CHAPTER 2

OVERVIEW OF MINE COMPRESSOR SYSTEMS

2.1 Preamble

In this chapter compressor operation is discussed in detail, with specific reference to the influence of compressor control on compressor performance. Implications of compressor limitations such as the surge-and-choke phenomenon are discussed with emphasis on safe compressor control. A study of existing approaches and attempts at this type of energy management forms a vital part of this literature study and facilitates the development of a comprehensive solution.

2.2 Use of compressed air for mining

Compressed-air systems found in the mining industry are either stand-alone systems or compressed-air rings. Stand-alone systems consist of either single or multiple compressors supplying a single mining shaft. These compressors are typically located above ground, in a compressor house. A compressed-air ring consists of multiple compressor houses, which are connected to several shafts. Compressors form the supply of a compressed-air system and are collectively referred to as the compressor system. The compressed-air system consists of the compressor system together with the air reticulation network.

Table 2-1 provides a list of compressed air equipment frequently found at South African mines.

<table>
<thead>
<tr>
<th>Category</th>
<th>User</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock drills</td>
<td></td>
</tr>
<tr>
<td>Mechanical ore loaders</td>
<td></td>
</tr>
<tr>
<td>Loading boxes</td>
<td></td>
</tr>
<tr>
<td>Pneumatic pumps</td>
<td></td>
</tr>
<tr>
<td>Air fans</td>
<td></td>
</tr>
<tr>
<td>Hoists</td>
<td></td>
</tr>
<tr>
<td>Air movers (venturis)</td>
<td></td>
</tr>
<tr>
<td>Pneumatic rock breakers</td>
<td></td>
</tr>
<tr>
<td>Actuators</td>
<td></td>
</tr>
<tr>
<td>Agitation</td>
<td></td>
</tr>
<tr>
<td>Refuge bays</td>
<td></td>
</tr>
<tr>
<td>Service bays</td>
<td></td>
</tr>
<tr>
<td>Air leaks</td>
<td></td>
</tr>
<tr>
<td>Misuse (drying clothes, cleaning, etc)</td>
<td></td>
</tr>
</tbody>
</table>
Compressed air is used to facilitate production. It is therefore important to ensure correct compressor management so that production losses do not occur. If demand for compressed air exceeds the supply, certain production problems will be unavoidable. These problems include:

- Loading boxes may open and lose their load
- Lack of proper agitation
- Insufficient drilling
- Insufficient ventilation
- Equipment breakdown [23]

Proper compressor control will help to avoid insufficient supply pressure and associated production losses.

2.3 Compressors

2.3.1 Different compressor types

Various types of compressors are available, each with unique and specific characteristics. Compressors can be categorised as either intermittent-flow positive-displacement compressors or continuous-flow compressors. A breakdown of compressor classification is shown in Figure 2-1.

Flow and discharge pressures are key parameters when selecting a compressor for a specific application [25]. The pressure and flow properties of different compressor types are shown in Figure 2-2.
Chapter 2: Overview of mine compressor systems

Positive-displacement compressors provide high pressure ratios, at relatively low flow rates, compared to continuous-flow compressors [25]. Continuous-flow compressors are able to sustain the airflow required by large compressed-air systems at mines. The characteristics of the centrifugal compressor make it the most widely used compressor in the mining industry [23], [26].

2.3.2 Centrifugal compressors

Characteristics

Centrifugal compressors are simple and compact in design, while providing relatively high pressure ratios and discharge flow rates. Service intervals usually range from three to six years [25], [26]. General characteristics of centrifugal compressors are shown in Table 2-2.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Centrifugal compressor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency at full load</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency at part load</td>
<td>Poor (&lt; 60% of full load)</td>
</tr>
<tr>
<td>Efficiency at no load</td>
<td>Medium - High (20% to 30% of full load)</td>
</tr>
<tr>
<td>Size</td>
<td>Compact</td>
</tr>
<tr>
<td>Vibration</td>
<td>Minimal</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Sensitive to dust in air</td>
</tr>
<tr>
<td>Mass flow capacity</td>
<td>500 - 200,000 m³/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>100 - 400 kPa</td>
</tr>
</tbody>
</table>

Centrifugal compressors are ideally suited for compressed-air supply on mines.
Integrated compressor system

An integrated compressor system consists of a compressor unit and the components necessary to make compressor operation possible. The following components form part of this system:

- Compressor driver (prime mover)
- Lubrication-and-sealing system
- Instrumentation [26]

The compressor drivers can be steam turbines, gas turbines, gas expanders or electrical motors. Of these, the electric motor is predominantly used. These motors are either three-phase induction or synchronous machines with a speed-increasing gear [25].

The main aim of the lubrication-and-sealing system is to provide filtered oil at a regulated pressure and temperature to the motor and compressor [26]. Figure 2-3 is a representation of a typical lubrication-and-sealing system of a compressor.

![Figure 2-3: Simplified lubrication and seal oil schematic (adapted from [26])](image-url)
Oil is used for lubrication and shaft sealing to ensure that the compressor functions correctly. From a cold start-up, heating elements in the reservoir are used to heat the oil to the appropriate operating temperature of between 40 °C and 45 °C. When the oil is at the correct operating temperature, the heaters are turned off. Circulation of the oil ensures that the correct operating temperature is maintained with the help of the water cooling system. Water pumps supply coolers with water cooled by fans. The oil is finally delivered to appropriate locations, to provide the required lubrication [26].

Control of the oil pumps, water pumps, cooling fans and oil heaters is necessary to enable complete compressor control. Instrumentation on the compressor, compressor motor and lubrication-and-sealing system is required to ensure safe compressor operation.

**Compressor components and function**

Centrifugal compressors are designed as single- or multistage compressors [26]. A single compression stage has practical limitations which restrict the maximum pressure ratio of that stage [27]. A large compression ratio can result in excessive discharge temperatures, which are damaging to the compressor [26]. Multistage compressors allow for two or more stages of compression with reduced compression ratios. Inter-cooling between the stages will prevent excessive temperatures and still provide a high supply-pressure ratio. The basic components for single- and multistage compressors are the same. Components of a typical centrifugal compressor are shown in Figure 2-4.

![Diagram of a centrifugal compressor](image)

*Figure 2-4: Main components of a centrifugal compressor [25], [26]*
Chapter 2: Overview of mine compressor systems

Figure 2-5 and Figure 2-6 show cutaway views of single- and multistage centrifugal compressors respectively.

![Figure 2-5: Single-stage centrifugal compressor (adapted from [26])](image)

Most of the components listed in Figure 2-4 are indicated in Figure 2-6.

![Figure 2-6: Multistage centrifugal compressor (adapted from [26])](image)

The typical flow path through a multistage compressor is shown in Figure 2-7.
Air is drawn through the inlet casing into the eye of the rotating impeller. A typical impeller is shown in Figure 2-8.

The energy level of the incoming air is increased by whirling it outwards in a radial direction. This increases the angular momentum, where both the static pressure and air velocity are increased. This air then enters a diffuser where kinetic energy is converted into pressure energy [25], [27], [28]. The velocity and pressure profiles, from the eye of the impeller to the diffuser, are shown in Figure 2-9.
After passing through the diffuser, air enters the volute from where it is delivered into each consecutive impeller stage, until the last stage is reached. From here the air is collected in a discharge volute and directed to the discharge nozzle [26]. The discharge nozzle reduces the air velocity further, with an associated increase in static pressure, before entering the compressed-air system [27].

### 2.4 Compressor performance

#### 2.4.1 Background

Consider the compressor setup in Figure 2-10. The compressor is connected to the compressed-air system with an isolation valve installed downstream of the compressor. $P_{in}$ and $P_{out}$ are the total input and output pressures respectively.

If the compressor is operating at a constant speed, with the isolation valve closed, the mass flow will be zero and the pressure ratio will have a certain pressure, corresponding to the no-flow characteristics of the compressor. This operating point is shown as Point 5 in Figure 2-11.
When the valve is gradually opened the diffuser will contribute to a rise in pressure. The pressure ratio will increase until the point of maximum efficiency is reached. This point corresponds to Point 3 in Figure 2-11. Any further increase in mass flow will be accompanied by a decrease in the overall pressure ratio, to the right of Point 3 on the compressor curve in Figure 2-11.

Consider now the case with the isolation valve fully open and the compressor operating at a constant speed. The compressor has a constant mass-flow rate and a stationary operating point. This is indicated by Point 1 on the negative slope of the constant speed compressor curve shown in Figure 2-11. If the isolation valve is closed slightly the mass flow through the compressor is reduced. The operating point shifts to the left on the compressor curve, to Point 2. This operation is stable because the upstream pressure remains higher than the downstream pressure.

2.4.2 Surge and stall

In practice, although the zero mass-flow point can be obtained, most of the operating points between this point and the maximum pressure-ratio point cannot be sustained due to the phenomenon known as surge [25], [27]. This occurs fairly easily at any point on the positive slope of the characteristic compressor curve and can be explained as follows:

If the compressor is operating at the Point 4 on the compressor curve shown in Figure 2-11 and a decrease in mass flow occurs, the delivery pressure will fall. If the downstream pressure does not fall fast enough, the airflow will tend to reverse, in the direction of the temporary pressure gradient. In the meantime, the downstream pressure will have fallen and normal flow direction will be promoted. This cycle may be repeated at a very high frequency, resulting in violent pressure pulses that pass throughout the entire compressor [28], [29]. The magnitudes of the flow and delivery pressure during surge are shown in Figure 2-12.
This surge limit line represents the minimum flow limit through the compressor at the peak pressure head [27]. Flow reversal causes heavy loads on the thrust bearing and impellers [25]. In full surge, the compressor exhibits extreme instability, causing vibration and rising air temperature [29], [28]. The occurrence of surge is accompanied by loud mechanical noise [26], [30], [31].

A second important cause of compressor instability and reduced performance is rotating stall, which is most commonly encountered in axial flow compressors. Any non-uniform flow into the impeller intake may result in an early or unexpected boundary layer breakaway over the low-pressure side of the compressor blade. This will cause a reduced flow of air through that specific channel. The reduced mass flow causes an increased angle of attack ($i$), on impeller Blade 1, as shown in Figure 2-13 [27].

An increased angle of attack ($i$) results in further separation on the low-pressure side of Blade 1 as shown in Figure 2-13 [32]. This separation layer disrupts the normal flow path of air moving through the impeller [27], [33]. This disruption is known as a **stall cell** [33].
Air is deflected to Blade 2 because of the flow obstruction on Blade 1. This deflection causes an increased incidence angle on Blade 2, which results in flow separation on Blade 2. Separation on this blade allows the flow over Blade 1 to be restored. Separation starts at one or more blades and continues in the opposite direction to impeller rotation [27], [32].

Stall cells form partial obstruction to flow, causing a significant drop in discharge pressure [30]. A compressor is capable of stable operation when slight stall is present, because the complete flow is stable over time [33]. However, stall causes the compressor to operate at reduced performance and efficiency and blade failure is possible due to resonance, induced by rotating stall [32].

2.4.3 Choke

If the relative blade air velocity inside the compressor reaches Mach 1, choking occurs [29]. At this point the airflow rate cannot increase further, even if the system pressure is decreased and rotational speed is increased [33], [32]. The choke point is reached at maximum flow and minimum pressure [27]. These conditions are usually encountered only on aircraft-type compressors. Centrifugal compressors, used on South African mines, supply air to a pressure-charged air system and are not known to exhibit the choke phenomenon.
2.4.4 Performance maps

Compressor and system curves

A compressor performance map consists of compressor curves and system curves. Discrete changes of speed result in a family of compressor curves, similar to the curve in Figure 2-14 [26]. Different combinations of air properties, vane positions and back pressure (network resistance) result in a family of system curves. A system curve represents the amount of energy that must be added to the inlet air to sustain the given flow, and is an indication of the resistance of the air network [26]. Compressor and system curves are shown in Figure 2-14.

![Compressor map with efficiency contours](image)

In Figure 2-14 the dotted lines represent incremental compressor and system curves; with the solid black line representing the constant speed compressor curve.

Operating point

The intersection of the applicable compressor and system curves is known as the operating point. Flow rate at this point is such that energy added to the inlet air is equal to the energy required to overcome the network resistance [26]. At a fixed rotational speed and inlet-flow rate, a fixed pressure head is developed, thus resulting in a stationary operating point [34].

Limitations

The performance of the compressor has practical and physical limitations, which restrict the operational performance boundaries. Due to compressor geometry, there is a limit to the stable flow that can be maintained by the machine [27]. The surge-and-choke phenomenon restricts the stable mass-flow range...
of a compressor. The minimum and maximum rotational speed of the compressor also limits the area of stable operation [27]. These limitations are indicated in Figure 2-14.

Efficiency

The efficiency of the compressor, operating at a constant rotational speed, is indicated on the performance map by efficiency contours [35]. An operating point on the constant speed compressor curve, which falls within the area enclosed by the 0.75 efficiency contour, operates with an efficiency of greater than 75%. Efficiency contours are indicated in Figure 2-14.

2.5 Compressor control

2.5.1 Control strategies for energy management

Start/stop

The simplest form of compressor control — for energy management purposes — is starting-and-stopping a compressor. During periods of low pressure demand, a compressor may be shut down. Maximal energy reduction is possible when the compressor is shut down completely. However, frequent starting-and-stopping causes the electric motors of the compressors to overheat. As a result, maintenance intervals will be reduced. If the expected period between a compressor shutdown and the next start-up does not justify shutting down the compressor, the compressor can be unloaded instead [17].

Load and unload

A compressor is unloaded by isolating it from the compressed-air system. This is accomplished by opening the blow-off valve at the compressor discharge, and closing an isolation valve which disconnects the compressor from the air network. An unloaded compressor operates at part-load and can consume up to 70% less energy than the full-load energy consumption [19].

Capacity control

Capacity control is applied when the pressure demand does not allow shutting down or unloading a compressor in order to more closely match supply with the demand. This allows the compressor to be operated at reduced-load, consuming less electrical energy. Methods of capacity control include: variable structure control; non-linear bleed-valve control; variable speed control; inlet throttle-valve control; and Inlet Guide-Vane (IGV) control [17], [31], [36].
2.5.2 Methods of compressor capacity control

Variable structure control

The physical structure of a compressor determines the flow and pressure characteristics of the compressor. These characteristics can be changed by controlling the inlet conditions to the compressor. Variable geometry diffuser (VGD) is one method of controlling the flow through the diffuser of a compressor. This method can allow full flow through the diffuser; or partially restrict the flow to achieve capacity control [37].

Bleed-valve control

A bleed valve at the discharge of the compressor can be used to reduce the flow to the air system. Opening this valve allows air to blow off into the atmosphere, resulting in reduced airflow to the system. The bleed valve can also redirect the air back to the inlet of the compressor. This type of capacity control is not considered for energy management due to the wasteful nature of bleed flow [17].

Variable speed control

Constant speed electric motors are typically used to drive the compressors on South African mines [27]. A variable speed drive (VSD) can be used to control the speed of the motor and thus the rotational speed of the centrifugal compressor. The pressure head of a compressor is proportional to the square of the rotational speed [26]. Reducing the rotational speed of the compressor will result in a reduction in delivery pressure.

Because the characteristic curves are relatively flat near maximum efficiency, small changes in pressure head is only achieved with large changes in the mass-flow rate. Speed reduction below 40% of the design speed causes increased vibration on rotating components [27]. Implementation of variable speed control has a large initial cost, which is proportional to the capacity of the compressor motor [25]. This high cost is generally not practical for compressor control in the South African mining industry, with compressor motors rated from 1 MW to 15 MW.

Inlet throttle-valve control

The airflow to the compressor can be throttled by a sleeve, gate or butterfly valve. These valves can be actuated pneumatically, hydraulically or electrically [38]. Electric actuator motors have linear characteristics that can maintain the valve accurately in a specific position [38].
Different throttle-valve positions result in different systems curves. The system curves for four different throttle-valve positions \((S_1, S_2, S_3, \text{ and } S_4)\) are shown in Figure 2-15 [32].

![Figure 2-15: Compressor performance with different throttle positions (adapted from [32])](image)

Assume that a compressor has a static operating point at the intersection of the compressor curve and \(S_1\) in Figure 2-15. At this point, the system pressure is approximately equal to the desired supply pressure. If the demand decreases, the system pressure increases and the airflow will be reduced. The operating point shifts to the left on the compressor curve, to the intersection with \(S_2\) in Figure 2-15.

Opening the inlet throttle valve increases the flow through the compressor and in effect shifts the operating point to the right on the compressor curve. The operating point is shifted back to its original position, where the system pressure and the desired pressure are approximately equal.

This type of control — continually working to reduce the error between the desired and actual pressure — is commonly done as Proportional–Integral (PI) and Proportional-Integral-Derivative (PID) control [25], [26], [39]. Airflow control must be undertaken with care because inlet conditions and rotational speed have a direct effect on the performance of the compressor. Unrestricted flow control can result in compressor surge.

### 2.5.3 Methods of preventing surge

**Surge avoidance**

Surge avoidance aims to manage the operation of the compressor so that the operating point is kept to the right of the surge limit line [40], [41]. A surge control line is defined at a safe position to the right of the surge limit line as illustrated in Figure 2-16 [30]. The surge limit line can be constructed by evaluating the position of the surge points during experimental compressor control [27], [29].
A surge avoidance system ensures that the compressor operates in the area to the right of the surge control line. This is achieved by bleeding airflow from the discharge of the compressor when the surge control line is reached [27], [29]. A typical compressor surge avoidance system is shown in Figure 2-17.

Bleed flow reduces the pressure at the discharge of the compressor, while increasing flow through the compressor, thus avoiding surge [29]. The controller accomplishes this by incrementally opening the blow-off valve once the surge control line is reached. This valve has a slow closing time of between 10 seconds and 20 seconds to keep the air system stable [27]. Ideally the blow-off valve is a fail-open valve, which means that the valve will open in case of electrical failure on the actuator [29].

Surge avoidance has the capability of improving overall compressor efficiency by avoiding the unstable and inefficient area leading to full surge [42]. There is however an efficiency penalty because of energy loss due to bleed flow through the blow-off valve.
Surge detection and avoidance

This type of surge prevention detects the approach to a surge condition and reacts to prevent the compressor from reaching full surge. Flow rate or the rotational speed can be increased to prevent surge [30]. This can be accomplished with PI and adaptive control, fuzzy control, self-tuning fuzzy control and Linear Quadratic Gaussian (LQG) [40]. Surge detection and avoidance extends the stable operating area of the compressor, when compared to surge avoidance.

Surge suppression

Surge suppression keeps the compressor in stable operation even to the left of the surge limit line, increasing the stable flow range of the compressor [32]. The stable operating area is extended even further than with surge detection and avoidance [40], [41]. An inlet valve, with feedback control, can be used for active suppression of aerodynamic instability, thereby increasing compressor stability and performance [30], [42], [43]. This method reduces wasteful blow-off of air [38].

To summarise, Figure 2-18 illustrates the difference between these methods of preventing surge.

![Figure 2-18: Surge avoidance; surge detection and avoidance; and surge suppression (adapted from [30])](image)

Table 2-3 lists the technologies used in surge prevention patents registered up to 2007.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Patents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge avoidance</td>
<td>148</td>
</tr>
<tr>
<td>Surge detection</td>
<td>53</td>
</tr>
<tr>
<td>Surge suppression</td>
<td>1</td>
</tr>
</tbody>
</table>

Surge avoidance is the most widely used technology because it is simple to implement and has a built-in safety margin [30].
### 2.5.4 Integrated compressor control systems

Centrifugal compressor control is a complex task. A control system may be divided into several stand-alone systems, which are interfaced with the overall control system [27]. Compressor control includes:

- Load control
- Capacity control
- Anti-surge control
- Multiple parameter monitoring for safe shutdown (safety trip)
- Communication and remote monitoring [27]

Individual control systems are used for anti-surge control, speed control, vibration monitoring etc. Controls for centrifugal compressors must have rapid response times to prevent machine damage. A complete compressor control system manages all the sequences involved in automated control. The sequences for starting-and-stopping compressors are shown in Table 2-4.

#### Table 2-4: Procedures for starting-and-stopping a compressor

<table>
<thead>
<tr>
<th>Action</th>
<th>Equipment monitored</th>
<th>Initial</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start</strong></td>
<td>Discharge valve</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Inlet valve</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Blow-off valve</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Close</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td>Stopped</td>
<td>Stopped</td>
<td>Start</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
</tr>
<tr>
<td></td>
<td>Lubrication system</td>
<td>Stopped</td>
<td>Start</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
</tr>
<tr>
<td><strong>Stop</strong></td>
<td>Discharge valve</td>
<td>Open</td>
<td>Open</td>
<td>Close</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Inlet valve</td>
<td>Open</td>
<td>Open</td>
<td>Close</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Blow-off valve</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Stop</td>
<td>Stopped</td>
</tr>
<tr>
<td></td>
<td>Lubrication system</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Stop</td>
</tr>
</tbody>
</table>

The sequences for loading and unloading compressors are shown in Table 2-5.

#### Table 2-5: Procedures for loading and unloading a compressor

<table>
<thead>
<tr>
<th>Action</th>
<th>Equipment monitored</th>
<th>Initial</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load</strong></td>
<td>Discharge valve</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Inlet valve</td>
<td>Closed</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Blow-off valve</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Close</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
</tr>
<tr>
<td></td>
<td>Lubrication system</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
</tr>
<tr>
<td><strong>Unload</strong></td>
<td>Discharge valve</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Close</td>
</tr>
<tr>
<td></td>
<td>Inlet valve</td>
<td>Open</td>
<td>Open</td>
<td>Close</td>
<td>Closed</td>
</tr>
<tr>
<td></td>
<td>Blow-off valve</td>
<td>Closed</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
</tr>
<tr>
<td></td>
<td>Lubrication system</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
<td>Running</td>
</tr>
</tbody>
</table>
Examples of the manual procedures followed to start-and-stop compressors at a specific mine are included in Appendix A. During compressor start-up, shutdown and trip-outs, surge can occur due to low airflow [27]. Anti-surge control has to be operational, particularly during start-ups, stops and trip-outs, to prevent compressor surge at low flow rates.

### 2.6 Measurement instrumentation

Instrumentation, which is used to monitor the integrated compressor system, typically monitors the following [25]:

- Inlet and discharge pressure [kPa]
- Mass flow [kg/s] or volumetric flow [m³/h]
- Power consumption [kW]
- Rotational speed [rpm]
- Torque [Nm]
- Inlet and outlet temperature [°C]
- Vibration [sensor dependent]

Measurements which are necessary for compressor control depend on the control method. Airflow rate and inlet and discharge pressure are measured irrespective of the control method. Temperature and vibration is monitored to evaluate compressor stability and is used to prevent compressor damage [27].

The lubrication-and-sealing system described in Section 2.3.2 must be automated in order to make compressor control possible. Before the electric motor is started, the prelubrication cycle of the compressor should be completed according to manufacturer specification. A timer or pressure switch, in conjunction with oil temperature measurement, acknowledges completion of prelubrication cycle. This cycle may take up to 15 minutes, mainly depending on the time required for oil heating. The compressor should be tripped if oil flow or temperature is insufficient. Electronic systems can measure the actual flow and pressure and transmit the data to a computer to allow for comprehensive control [27].

Temperature and pressure indicators should be placed in easily accessible locations [27]. Valves; strainers; noise dampers; or other components that could cause a significant pressure drop between pressure tap points and compressor flanges, must be avoided [27]. Pressure measurement points are installed on the top of the pipe diameter. Points near an elbow should be normal to the bend and not in the plane of the bend [27]. The static pressure measurement hole should be small relative to the boundary
layer thickness, with a diameter of approximately 6 mm considered as being adequate [27]. A pressure transmitter with a 0.25% sensitivity and maximum error of 0.5% is ideal [27].

To minimise the effect of the system transient, data should be collected via a digital monitoring system to ensure that all data is collected simultaneously [27].

### 2.7 Existing compressor energy management systems

Automated energy management is not a new concept and there are various different energy management systems in use throughout the industrial and mining sectors. A comparison of several energy management systems is summarised in Table 2-6.

<table>
<thead>
<tr>
<th>Control system</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity control</td>
</tr>
<tr>
<td>ecControl [44]</td>
<td>●</td>
</tr>
<tr>
<td>CAMS 320</td>
<td>●</td>
</tr>
<tr>
<td>US patent no 5343384 by Ingersoll-Rand Company [45]</td>
<td>●</td>
</tr>
<tr>
<td>Air Miser® [46]</td>
<td>●</td>
</tr>
</tbody>
</table>

These systems are individually discussed in the paragraphs that follow. A brief overview of Programmable Logic Controller (PLC) programming and Supervisory Control and Data Acquisition (SCADA) packages, for application in energy management, is also provided.

**ecControl [44]**

This system is a tariff- and calendar-based control software package. Year schedules are configured by defining each day as either a weekday, Saturday, Sunday or holiday. Schedules are configured for each day type. Equipment is then controlled according to these schedules. However, this system is intended for general energy management and not specifically designed for compressors.
CAMS 320

This system is capable of managing compressors with different capacities. Compressor capacity control, unloading, starting-and-stopping is done according to daily and weekly schedules.

This system is however limited to managing a maximum of eight compressors simultaneously. The user interface consists of a six-position, light-emitting diode (LED) display and a four-character alphabetic display, which does not support remote access.

US patent number 5343384 by Ingersoll-Rand [45]

This patent proposes that the user chooses a lead compressor. The lead compressor is followed by all the other compressors, known as lag compressors. All the compressors are operated with the same pressure set-point, to share the load equally. The patent claims to do compressor capacity control, unloading, starting-and-stopping to achieve optimal energy management.

This patent is however designed to control compressors with equal capacities. Compressor sequencing is executed on the concept of first-in/first-out, which does not take compressor capacity into consideration. The response of this patent to compressors with different capacities is unknown.

Air Miser® [46]

Air Miser accomplishes compressor energy management by capacity control, unloading and starting-and-stopping according to the demand. Remote access to Air Miser® is possible via serial communication and Ethernet. Access control consists of two-level password protection.

This system offers a comprehensive automation solution. This solution will however render existing compressor PLCs worthless, seeing as all the PLC functionality is handled by the Air Miser® system. This might pose a problem for some mine groups, who have standardised on a specific brand of PLC.

PLC programming and SCADA packages

PLCs are commonly used by South African mines to automate electrical equipment. These controllers are programmed for the specific automation task it is required for. Disadvantages of using PLC programming to develop a compressor energy management system include:

- PLC programming does not support the flexible mathematical capabilities of computer systems, thus inhibiting the capability of this approach to accomplish optimised control.
• PLCs do not offer extensive database capabilities.

SCADA packages are interfaced with PLCs to extend the capability of the PLC with more advanced control algorithms and database storage. The most common SCADA packages used by South African mines include Citect [47], Proficy iFix, Adroit [48], Wonderware Intouch® [49] and Simatic WinCC [50]. An investigation showed that none of these SCADA packages are currently used for compressor energy management.

2.8 Summary

This chapter gives an overview of the uses of compressed air in the mining industry. Different types of compressors are discussed with particular focus on centrifugal compressors, which are widely used on South African mines. Compressor maps are used to illustrate the impact that control changes have on compressor performance and to highlight the implications of compressor limitations such as the surge-and-choke phenomenon.

Compressor control aspects addressed in this chapter include:

• Load control
• Capacity control
• Anti-surge control

Automation requirements such as lubrication and cooling system control and valve control are discussed in addition to the measurement instrumentation required for complete compressor automation.

Existing energy management systems are evaluated and compared. The functionality most common to these systems includes:

• Load control
• Capacity control
• Anti-surge control
• Compressor energy management
• Full real-time manual control
• Automated operation
• Remote access with access control
A comprehensive compressor energy management solution should provide the mentioned functionality together with the flexibility to be easily adapted for individual compressor systems. It must be possible to implement this solution on a compressor system with no compressor automation. In addition, the solution should be flexible enough to integrate with existing control system hardware.