide vane control, pressure offsets, flow and unloading. The flow section must be enabled to allow the controller to automatically prioritise compressors according to flow. The maximum start time will allow the user to specify the maximum number of times a compressor can be started per day.

2.6. Summary

This section discussed the specific components that make up DCS. The components are discussed in detail and each specific function in the dynamic compressor selector is also discussed. The requirements for a successful dynamic compressor selector were identified which will allow the successful testing of the final product. The REMS design was discussed and also why the dynamic compressor selector was created with the REMS design.

3. Implementation and results

3.1. Foreword

This chapter focuses on the performance obtained from the DCS system. In this section attention will be given to the procedure as well as the obtained results. Implementation of this system, as well as problems observed will also be discussed. The theoretical results are tests of the accuracy of the simulations in the dynamic compressor sector system as well as the compressor selection. The requirements section will discuss tests to be compared to the requirements discussed in section 2.2.

3.2. Theoretical results

3.2.1. Node flow balance results

Purpose and setup

The purpose of this test was to determine if the Air Simulator can successfully do a flow balance on a node with three and four connecting pipes. The ability to perform a flow balance on an Air Node is critical to the network simulation since the network is divided into nodes before simulation. This test will determine if the Air Simulator can determine the centre air pressure where all the flows of the network are balanced.

The network comprises of the following two nodes seen in Figure 47 and Figure 48. The two networks were recreated in DCS and then applied to simulate the two networks. The pressure at the centre of the junction as well as the flow difference was plotted to examine the convergence of the networks.

For simplification all pipes in both these networks have a diameter of 0.6m, a length of 1000m, k-loss factor of 0 and a roughness of 45um. All the node types in the network were chosen as a supply type node. This was done to leave out flow based pressure calculations since this test only focuses on the flow balance of the nodes.

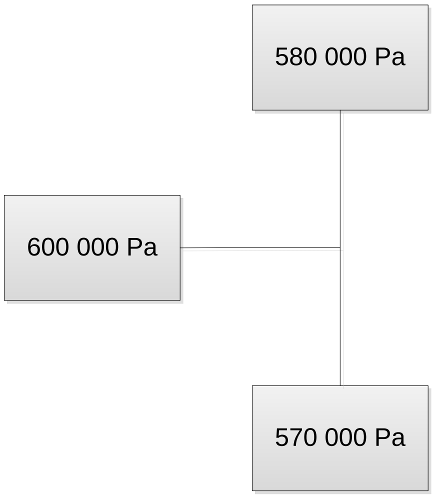


Figure 47: Test network 1

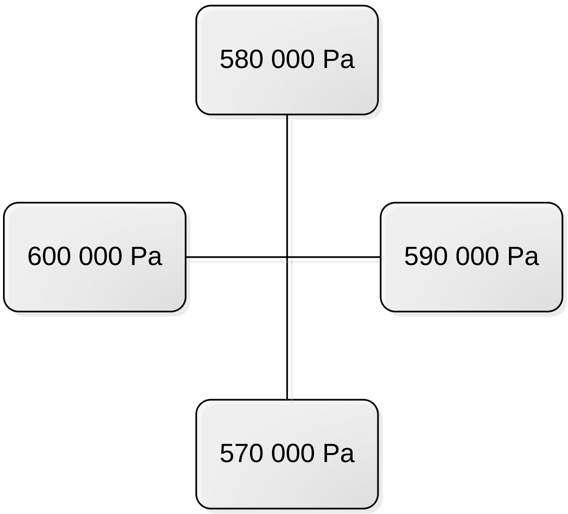


Figure 48: Test network 2

Results and observations

The junction pressure and the flow difference of test network 1 can be seen in Figure 49 and Figure 50. At the start of the simulation the average pressure at the end of all connected pipes are assigned to the centre node, in this case the average value was too high as can be seen from both figures. From past testing results the average pressure was established as a good estimated value for a starting point. Also because the average pressure is usually closer to the maximum pressure, the pressure is adjusted upwards at first.

As the pressure in the network as seen in Figure 47 was estimated too high, flow difference keeps increasing from the initial value. This keeps on happening until the pressure reaches the maximum pressure value, which is in this case 600,000 Pa. It then resets back to the average value and gets adjusted negatively. As soon as this occurs, the flow difference starts to decrease to 0. Figure 51 shows the results of network 1.

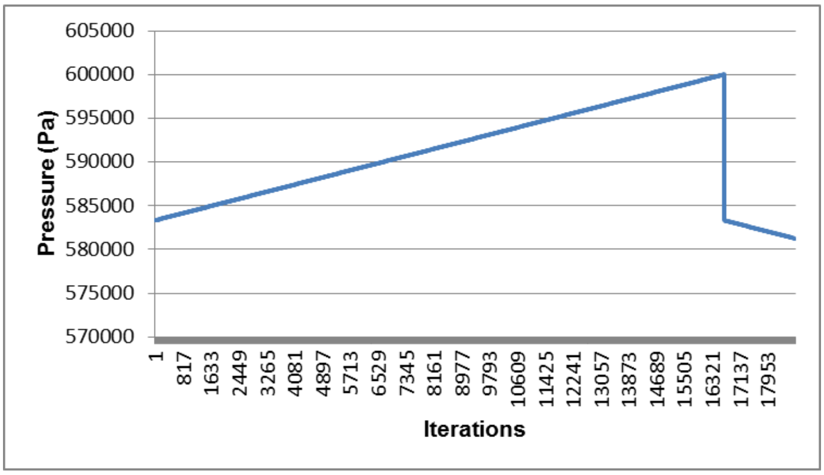


Figure 49: 3 Node junction pressure

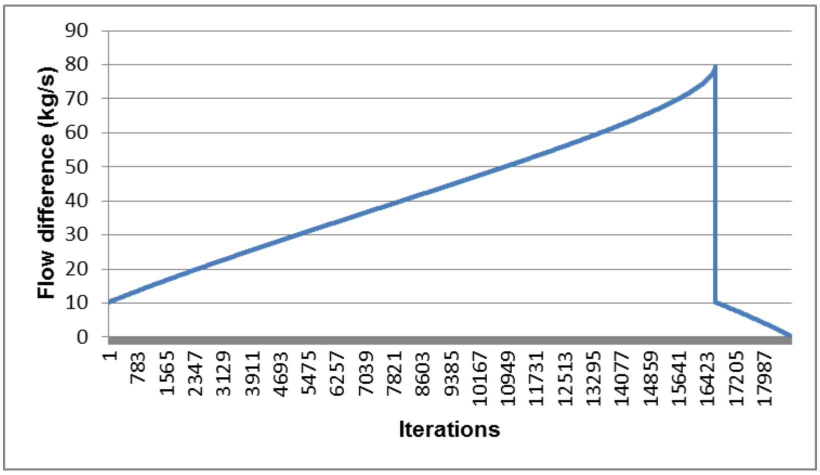


Figure 50: 3 Node flow difference

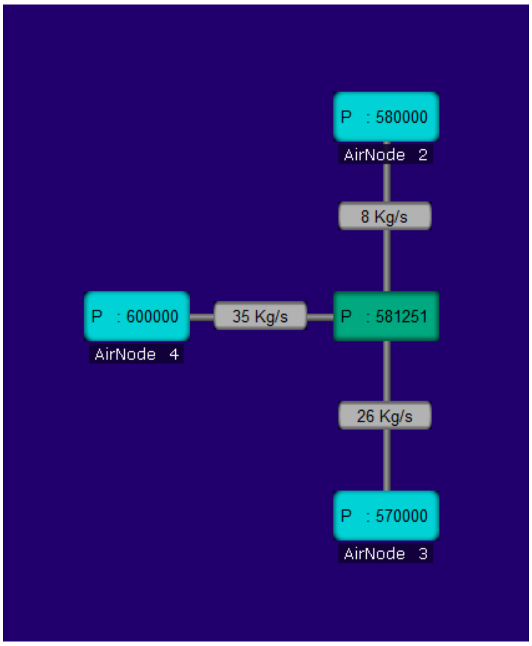


Figure 51: Network 1 results

The junction pressure and the flow difference of test network 1 can be seen in Figure 52 and Figure 53. The amount of iterations required to solve the network is much less in network 2 than in network 1 because the average pressure was much closer to the actual junction in test 2 than in test 1. Here the junction pressure only had to be adjusted upwards and not downwards. As the junction pressure gets closer to its actual pressure the flow difference keeps dropping until it drops below 0.2.

When it reaches 0.2 it is seen as an acceptable error and is presumed to be 0. The iterations stop at 0.2 because the values will keep on iterating and will eventually start oscillating. From historical data this can happen from as high as 0.1. The results of the solved network can be seen in Figure 54. The flow of AirPipe 4 is shown as negative because on the network the direction of flow is stated as flowing from the centre junction to AirNode 5 while in practice the flow is in the opposite direction, hence the negative flow.

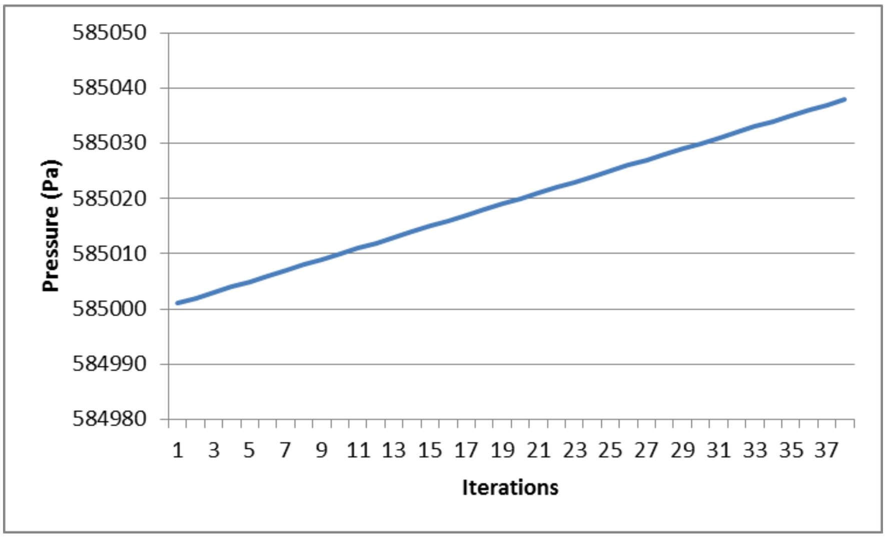


Figure 52: Junction pressure

Figure 53: Flow difference

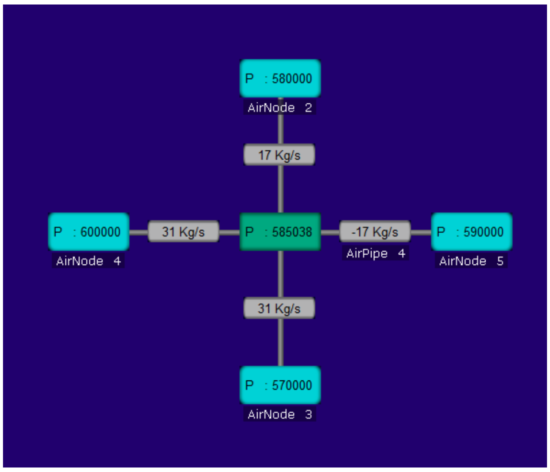


Figure 54: Network 2 results

3.2.2. Network simulation results

Purpose and setup

The flow balance was tested in section 3.2.1 and it was shown that DCS could solve a network node with flow balance. In this test it was tested if DCS could simulate a full network. The accuracy of the simulation was then compared to K-pipe[7] to establish if DCS can accurately simulate compressed air networks. The networks tested can be seen in: Figure 55 and Figure 56. These networks were recreated in DCS to test them.

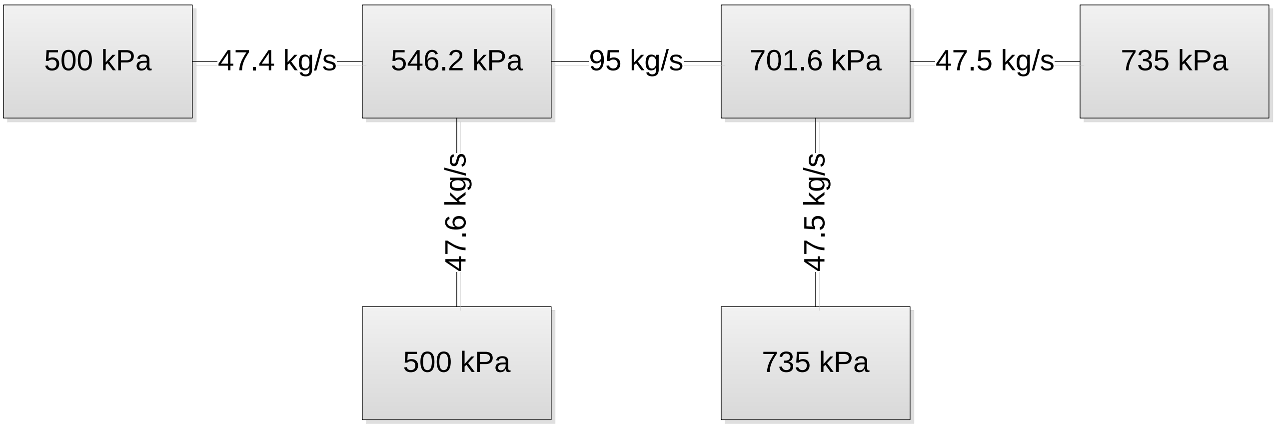


Figure 55: Test network 1

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[7] K-Pipe is a commercial fluid dynamic program used to simulate whole networks.

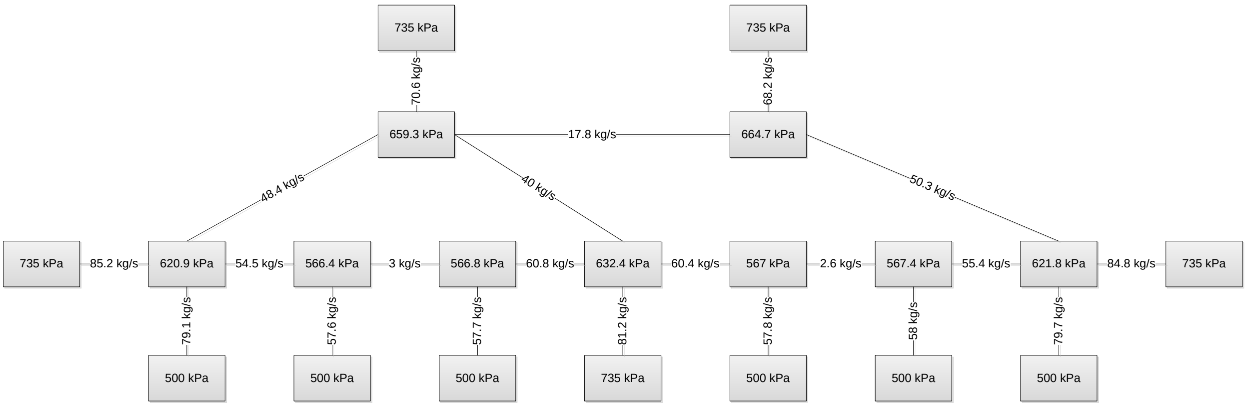

Figure 56: Test network 2

Results and observations

The results of the network simulations can be seen in Figure 57 and Figure 58. The accuracy of the network simulations can be seen in Table 3, Table 4 and Table 5. Because DCS only works with gauge pressure[8], the pressure readings will be lower than the ones in K-pipe. The atmospheric pressure used by DCS was 89,000 Pa. To be able to compare the gauge pressure used by DCS to the actual pressure used by K-pipe, 89,000 Pa should be added to the pressure.

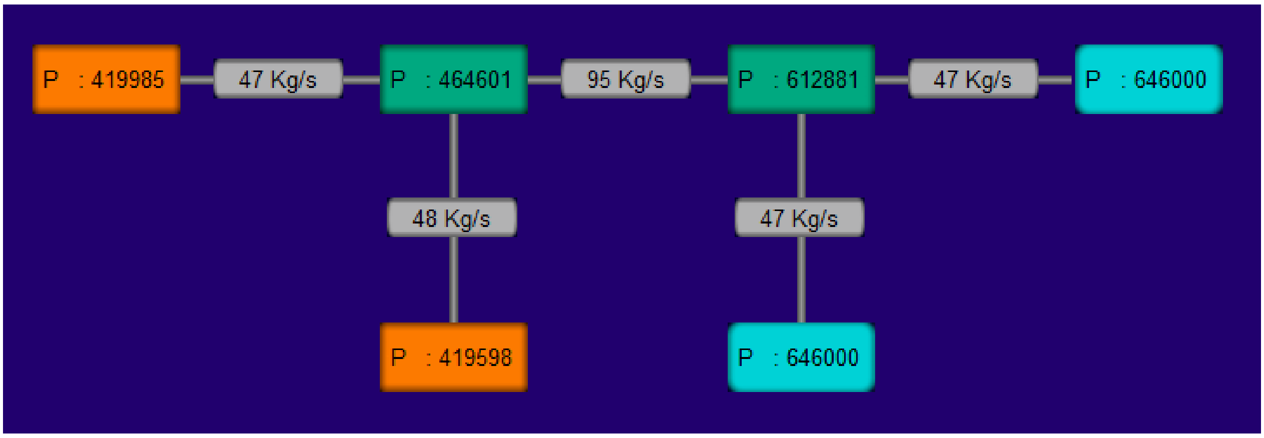

Figure 57: Solved test network 1

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[8] Gauge pressure is a pressure that is read by a pressure gauge on a pipe with the reading excluding atmospheric pressure.

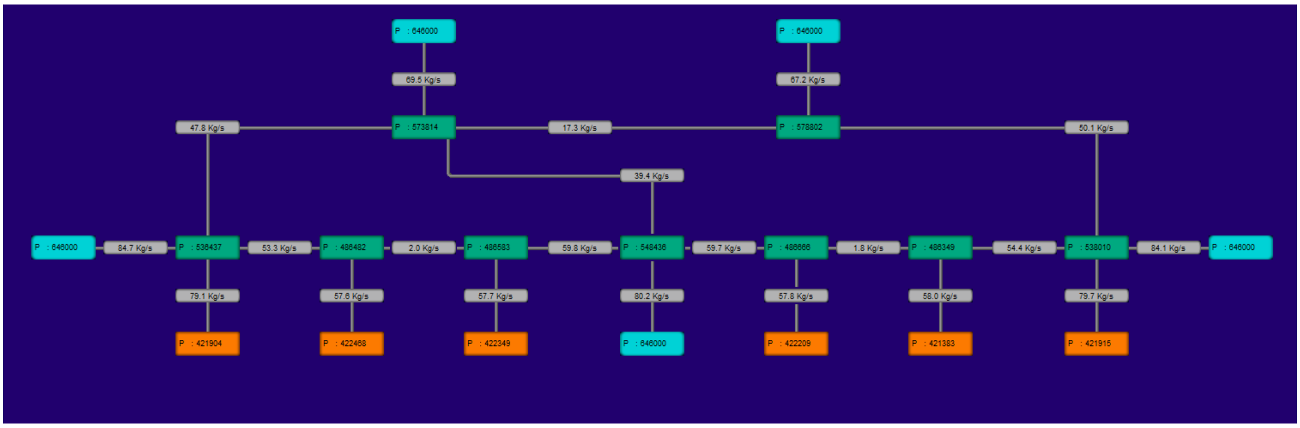


Figure 58: Solved test network 2

From Figure 59 it can be seen how the flow difference converges down to 0, after the neighbouring nodes are updated. In Figure 53 the flow difference can be seen with a single node network. Figure 58 shows a multinode network where the nodes influence each other. Figure 59 shows the rate of change between the first node's exit flow and the second node's in flow. This should converge down to 0.

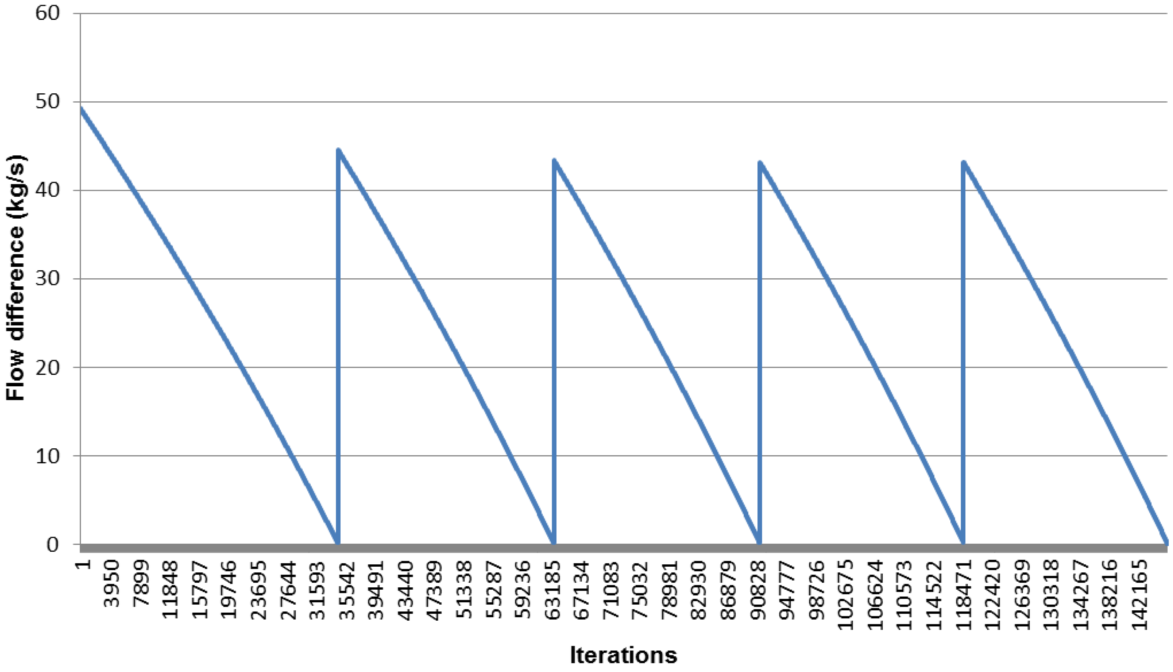


Figure 59: Network 1 flow difference

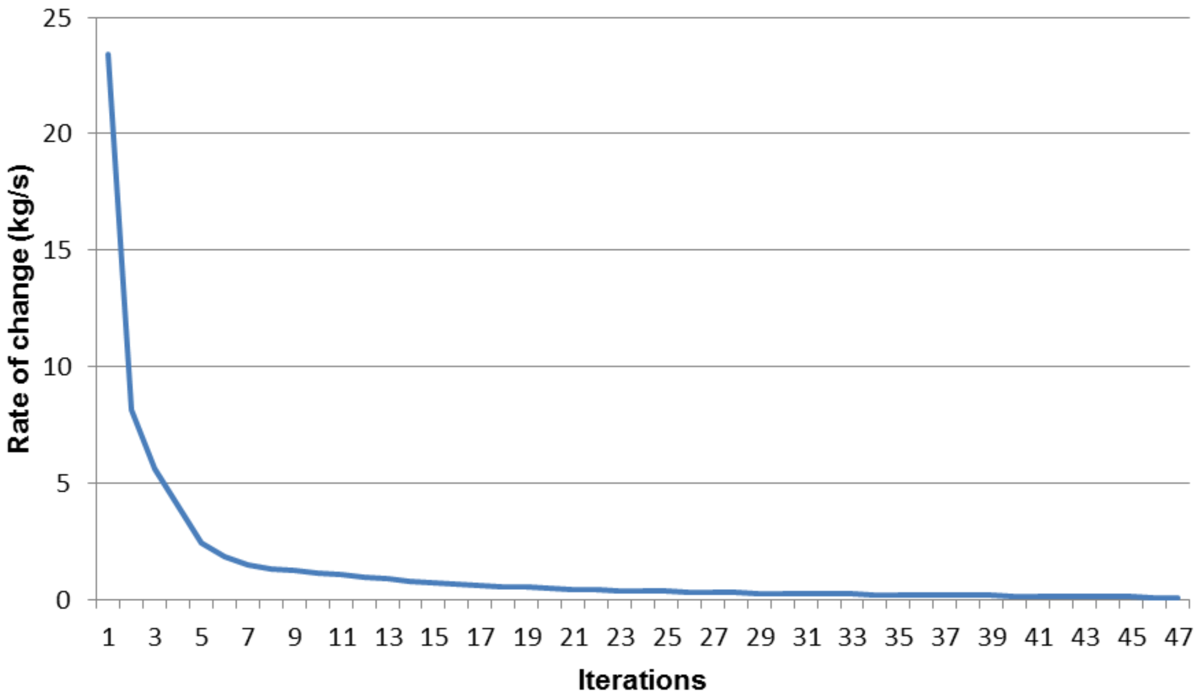


Figure 60: Network 2 rate of change

Table 3: Network 1 comparison

K-Pipe value	DCS value	Difference	Accuracy
500.0 kPa	508.8 kPa	8.8 kPa	98.3%
500.0 kPa	508.4 kPa	8.4 kPa	98.3%
546.2 kPa	553.4 kPa	7.2 kPa	98.7%
701.6 kPa	701.8 kPa	0.2 kPa	99.9%
47.5 kg/s	47.4 kg/s	0.1 kg/s	99.8%
47.5 kg/s	47.6 kg/s	0.1 kg/s	99.8%
95 kg/s	94.8 kg/s	0.2 kg/s	99.8%

From Figure 57, Figure 58, Table 3, Table 4 and Table 5 it can be seen that the accuracy of the pressure calculations alternate between 97% and 99%. The flow readings also alternate between 97% and 99% if two very low flow readings are left out. These two very low flow equations differ 1 kg/s and 0.8 kg/s from the K-pipe values. Because the calculated flow never deviates above 1.2 kg/s it can be said that the accuracy of the DCS calculation is comparable to that of K-Pipe.

Table 4: Network 2 comparison (pressure)

K-Pipe value	DCS value	Difference	Accuracy
659.3 kPa	662.8 kPa	3.5 kPa	99.5%
664.7 kPa	667.7 kPa	3.0 kPa	99.5%
620.9 kPa	625.4 kPa	4.5 kPa	99.3%
566.4 kPa	575.4 kPa	9.0 kPa	98.4%
566.8 kPa	575.5 kPa	8.7 kPa	98.5%
632.4 kPa	637.4 kPa	5.0 kPa	99.2%
567.0 kPa	575.6 kPa	8.6 kPa	98.5%
567.4 kPa	575.3 kPa	7.9 kPa	98.6%
621.8 kPa	627.0 kPa	5.2 kPa	99.2%
500.0 kPa	510.8 kPa	10.8 kPa	97.9%
500.0 kPa	511.4 kPa	11.4 kPa	97.8%
500.0 kPa	511.3 kPa	11.3 kPa	97.8%
500.0 kPa	511.1 kPa	11.1 kPa	97.8%
500.0 kPa	510.3 kPa	10.3 kPa	98.0%
500.0 kPa	510.9 kPa	10.9 kPa	98.0%

Table 5: Network 2 comparison (flow)

K-Pipe value	DCS value	Difference	Accuracy
70.6 kg/s	69.5 kg/s	1.1 kg/s	98.4%
68.2 kg/s	67.2 kg/s	1.0 kg/s	98.5%
17.8 kg/s	17.3 kg/s	0.5 kg/s	97.2%
48.4 kg/s	47.8 kg/s	0.6 kg/s	98.9%
40.0 kg/s	39.4 kg/s	0.6 kg/s	98.5%
50.3 kg/s	50.1 kg/s	0.2 kg/s	99.6%
85.2 kg/s	84.7 kg/s	0.5 kg/s	99.4%
54.5 kg/s	53.3 kg/s	1.2 kg/s	97.8%
3.0 kg/s	2.0 kg/s	1.0 kg/s	66.7%
60.8 kg/s	59.8 kg/s	1.0 kg/s	98.4%
60.4 kg/s	59.7 kg/s	0.7 kg/s	98.9%
2.6 kg/s	1.8 kg/s	0.8 kg/s	69.2%
55.4 kg/s	54.4 kg/s	1.0 kg/s	98.2%
84.8 kg/s	84.1 kg/s	0.7 kg/s	99.2%
81.2 kg/s	80.2 kg/s	1.0 kg/s	98.8%

3.3. Verification of design requirements

3.3.1. Intro

As the requirements listed in section 2.2.2 are of utmost importance, it requires concrete verification. In *Table 6* a quick overview of all test results can be seen. The tests were only done on the critical requirements listed in 2.2.2. More detailed test results and observations can be seen in the specific tests listed below.

Table 6: Test results for critical requirements

Requirement	Outcome	Test number
Component based	Passed	1
Prioritise compressors dynamically	Passed	2
Calculate compressor set-point dynamically	Passed	4
Start and stop compressors automatically	Passed	3
Simulate an air network	Passed	4
Estimate future state of network	Passed	4
Log all data	Passed	4
User access control	Passed	1
Gather data from SCADA	Passed	4
Can connect via OPC	Passed	4
GUI to display data	Passed	1

3.3.2. Test 1 - REMS

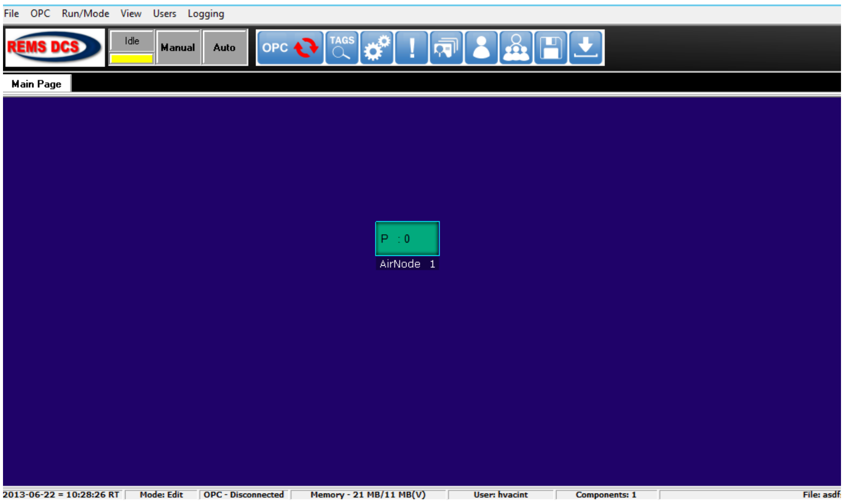
Purpose and setup

The purpose was to test all of the requirements that were met by using the REMS design as the basis of DCS. This test will establish if DCS is component based, has different user access levels and features a GUI. The testing procedure will be as follows:

- Create a new platform and determine whether components can be placed in the platform;
- Create a user of each level;
- Test the user access rights of each user;
- If this was all displayed visually, then GUI requirement has been passed.

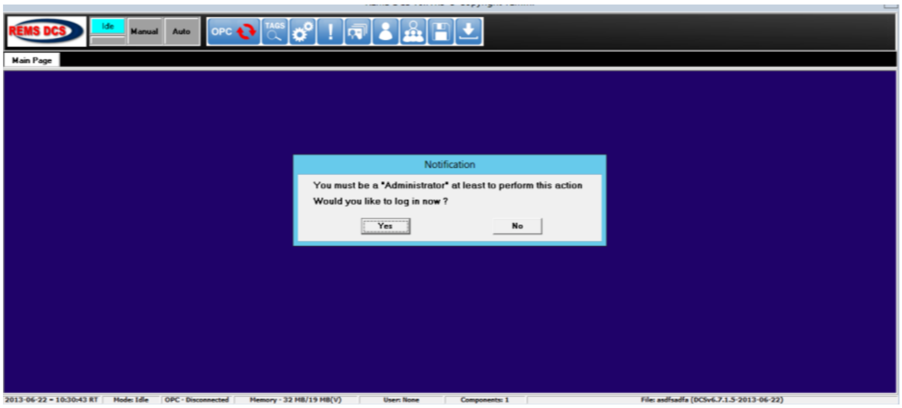
Results and observations

A new platform was created and a few components were placed at locations specified by the user. The result can be seen in Figure 61. The user was able to place the components at the desired locations without problems. The user then tried to change the mode of the system from manual to edit mode. The program blocked the user since the user was not logged in as an administrator. This can be seen in Figure 62.



2013-06-22 = 10:28:26 RT | Mode: Edit | OPC - Disconnected | Memory - 21 MB/11 MB(V) | User: hvacint | Components: 1 | File: asdf

Figure 61: Placing a custom component



You must be a "Administrator" at least to perform this action
Would you like to log in now ?

2013-06-22 = 10:30:43 RT | Mode: Idle | OPC - Disconnected | Memory - 32 MB/19 MB(V) | User: None | Components: 1 | File: asdfsadfa (DCSv6.7.1.5-2013-06-22)

Figure 62: User access control

The rest of the access rights were tested according to Table 2 and the results can be seen in Table 7. Table 7 is an exact match to Table 2. It can, therefore, be concluded that test one is deemed successful.

Table 7: User access rights sub-tests

Action	Viewer	Operator	Supervisor	Administrator
Connect/Reconnect OPC	Yes	Yes	Yes	Yes
Log In	Yes	Yes	Yes	Yes
Switch modes(auto/manual)	No	Yes	Yes	Yes
Save	No	Yes	Yes	Yes
Backup	No	Yes	Yes	Yes
Change component settings	No	No	Yes	Yes
User Manager	No	No	No	Yes
Contacts	No	No	No	Yes
Alarms	No	No	No	Yes
Options	No	No	No	Yes
Tags	No	No	No	Yes
OPC options	No	No	No	Yes
Idle/Edit	No	No	No	Yes

3.3.3. Test 2 - Compressor prioritisation

Purpose and setup

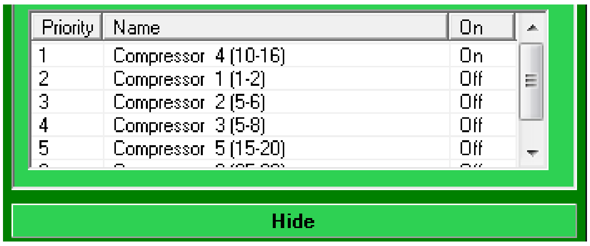
This test will determine whether the compressor controller component can prioritise compressors dynamically as the flow changes. For this purpose a new platform will be created with six compressors, each with a different flow rating. In the compressor controller the flow requirement will be changed to observe the change in the priorities of the compressors. Four sub-tests will be done with priorities.

The flow ranges of the compressor will be set as follows:

- Compressor 1: 1-2 kg/s;
- Compressor 2: 5-6 kg/s;
- Compressor 3: 5-8 kg/s;
- Compressor 4: 10-16 kg/s;
- Compressor 5: 15-20 kg/s;
- Compressor 6: 25-30 kg/s.

Results and observations

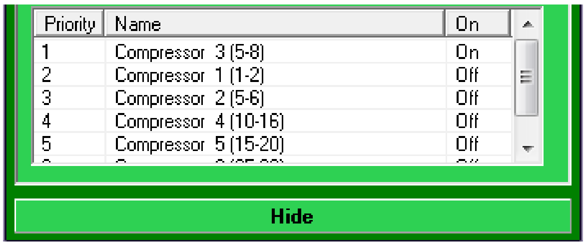
For the first sub-test the requirement was set at 10kg/s. The priorities according to the compressor controller can be seen in Figure 63. It selected only compressor 4 which can deliver a range of 10-16 kg/s. While the range of the selected compressor is not ideal, it selected the only compressor that can deliver the required flow of 10 kg/s.



Priority	Name	On
1	Compressor 4 (10-16)	On
2	Compressor 1 (1-2)	Off
3	Compressor 2 (5-6)	Off
4	Compressor 3 (5-8)	Off
5	Compressor 5 (15-20)	Off

Figure 63: Compressor priorities sub-test 1

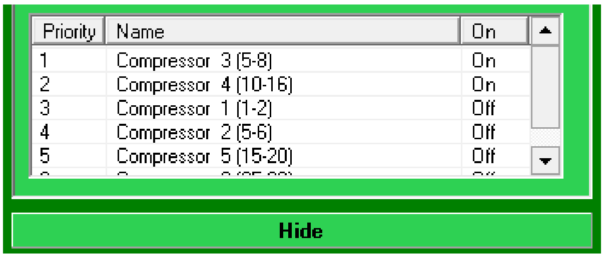
For the second sub-test the required flow was changed to 6 kg/s. The priorities according to the compressor controller can be seen in Figure 64. While there are two compressors that can deliver 6 kg/s it selected the larger one of the two because it offers a higher average delivery flow. This will give the compressor a higher range of flow to deliver and will reduce compressor cycling since it can deliver up to 8kg/s while the other compressor can only deliver 6 kg/s.



Priority	Name	On
1	Compressor 3 (5-8)	On
2	Compressor 1 (1-2)	Off
3	Compressor 2 (5-6)	Off
4	Compressor 4 (10-16)	Off
5	Compressor 5 (15-20)	Off

Figure 64: Compressor priorities sub-test 2

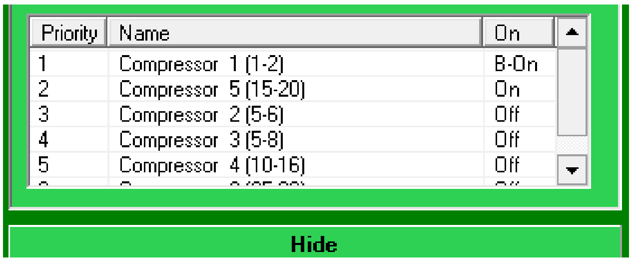
For the third sub-test the required flow was changed to 15 kg/s. The priorities according to the compressor controller can be seen in Figure 65. In this sub-test compressor 3 is already running. Compressor 3 cannot deliver the required flow so compressor 4 is added. Both compressors will run at a reduced speed or guide vanes so as to reduce energy consumption due to integrated compressed control.



Priority	Name	On
1	Compressor 3 (5-8)	On
2	Compressor 4 (10-16)	On
3	Compressor 1 (1-2)	Off
4	Compressor 2 (5-6)	Off
5	Compressor 5 (15-20)	Off

Figure 65: Compressor priorities sub-test 3

For the fourth sub-test the required flow was changed to 20 kg/s. The priorities according to the compressor controller can be seen in Figure 66. Because compressor 1 is set as a base-load compressor, it cannot be turned off. Compressor 5 can deliver the required flow but compressor 1 cannot, so they have to run together to deliver the required flow. Compressor 5 will run on reduced speed or guide vanes resulting in reduced power consumption. From the four sub-tests in test 2, it can be seen that test 2 was a success.



Priority	Name	On
1	Compressor 1 (1-2)	B-On
2	Compressor 5 (15-20)	On
3	Compressor 2 (5-6)	Off
4	Compressor 3 (5-8)	Off
5	Compressor 4 (10-16)	Off

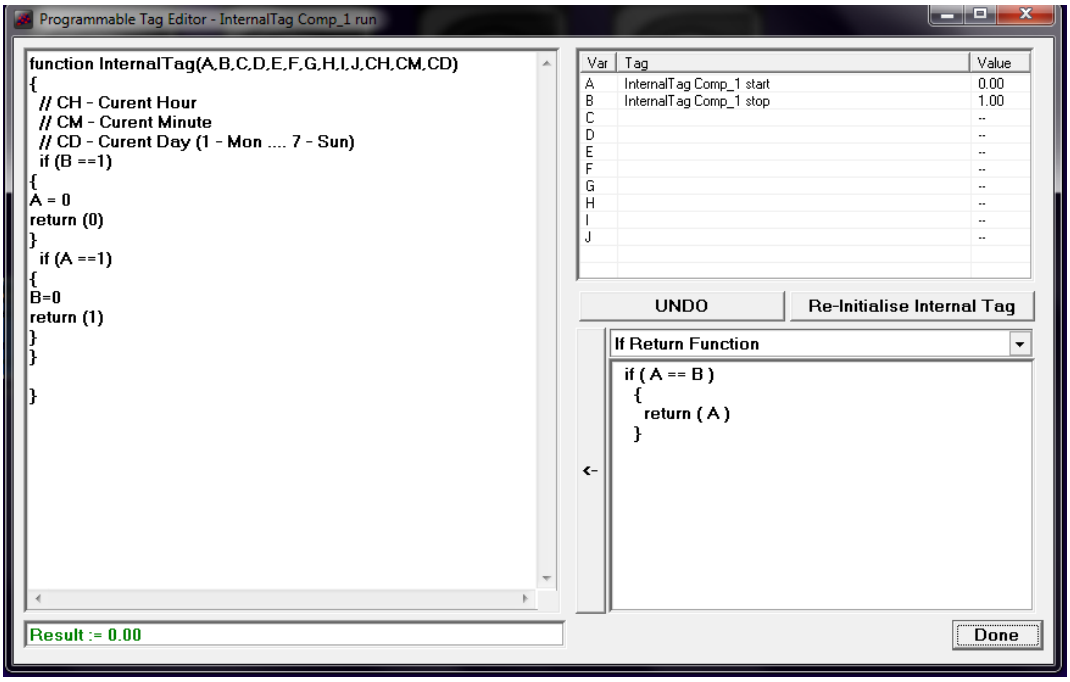
Figure 66: Compressor priorities sub-test 4

3.3.4. Test 3 - Compressor control

Purpose and setup

This test aims to establish if the controller can start and stop a compressor. Compressors are started via PLCs (Programmable Logic Controller) which run the integrated controller which in turn is controlled by the SCADA. To establish whether a compressor can be started or stopped it is only necessary to send a start and or stop bit to the SCADA. This can be tested without an actual SCADA and compressor.

To simulate the role of the SCADA, an internal tag will be used. This tag will be programmable so that it allows the user to create a small script. The code for the script can be seen below in Figure 67. Using this internal tag as the running status of the compressor, it can be used to simulate a SCADA turning a compressor on or off depending on the status of the start and stop bits.



```
function InternalTag(A,B,C,D,E,F,G,H,I,J,CH,CM,CD)
{
 // CH - Curent Hour
 // CM - Curent Minute
 // CD - Curent Day (1 - Mon .... 7 - Sun)
 if (B ==1)
{
A = 0
return (0)
}
 if (A ==1)
{
B=0
return (1)
}
}

}
```

Var	Tag	Value
A	InternalTag Comp_1 start	0.00
B	InternalTag Comp_1 stop	1.00
C		--
D		--
E		--
F		--
G		--
H		--
I		--
J		--

```
if ( A == B )
 {
  return ( A )
 }
```

Result := 0.00

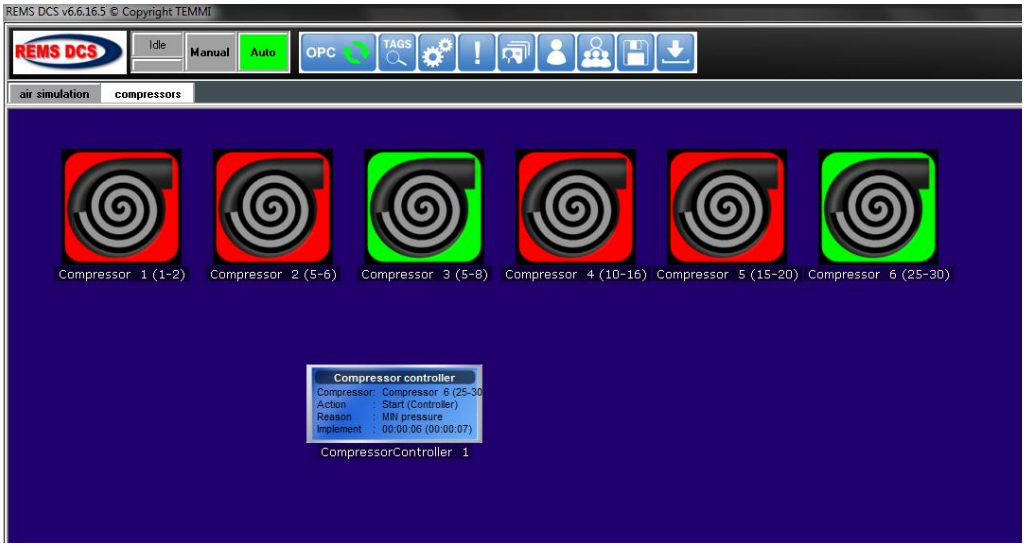
Figure 67: Compressor running script

To test whether the compressor controller can start and stop compressors, the delivery pressure will be dropped below the set-point pressure to establish if the controller will start a compressor and then the delivery pressure will be increased to above the set-point pressure to establish if the controller will stop a compressor. The compressor priorities were set at the same level as in test 2 (3.3.3).

Results and observations

For this test the compressors were all turned off except one compressor at the start. The set-point pressure was set at 500 kPa and the current pressure was set at 450 kPa. The control range was set at 20 kPa and the required flow was set at 35 kg/s. Compressor 3 was already running.

The controller successfully started compressor 6 as can be seen in Figure 68. After this the pressure was raised to 530 kPa. After the delay time the compressor controller unloaded compressor 3 and after the next delay time stopped compressor 3. From this result it can be concluded that test 3 was a success.



Compressor controller
Compressor: Compressor 6 (25-30
Action : Start (Controller)
Reason : MIN pressure
Implement : 00:00:06 (00:00:07)

Figure 68: Compressor control test

3.3.5. Test 4 - Network simulation

Purpose and setup

This test will establish whether DCS can simulate and establish the future state of a network while acquiring all the required data from the SCADA via an OPC connection. To easily test the OPC connection a virtual SCADA simulator program (Iconics OPC simulator) was used. The test will simulate a full network with set-point pressures and future set-point pressures.

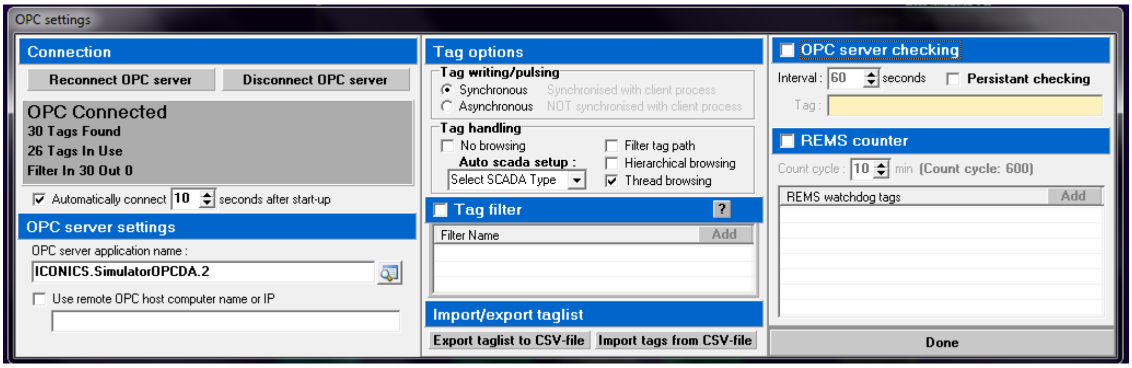
The future pressure set-points will be higher than the current set-points. If the simulation reports the future required flow to be higher than the current required flow, the network will have successfully simulated and estimated the future state of the network. Because the components cannot run if no OPC connection is present, the connection to the SCADA via an OPC connection will be successful if a simulation was run.

DCS must also supply a required pressure set-point for the compressors to deliver the required flow at the required pressure. The required pressure set-point is calculated from the set-points of the end-users.

Results and observations

DCS successfully acquired all data from the simulated SCADA server via an OPC connection. The OPC settings can be seen in Figure 69. DCS also successfully simulated the entire network and the future state from the acquired data. The flow of the future state of the network is shown in the window as proof that the future state of the network was established.

DCS successfully calculated the required set-point pressure to deliver the required flow and pressure to all end-users. The window displaying all results can be seen in Figure 70. Because all the requirements were met, test 4 can be deemed a success.



OPC Connected
30 Tags Found
26 Tags In Use
Filter In 30 Out 0

☑ Automatically connect 10 seconds after start-up

OPC server application name : ICONICS.SimulatorOPCDA.2

☐ Use remote OPC host computer name or IP

Tag writing/pulsing
● Synchronous Synchronised with client process
○ Asynchronous NOT synchronised with client process

Tag handling
☐ No browsing
Auto scada setup : Select SCADA Type
☐ Filter tag path
☐ Hierarchical browsing
☑ Thread browsing

☐ Tag filter

☐ OPC server checking
Interval : 60 seconds ☐ Persistant checking
Tag :

☐ REMS counter
Count cycle : 10 min (Count cycle: 600)

Figure 69: OPC settings

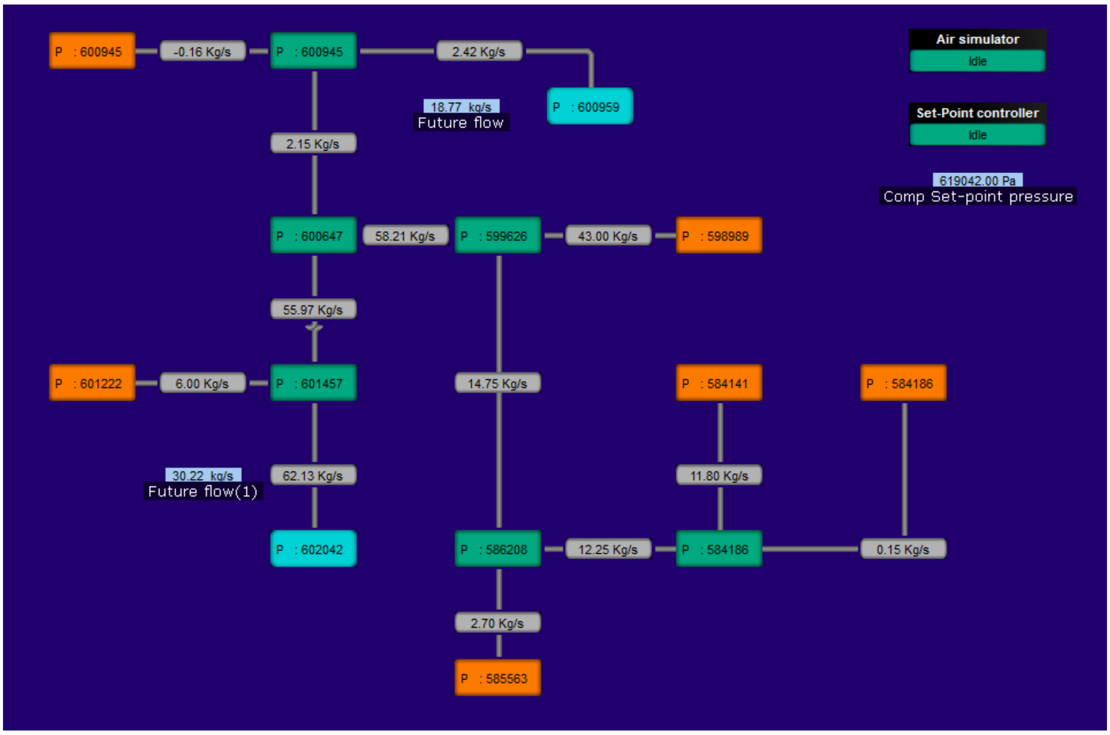


Figure 70: Network simulation test results

3.4. Practical implementation constraints

3.4.1. Intro

The implementation of DCS uncovered quite a few problems [48]: inaccurate field instrumentation, faulty valves, high set-points and client IT policies were identified. These all inhibit DCS to work as intended and solutions were required.

3.4.2. Inaccurate field instrumentation

Pressure and flow meters are designed for a certain range of flows and/or pressures. The error for flow meters can be as small as 0.1% [49]. If the reading goes beyond the calibrated range the meter can give an erroneous reading. These spikes only occur momentarily and they do not last very long. But if the timing is just right, the spike can occur while the Air Simulator component is busy gathering data.

The simulations in DCS are very sensitive to the data readings, especially the flow readings. If the input data to these simulations are inaccurate, the resulting output data will also be inaccurate. This can lead to compressors being incorrectly prioritised or the network delivery set-points being miscalculated.

To prevent this from happening DCS creates a buffer of all the data. This buffered data is checked to ensure that it is within reasonable boundaries before simulation starts. If the data is outside of these boundaries the simulation will not start, and DCS will wait for the input data to stabilise before attempting to simulate again. This will allow DCS to keep using the previous values until better values are available.

3.4.3. Faulty valves

Air valves are used by the mine to restrict air to end-users who do not need high flow or high pressure. These valves are controlled by a downstream pressure meter running on a set-point pressure. If the pressure is higher than the set-point, the valve will restrict air until the pressure equals the set-point.

If these valves are broken or do not function properly they will not control the downstream pressure. If the downstream pressure is not controlled, a higher set-point must be run to ensure that all users still get their required pressure. This will in turn increase energy usage and can possibly damage equipment. Faulty valves are a mechanical problem and cannot be addressed by software.

3.4.4. High set-points and client IT policies

Air pressure at mines is usually controlled from the supply side because end-users rarely know how much air they use or need. During drilling shifts, the end-users require the maximum allowable pressure to ensure no production losses. To ensure that maximum pressure is available to the end-users the valves are kept open by using unrealistically high set-points. These high set-points are sometimes maintained until long after the drill period.

On normal compressor control this does not present a problem since the supply set-point is dropped to lower levels, so the pressure is lower. With DCS the controller dynamically adjusts the set-point to ensure all end-users get the correct pressure. If this set-point is too high the controller will not drop the supply set-point.

Another problem this causes is with the future set-point. If the supply side is low and the demand side is above normal the controller might conclude that the end-users started to supply air to the suppliers. This is because DCS does not distinguish between end-users and suppliers. If the end-users have the highest pressure they will be considered as suppliers.

The solution to this will be to set the set-point valves to realistic values, but client IT policies sometimes stand in the way of this. Some of the valve control is done at the PLC level and the higher order control programmes do not always have write privileges to the PLCs. This makes it very difficult to change set-points as they need to be changed at the PLCs each time.

3.5. Case study and measured results

3.5.1. Introduction

To test DCS in an actual mining environment, the controller was installed on a server in the mining air compressor control room with access to the SCADA system. The layout of the mine compressed air network can be seen in Figure 71. When implementation of the system began the mine did not have any automated valves installed at the shafts of the mines. As part of the project these were installed to help DCS control the air supply.

Figure 72 shows the layout of the mine built in DCS. Table 8 shows the current compressors, their flow rating, rated capacity and location. The compressor locations are K3 and K4 compressor houses. This section will discuss the compressor priorities and the calculated set-points.

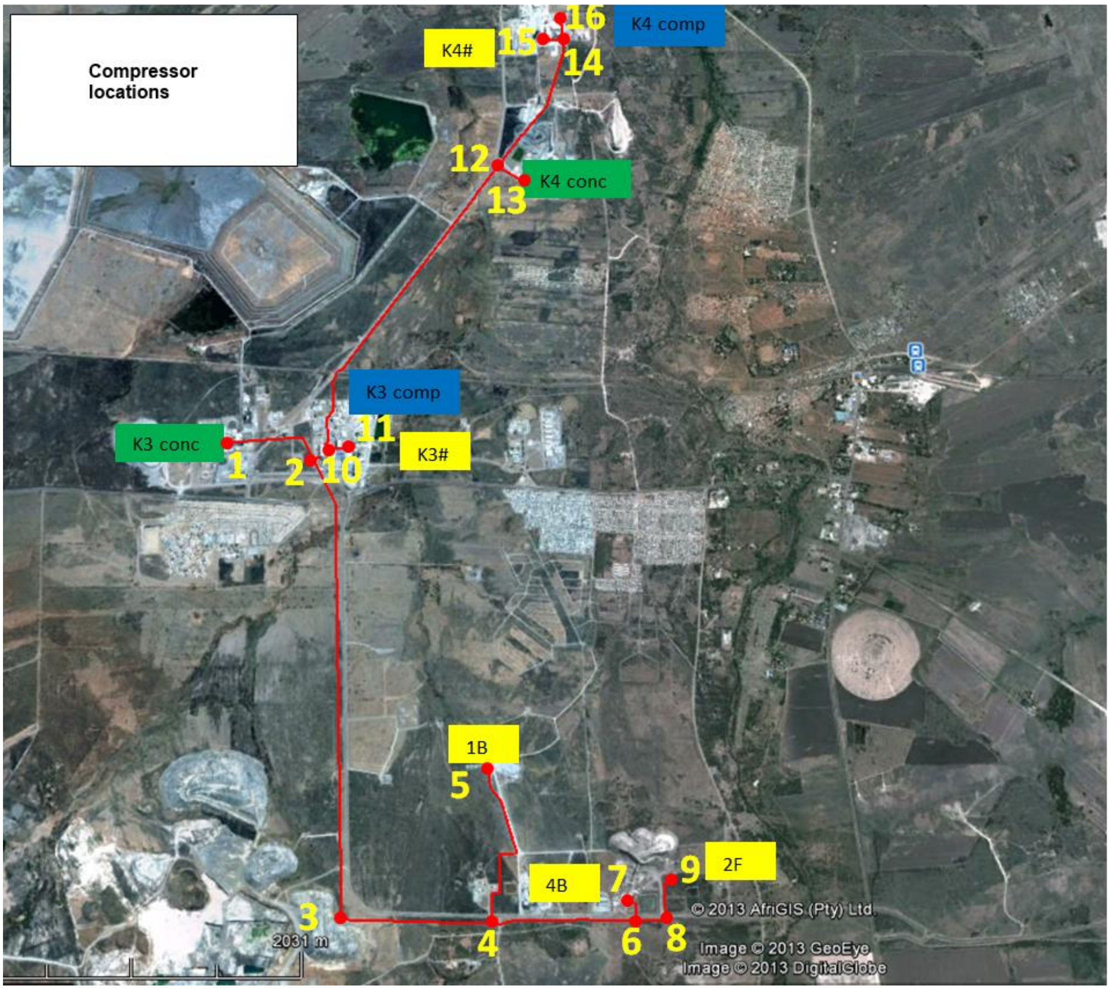
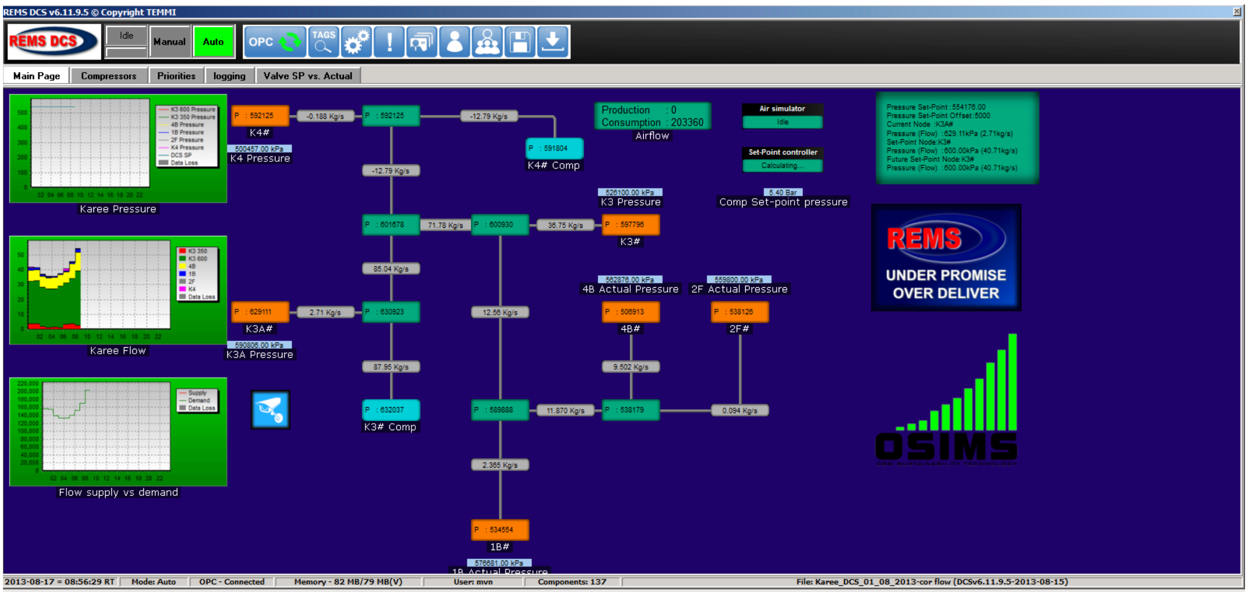


Figure 71: Mine Layout

Table 8: Mine compressors

Name	Flow rating (kg/s)	Rated capacity (MW)	Location
K3_VK40	6.4-9.1	4	K3 Compressor house
K3_VK50_1	11.3-14.9	5	K3 Compressor house
K3_VK50_2	10.4-15.7	5	K3 Compressor house
K3_VK50_3	9.8-15.4	5	K3 Compressor house
K3_VK10_1	2.2-2.3	1	K3 Compressor house
K3_VK10_2	2.1-2.2	1	K3 Compressor house
K4_VK40_1	6.5-9.8	4	K4 Compressor house
K4_VK40_2	6.7-9.8	4	K4 Compressor house



Pressure Set-Point :554176.00
Pressure Set-Point Offset:5000
Current Node :K3A#
Pressure (Flow) :629.11kPa (2.71kg/s)
Set-Point Node:K3#
Pressure (Flow) :600.00kPa (40.71kg/s)
Future Set-Point Node:K3#
Pressure (Flow) :600.00kPa (40.71kg/s)

2013-08-17 = 08:56:29 RT | Mode: Auto | OPC - Connected | Memory - 82 MB/79 MB(V) | User: mvn | Components: 137 | File: Karee_DCS_01_08_2013-cor flow (DCSv6.11.9.5-2013-08-15)

Figure 72: Mine DCS platform

At this site DCS will only be employed as an advisory system and will feed its inputs to the existing controller. DCS will not control the compressors directly, it will only supply compressor priorities and set-points as per arrangement with the mine.

3.5.2. Priorities

Figure 73 shows the current compressor priorities during the day and Figure 74 the priorities of DCS. The latter is influenced by the priorities shown in Figure 73. This is done to try and reduce cycling of compressors. From the two figures it can be seen that the dynamic priorities from DCS use less total power than those from the static priorities.

At first glance the compressor priorities shown in Figure 74 are worse than those in Figure 73, but this is not the case when examined closely. On the data it shows that K3_VK50_3 and K3_VK50_2 ran on guide vanes of only 20% each. While this stops the compressors from cycling, as shown in Figure 75, which were the running compressors from an earlier day, it does not reduce power since one of the VK50 compressors can be shut down.

The cycling shown in Figure 74 can be explained by the fact that DCS only wants to run one compressor on guide vanes. When that reduction occurs in the flow, the flow decreases below the minimum flow the VK_50s can supply. When that happens, the controller replaces the VK_50 with a VK_40. As the flow level increases again to levels that fall within the supply range of the VK_50s, the controllers do not want to stop the VK_50 anymore. This is because it always takes in, as input, the actual running compressors, which are the VK_50 compressors. All of the cycling can be explained by this.

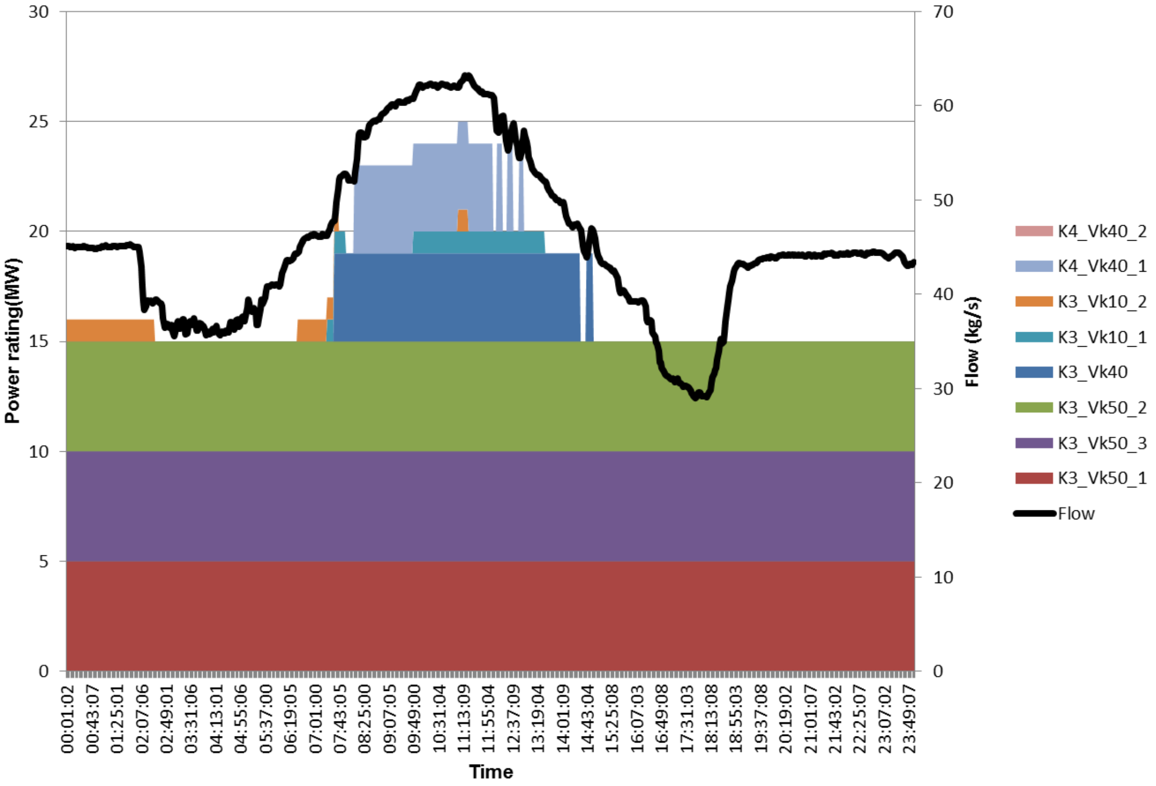


Figure 73: Static compressor priorities

By comparing Figure 73 and Figure 74 it can be seen that the power requirement of the dynamic DCS priorities is lower than that of the static power requirement. During the time period between 08:00 to 12:00 the saving on power was 1-2 MW. During the time 15:00 - 19:00 the saving was 5 MW. During the evening time between 20:00 to 00:00 the priorities were the same, as well as the power requirement. It can be said that DCS can potentially save up to 5MW on this mine.

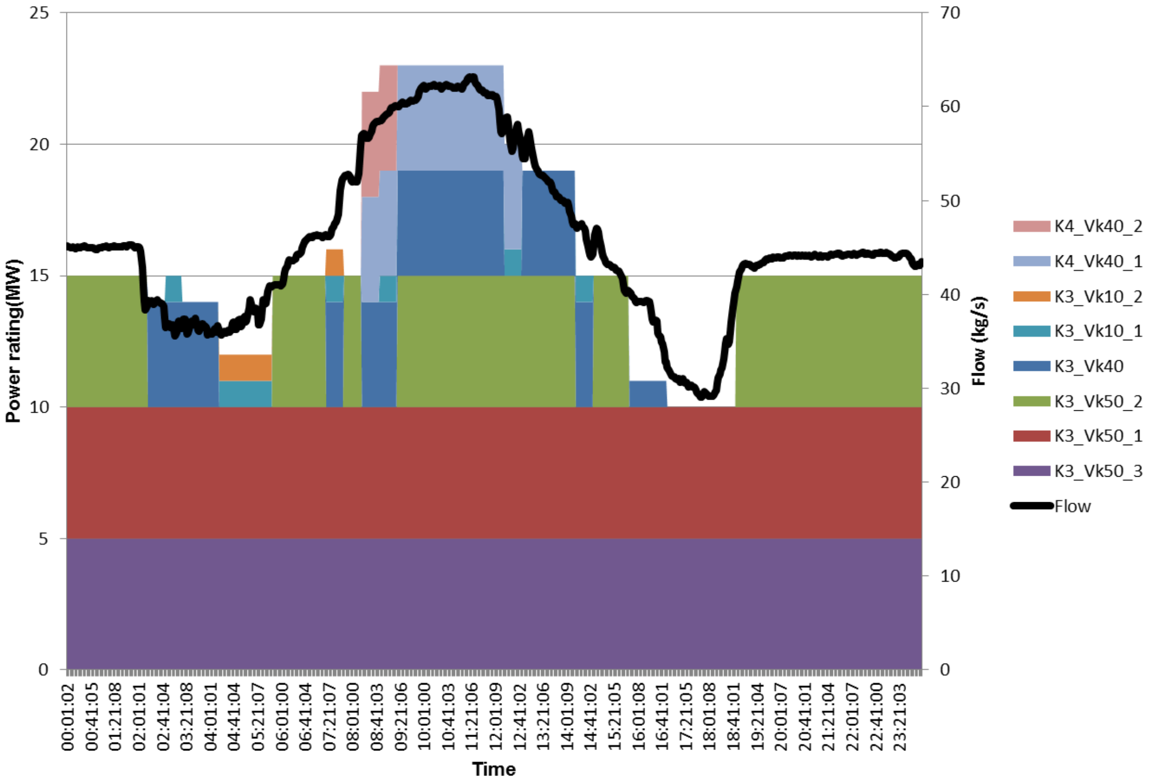


Figure 74: Dynamic DCS priorities

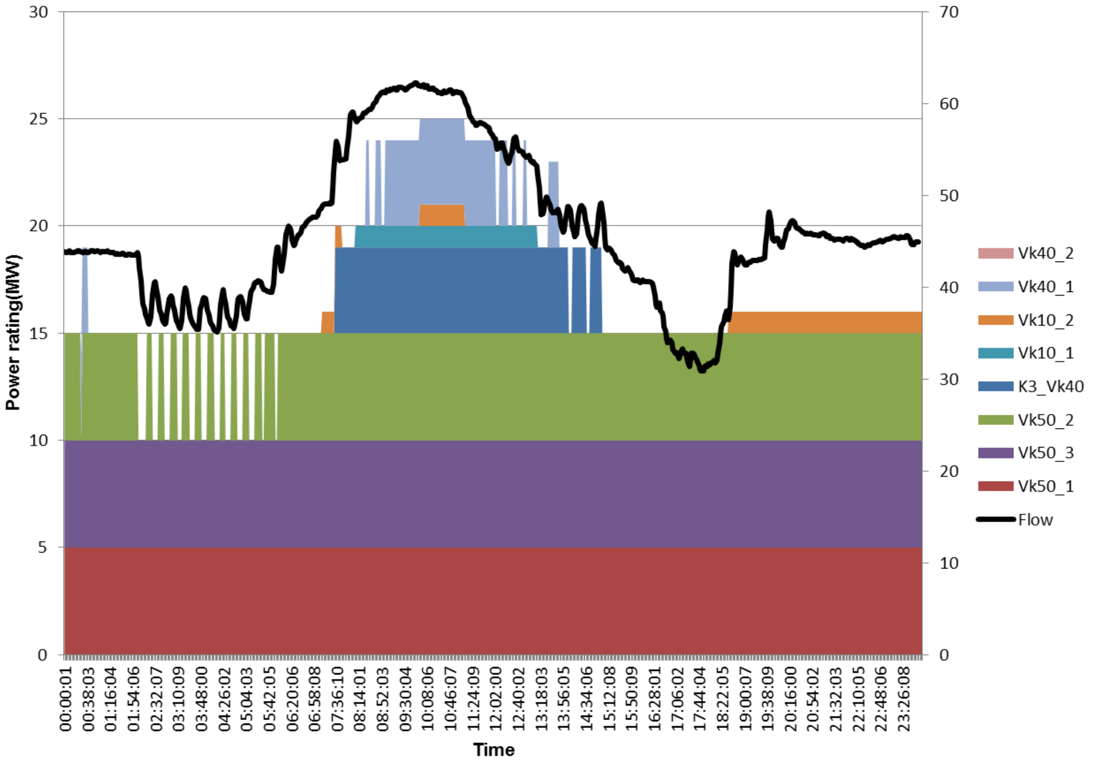


Figure 75: Static priorities not working

3.5.3. Set-point pressure

The mine uses individual pressure set-points assigned to each running compressor as well as a master running set-point. This master running set-point is assigned to the lowest priority running compressor. Other running compressors are assigned higher set-points which are calculated by an offset of the current running master set-point. This offset increases to 40 kPa and is assigned from lowest to highest following the same order of the running compressors. When asked how this was calculated, the response was that they used trial and error to establish the offsets.

By assigning the lowest running set-point to the lowest running priority compressors, the Compressor Controller can ensure that all other compressors run at maximum output and only the lowest running priority compressor will run on reduced output. By doing this it is assured that a scenario is not created by which more compressors are run than necessary because all the compressors are run at reduced output.

The following data was acquired over 6 days and is used as an average. Figure 76 displays the current master controller set-point as well as the average compressor delivery pressure. Figure 77 displays the Set-Point Controller's calculated set-point as well as a scaled set-point. This scaled set-point was calculated with Equation 3-1. The average pressure difference was calculated between the master controller set-point and the actual average delivery pressure is 12 kPa.

$$SP_{scaled} = SP_{calculated} - P_{avg\,differance} \qquad \textit{Equation 3-1}$$

Figure 78 shows a comparison of the average pressure and the calculated DCS set-point pressure. In Figure 79 the scaled calculated set-point is compared to the actual master controller set-point. The differences between the two can be attributed to incorrectly selected set-points on the demand side. Figure 79 shows the set-points of the demand side versus that of the calculated supply set-points.

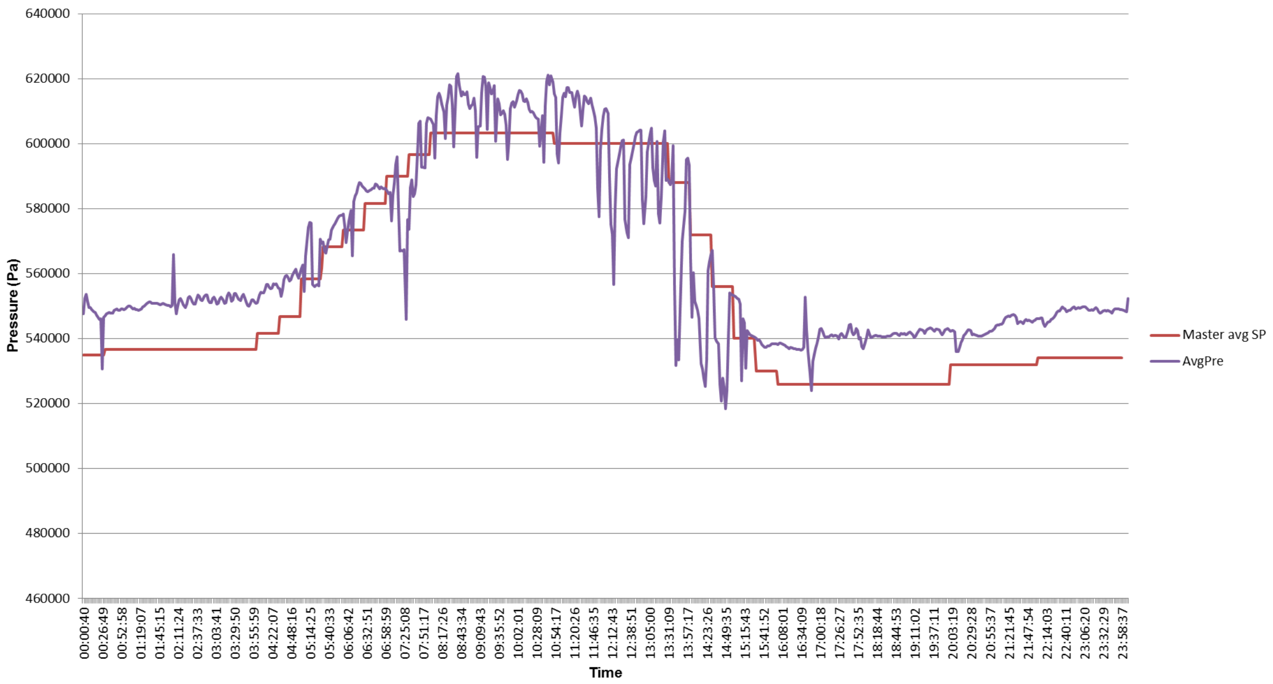


Figure 76: Master controller set-point and average compressor delivery pressure

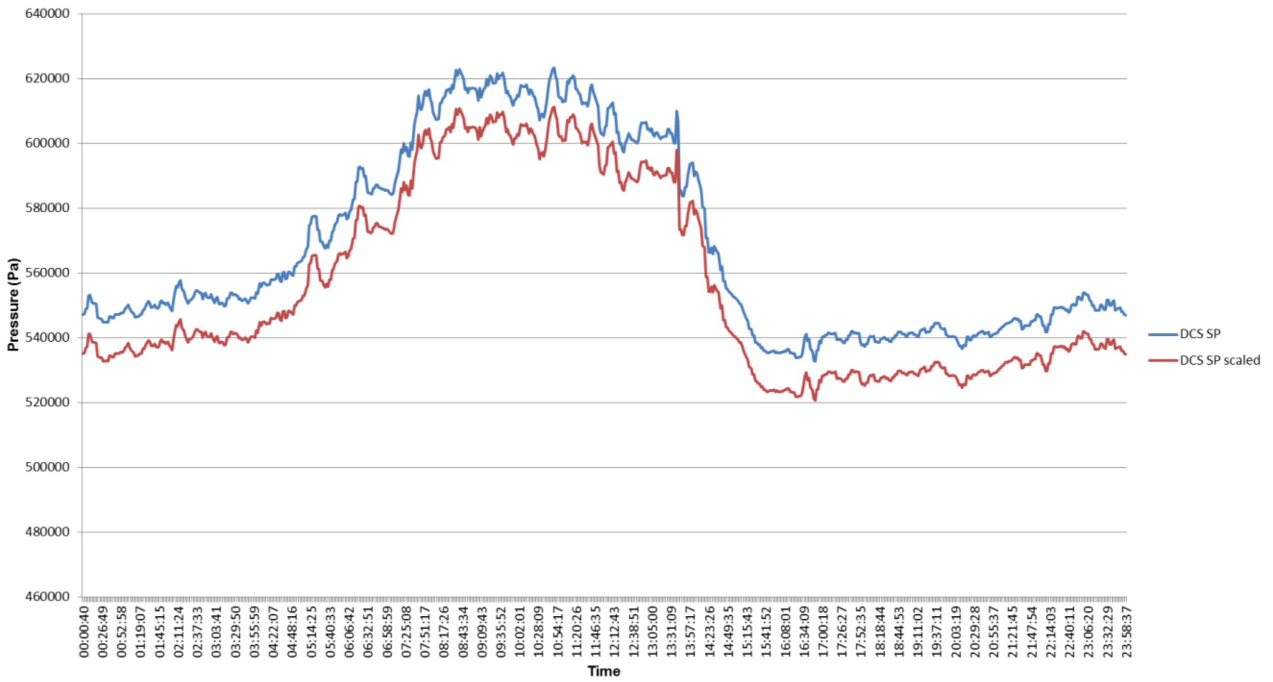


Figure 77: DCS set-point and DCS scaled set-point

Figure 78: DCS pressure and average pressure

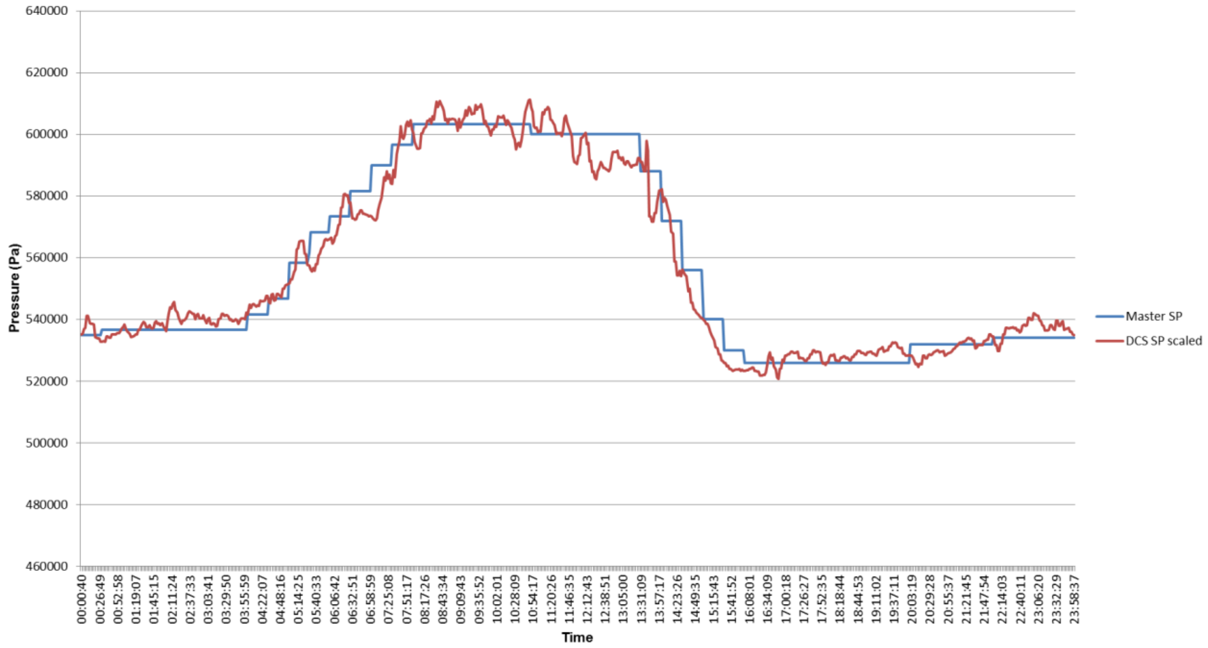


Figure 79: DCS scaled set-point and master controller set-point

Shown in Figure 80 is the actual set-point compared to the proposed DCS set-point of a day. From the graph it can be seen that on multiple occasions DCS proposed a lower set-point than the static set-point. The times DCS is higher than the master set-point can be attributed to set-points which are set too high on the demand side. The current demand during those times is dependent on the Master Controller (MC) set-point. If the set-points can be set more accurately, the proposed set-point will drop.

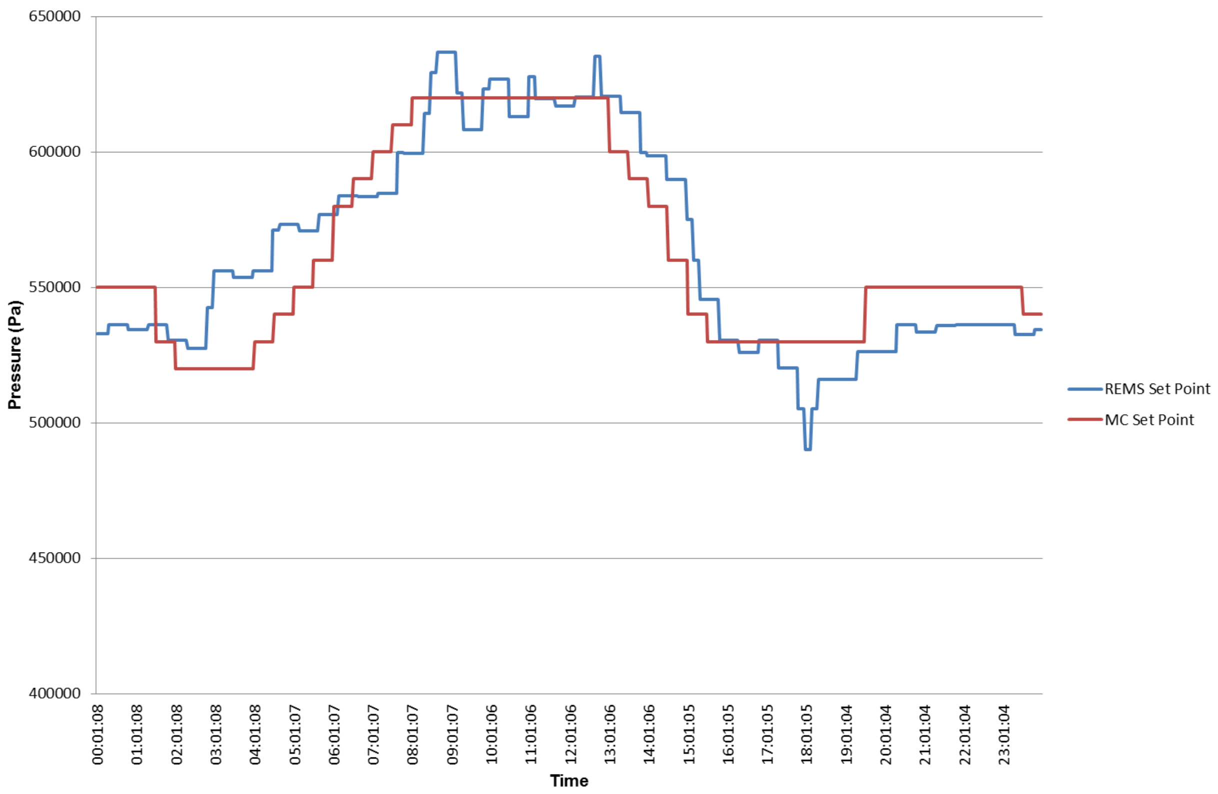


Figure 80: Actual set-point and proposed set-point

3.5.4. Reliability

For DCS to work as a mining compressed air controller, it has to function continuously without problems. When implemented on site numerous stability problems were encountered. DCS required inputs from more than one sensor to work. If one of these sensors fails, or gives a false reading, the controller will either give an erroneous solution or no solution at all.

Problems also occurred within DCS where the writing out of tags occurred. It will write out the data immediately and this can cause problems if the system is changing too rapidly. If pressure set-points are changed too rapidly, the system can trip the compressors. The same can be said for compressor priorities if they are changed too rapidly, which will merely in turn cause cycling.

3.5.5. Electricity savings

DCS was run for one day, for testing purposes with manual supervision to ensure that if something unintended occurred, the mine would not lose production. Below in Figure 81 the electricity usages of two days are compared. Because of the high dynamic nature of compressed air, two similar production days are compared. From the figure it can be seen that DCS gave a substantial electricity saving. This saving was incurred by reducing the running set-points of the compressors and selecting the right compressors to meet the set requirements.

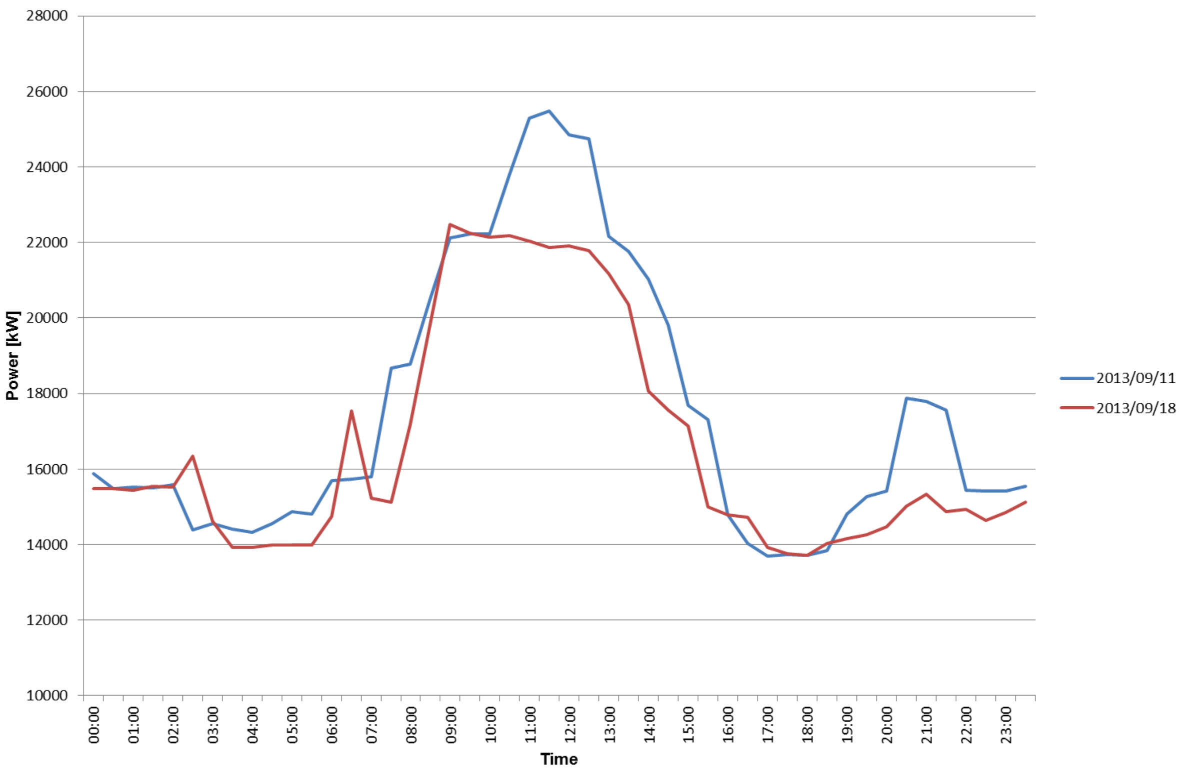


Figure 81: Comparison of compressor power profiles

The two large spikes in electricity usage in the morning was the result of switching compressors. The replacement compressor had to be up and running before the other compressor could be shut down. The average calculated demand saving for the day was calculated at 1.8MW, which results in a cost saving of R3.7-million per annum. The exact logged data can be seen in Appendix A.

3.6. Summary

In this section numerous tests were conducted on DCS at sub-system and system level. It was also verified that DCS accomplished all the requirements set out in Chapter 2. This chapter was divided into testing sub system calculations of compressed air networks, verification of requirements and finally a case study of implementation at a mine.

In the case study section it was discovered that DCS suffers from stability problems, caused by erroneous inputs which prevent it from being deployed full time as a compressor controller. On individual days the output of DCS was followed and from this output, the data was acquired. This data showed potential for continuous electricity savings. It can be argued that DCS reduces electricity consumption as well as cycling. This was established by selecting the compressors and changing the set-points dynamically.

4. Conclusion and future research

4.1. Conclusions

Mines currently use static controllers to control large compressed air rings. While these controllers can start and shut down compressors to adapt to the changing demand, they follow fixed compressor priorities and static supply pressure set-points. In this scenario the adaptability of the controller is limited and the controller will only work well on days following the set-points perfectly.

DCS was designed with the REMS design platform and consists of a server and software. DCS was designed to adapt dynamically to the changing the requirements of the compressed air network. This was established by dynamically changing the priorities of the compressors as well as calculating the exact supply pressure set-points to supply the exact demand pressure, for each of the mining shafts on the compressed air network.

DCS has shown that in certain instances it will work exactly as designed. The testing showed that it can calculate a set-point for compressors dynamically. This will ensure that all end-users on the compressed air network will receive their required pressure. The accuracy of these set-points is very dependent on the end-user's required set-points.

The running compressors on the DCS priorities show reduced cycling of compressors when compared to the actual running compressors on some days, but no reduction on other days. When compressors were cycled, it was always the small VK-10 compressors for which the effects of cycling are reduced. When this is compared to the mine's actual running compressors, the large VK-50's were cycling at times.

Because of the stability problems encountered in the case study, DCS was never left on automatic control. It was only employed as an advisory system whereby an additional controller would decide which set-point or priorities to use, the static or dynamic DCS set-points. By selecting lower set-points and running more optimised compressor combinations, it can be argued that DCS will also ensure a lower power consumption of the system.

It can also be argued that DCS has the potential to reduce cycling of the compressors feeding the network. When this is included in the dynamic nature of DCS it is also apparent that it can be done for any potential day no matter what the deviation from a normal day is. For this to work DCS must be able to run for extended periods of time without requiring human input for guidance or error correction. It should also be able to reduce the number of outputs (priorities and set-points) to give the entire system a chance to respond to the outputs.

On testing at a mine DCS saved an average of 1.8 MW (R3.7-million per annum). This reduction in electricity usage will result in a cost saving for the mine as well as a reduction of the load on the Eskom electricity grid. This testing was only done on one mine, but with the component based design of DCS it is possible to implement this on other mine compressed air rings as well.

When this is all combined with the potential to reduce cycling of compressors and thereby reducing maintenance costs, it can be argued that implementation of DCS is advantageous for the mine and Eskom. Each mine compressed air ring where DCS is implemented, will further improve the advantages for Eskom.

4.2. Future research

4.2.1. Intro

The future research can be divided into two main areas. At the time of the completion of this dissertation development was still ongoing.

4.2.2. Stability

DCS showed a weakness in stability of outputs and running for extended periods of time even with erroneous inputs occurring. The stability issues were caused each time by erroneous inputs. The system should be able to circumvent erroneous inputs caused by cable theft, component failure, water splashes on sensors etc.

For DCS to be a feasible controller it should be able to run for extended time periods without requiring user guidance or input. An effort should be made to improve DCS error detection as well as recovery after an error. DCS should also delay the writing out of priorities and set-points to give the system time to stabilise to the previous outputs before attempting to write out outputs again.

4.2.3. Compressor selection

DCS currently makes compressor selections based on the fact that a higher output compressor should be more efficient than a combination of lower output compressors. This is true because compressors are at their most efficient operating ranges when they are running at or near full guide vanes. DCS uses this to run as few as possible compressors and thus saves on power consumption.

The challenge is that most compressed air networks have more than one compressor location. Some of these rings can be as long as 40 km and thus it could be very inefficient to run a compressor that is far away from a shaft. In the case study mine the compressed air network ring was only 8.5 km in length and the compressors are only located 3.5 km apart. This makes the distance negligible.

Due to distance and pipe constraints, the distance between compressors might not be negligible to selection and this must be taken into consideration when selecting compressors to run. In order to ensure the optimum compressor selection, attention should be given not just to the size of the compressors and the required flow, but also their location, network characteristics and power efficiency.

References

[1] O. Davidson, et al, *Energy Policies for Sustainable Development in South Africa, Options for the Future.* Cape Town, Western Province, South Africa: Energy Research Centre University of Cape Town, 2006.

[2] Department of Minerals and Energy, No. 31741, Gazette, 19 December 2008.

[3] Energy information administration, Country analysis briefs: South Africa, 2011.

[4] *International energy statistics*. Available: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=1&pid=1&aid=2. DOI: 2013/10/05.

[5] *Google public data*. Available: https://www.google.co.za/publicdata/directory?hl=en#. DOI: 2013/05/14.

[6] F. Harvey, 2012 expected to be the ninth warmest year on record , The Guardian, 28 November 2012.

[7] K. Than, 2012: Hottest year on record for continent U.S. , National Geographic, 9 January 2013.

[8] Cameron, *Turbo Air 3000 Centrifugal Compressor.* Houston, Texas, United States of America: Cameron compression systems, 2007.

[9] US Department of Energy, Improving Compressed Air System Performance, A Sourcebook for Industry, 2003.

[10] H. H. Nguyen, V. Uraikul, C. W. Chan and P. Tontiwachwuthikul, A comparison of automation techniques for optimization of compressor scheduling, Advances in Engineering Software, 2007.

[11] S. A. Korpela, *Principles of Turbomachinery.* Hoboken, New Jersey, United States of America: John Wiley & Sons, Inc, 2011.

[12] B. Massey, *Mechanics of Fluids.* New York city, New York, United States of America: Taylor and Francis, 2006.

[13] V. Kadambi and M. Prasad, *An Introduction to Energy Conversion, Energy Conversion Cycles.* Daryaganj, New Delhi, India: New age international limited, 1974.

[14] General Electric, *Roots API-617 and API-672 IGCH Centrifugal Compressor*. Available: http://www.ge-energy.com/products_and_services/products/compressors/roots_igch_centrifugal_compressor.jsp. DOI: 2013/10/09.

[15] A. J. Schutte and M. Kleingeld, Case studies of optimised compressed air usage on gold mines, Industrial and commercial use of energy (ICUE), Cape Town, 2009.

[16] Department of Mineral Resources, Guideline for the compilation of a mandatory code of practice for emergency preparedness and response, Mine health and safety inspectorate, 2011.

[17] M. Kleingeld and J. H. Marais, A high level strategy plan for reducing a mine group's dependence on compressed air, Industrial and commercial use of energy (ICUE), Cape Town, 2010.

[18] J. N. du Plessis, Development of an energy management solution for mine compressor systems, dissertation, North-West Univ., Potchefstroom, 2010.

[19] J. H. Marais, An integrated approach to optimise energy consumption of mine compressed air systems, thesis, North-West Univ., Potchefstroom, 2012.

[20] W. Booysen, J. N. du Plessis and J. F. van Rensburg, Development of an energy management solution for mine compressor systems, Industrial and commercial use of energy (ICUE), Cape Town, 2010.

[21] R. N. Brown, *Compressors: Selection and Sizing.* Houston, Texas, United States of America: Gulf publishing company, 1997.

[22] S. L. Dixon, *Fluid Mechanics, Thermodynamics of Turbomachinery.* Jordan Hill, Oxford, United Kingdom: Reed educational and professional publishing Ltd, 1998.

[23] J. K. Casper, Ed., *Fossil Fuels and Pollution, the Future of Air Quality.* New York city, New York, United States of America.: Facts on file Inc., 2010.

[24] P. C. Hanlon, *Compressor Handbook.* McGraw-Hill, 2001.

[25] H. Cohen, G. F. C. Rogers and H. I. H. Saravanamuttoo, *Gas Turbine Theory.* Harlow, Essex, England: Longman group limited, 1996.

[26] H. P. Bloch, *A Practical Guide to Compressor Technology.* Hoboken, New Jersey, united States of America: John Wiley and Sons, Inc., 2006.

[27] M. T. Gresh, *Compressor Performance: Aerodynamics for the User.* Woburn, Massachusetts, United States of America: Butterworth-Heineman, 2001.

[28] W. E. Forsthoffer, *Forsthoffer's Rotating Equipment Handbooks Vol 3: Compressors.* New York City, New York, United States of America: Elsevier Science & Technology books, 2005.

[29] R. S. R. Gorla and A. A. Khan, *Turbomachinery Design and Theory.* Montecello, New York, United States of America: Marcel Dekker, 2003.

[30] T. Giampaolo, *Compressor Handbook, Principles and Practice.* Lilburn, Georgia, United States of America: Fairmont press, 2010.

[31] Honeywell, Garret turbocharger guide volume 5, 2013.

[32] P. N. Ananthanarayanan, *Basic Refrigeration and Air Conditioning.* New Delhi, India: McGraw-Hill, 2005.

[33] J. N. du Plessis and R. Pelzer, Development of an intelligent control system for mine compressor systems, in *Industrial and Commercial use of Energy (ICUE), 2011 Proceedings of the 8th Conference on The,* 2011, pp. 59-63.

[34] P. Goosen, Ed., *Efficient Monitoring of Mine Compressed Air Savings.* North West University, North West, South Africa: M.Eng. dissertation, North West University, 2013.

[35] C. F. Scheepers, *Implementing Energy Efficiency Measures on the Compressed Air Network of Old South African Mines.* North West University, North West, South Africa: M.Eng. dissertation, North West University, 2011.

[36] Pneu-Logic, Ed., *PL4000 Compressed Air Master Control System.* Portland, Oregon, United States of America: 2012.

[37]*Airtelligence provis 2.0*. Available: http://www.boge.com/en/artikel/en/Effektiv/airtelligence.jsp?msf=250,200&switchlang=en. DOI: 2013.

[38] J. Venter, Development of a dynamic centrifugal compressor selector for large compressed air networks in the mining industry, M.Eng. dissertation, North-west university 2012.

[39] D. S. Viswanath, T. K. Ghosh, D. H. L. Prasad, N. V. K. Dutt and K. Y. Rani, *Viscosity of Liquids, Theory, Estimation, Experiment and Data.* AA Dordrecht, The Netherlands: Springer, 2007.

[40] J. A. Schetz and A. E. Fuhs, Eds., *Fundamentals of Fluid Mechanics.* New York city, New York, United States of America: John Wiley and Sons, 1999.

[41] D. R. Durgaiah, *Fluid Mechanics and Machinery.* Daryaganj, New Delhi, India: New Age international, 2002.

[42] B. R. Muson, D. F. Young, T. H. Okiishi and W. W. Huebsch, *Fundamentals of Fluid Mechanics.* Hoboken, New Jersey, United States of America: John Wiley and Sons, 2009.

[43] Reuters, Eskom warns power reserve is razor thin, 10 June 2013.

[44] R. C. Binder, *Fluid Mechanics.* New York City, New York, United States: Prentice Hall, 1964.

[45] E. W. McAllister, *Pipelines Rules of Thumb Handbook.* Oxford, United Kingdom: Gulf professional publishing, 2005.

[46] J. W. Lodewyckx, R. Pelzer and M. Kleingeld, Investigating the effects of different DSM strategies on a compressed air ring, Industrial and commercial use of energy (ICUE), Cape Town, 2008.

[47] A. Thumann and D. P. Mehta, *Handbook of Energy Engineering.* Georgia, United States of America: Fairmont press, 2001.

[48] G. D. Bolt, K. van Tonder and S. W. van Heerden, Practical challenges faced with implementing a dynamic compressor selection program, Industrial and commercial use of energy (ICUE), Cape Town, 2013.

[49] *Fuji Electric France*. Available: http://www.fujielectric.fr/. DOI: 23 October 2012.

Appendix A Electricity savings

Below is the exact power usage data measured on the mine during the test day for DCS.

Table 9: Half hour savings

Time	Static control (kW)	DCS control (kW)
00:00	15876	15487
00:30	15485	15487
01:00	15522	15445
01:30	15492	15534
02:00	15586	15515
02:30	14398	16333
03:00	14565	14617
03:30	14414	13934
04:00	14321	13923
04:30	14566	13997
05:00	14862	13988
05:30	14804	13988
06:00	15697	14753
06:30	15725	17541
07:00	15786	15233
07:30	18666	15119
08:00	18780	17174
08:30	20509	19821
09:00	22119	22482
09:30	22226	22242
10:00	22222	22141
10:30	23793	22177
11:00	25301	22045
11:30	25480	21863
12:00	24845	21914
12:30	24742	21793
13:00	22156	21167
13:30	21757	20364
14:00	21023	18057
14:30	19811	17561

15:00	17678	17142
15:30	17319	14989
16:00	14789	14791
16:30	14024	14726
17:00	13687	13936
17:30	13731	13760
18:00	13724	13712
18:30	13850	14039
19:00	14801	14154
19:30	15279	14267
20:00	15428	14465
20:30	17880	15013
21:00	17795	15342
21:30	17566	14863
22:00	15448	14931
22:30	15409	14644
23:00	15426	14856
23:30	15545	15132
Total	**839935**	**796483**
Difference		**43451**
Hourly average		**1810**