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Simulating Energy Efficient Control of Multiple-Compressor Compressed Air Systems

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ABSTRACT

In many industrial facilities it is common for more than one air compressor to be operating simultaneously to meet the compressed air demand. The individual compressor set-points and how these compressors interact and respond to the facility demand have a significant impact on the compressed air system total power consumption and efficiency. In the past, compressors were staged by cascading the pressure band of each compressor in the system. Modern automatic sequencers now allow more intelligent and efficient staging of air compressors. AirSim, a compressed air simulation tool, is now able to simulate multiple-compressor systems with pressure band and automatic sequencer controls. AirSim can simulate a current compressed air system and a proposed system with changes to the equipment and/or controls. Thus, quickly and accurately, users can calculate the energy and cost savings expected from many proposed compressed air system upgrades.

INTRODUCTION

Nearly every industrial plant contain compressed air systems. In many industrial facilities air compressors use more electricity than any other single type of equipment. Commonly referred to as the "fourth utility", compressed air systems can typically be optimized to decrease the energy use of the system by 20% to 50%. In addition to energy and cost savings, an energy efficient compressed air system can reduce maintenance, extend the useful life of the system components, and improve system reliability [6].

Compressed air controls match the compressed air supply with the facility demand and can be one of the most important determinants in overall system energy efficiency. Compressed air systems are sized for the maximum expected plant air demand, thus these systems typically operate only partially loaded. Compressed air system controls coordinate how individual compressors operate and how multiple compressors interact to deliver the required pressure and volume of air to the facility in the most reliable and efficient manner. Systems with multiple compressors contain greater opportunity for controls optimization. The three main types of multiple-compressor control strategies which will be discussed in this paper are: pressure band control, network sequencer control, and automatic sequencer control (also referred to as system master control) [13].

Compressor air component manufactures are acutely aware of the potential for energy savings from multiple-compressor controls. Atlas Copco, Kaeser, and Quincy all market compressed air system central controllers to optimize system efficiency [1] [10] [12]. Furthermore, the 2013 California Building Energy Efficiency Standard, which became law July 1, 2014, requires a central controller for multiple-compressor compressed air systems with total rated power over 100-hp. This standard also requires a variable speed drive (VSD) trim compressor [8]. As will be discussed later, these two requirements cannot be met with pressure band control or network sequencer control. Only automatic sequencer control allows a trim compressor to always meet the part-load marginal system demand.

This paper begins by reviewing the basics of simulating individual air compressors, fundamental to the compressed air simulation tool AirSim. Next, the basic principles and control algorithms are detailed for pressure band control, network sequencer control, and automatic sequencer control strategies for multiple-compressor compressed air systems. Finally, a case study is presented demonstrating the use of the improved compressed air simulation tool, AirSim [9], to quickly and accurately model multiple-compressor compressed air systems.

SIMULATING SINGLE AIR COMPRESSOR PERFORMANCE

Individual air compressors can be controlled in several ways. Schmidt and Kissock describe these control methods as generalized linear relationships between fraction full-load power (FP) and fraction rated capacity (FC) [3]. Using linear generalizations and assigning FP_0 as the fraction of full-load power consumed when the compressor is producing no compressed air, the relationship between FP and FC can be modeled as:

$$FP = FP_0 + (1 - FP_0) \times FC \quad (1)$$

The normalized power and capacity coefficients in Equation 1 are the actual power and capacity divided by the maximum power and capacity:

$$FP = P / FLP \quad (2)$$
$$FC = C / FLC \quad (3)$$
$$FP_0 = P_0 / FLP \quad (4)$$

P is the actual compressor power, FLP is the full-load compressor power, C is the actual compressed air output, FLC is the full-load compressor output capacity, and P_0 is the compressor power when producing no compressed air.

Schmidt and Kissock originally graphed the linear relationships between FP and FC for different control methods [3]. Figure 1 shows these FP and FC relationships for several common compressor control methods with added insight. While Equation 1 can be used to model the part-load efficiencies of these different control types, it is important to notice the variations which occur for load/unload, variable speed, and on/off control. Load/unload and on/off only operate at full-load, 100% capacity and 100% power, or no-load, 0% capacity and FP_0. Variable speed control can operate on the continuum between full-load and about 25% FC. Blow off and modulation control operate continuously between full-load and no-load.

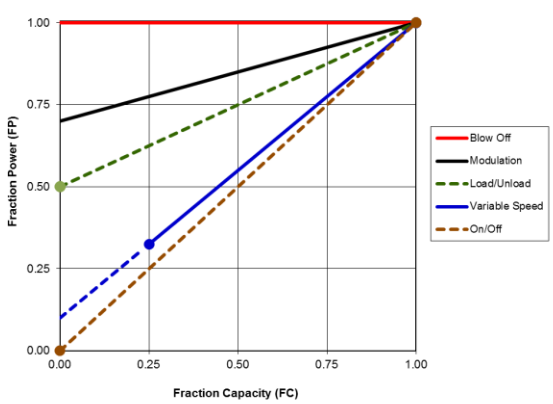

Figure 1. FP vs FC for Common Compressor Control Types

Other control methods not shown in the FP-FC graph in Figure 1 include dual, auto-dual, and variable displacement control. Dual and auto-dual control operate in load/unload control down to a certain capacity, below which they operate in on/off control. Variable displacement typically employs a turn-, spiral-, poppet-, or slide-valve to vary the effective length of the screw compressor [7].

Air compressors supply compressed air to the distribution system, which deliver it to end-uses. The system pressure depends on the volume of air supplied by the compressors, the volume of air demanded by the plant, and the fixed volume (storage and distribution) of the compressed air system. A first order model of this relationship, originally developed by Schmidt and Kissock, is revisited below, which leads to the underlying relationships AirSim uses to model air compressors. The model excludes the effect of pressure drop due to friction through the dryer and distribution system [3].

From the ideal gas law, the mass of air, m, enclosed in a volume, V, at a given air pressure, P, and temperature, T, where R is the gas constant for air can be written as:

$$m = (P \times V) / (R \times T) \quad (5)$$

The volume flow rates of air from the compressor and to the plant are defined as V_c and V_p, respectively. Similarly, the mass flow rates of air from the compressor and to the plant are defined as m_c and m_p, respectively. The volume of compressed air storage is defined as V_s. A mass balance on the compressed air distribution system, where t is time, is:

$$m_c - m_p = \delta m / \delta t = \delta[\, (P \times V) / (R \times T) \,] \; / \delta t \quad (6)$$

Assuming the compressed air system is isothermal and the changes happen over a finite time interval, Δt, Equation 6 can be simplified to:

$$(V \times \rho)_c - (V \times \rho)_p = (P^+ - P) \times V_s / (R \times T \times \Delta t) \quad (7)$$

where ρ is the density of air and P and P^+ are the pressures at the beginning and end of the time interval, respectively. When the volume flow rates are measured in terms of standard conditions (i.e. scfm), the air density is also taken at standard atmospheric conditions. Thus, the pressure at the end of a time interval, P^+, with varying volume flow rates from the compressor and to the plant, can be written as:

$$P^+ = P + (V_c - V_p) \times \rho \times \Delta t \times R \times T / V_s \quad (8)$$

Equation 8 is the fundamental equation AirSim uses for simulating air compressor performance, since air compressor output, V_c, is typically controlled based on the system pressure, P. Thus, a control algorithm for on/off and load/unload control modes can be written such that the compressor generates the full rated capacity of compressed air output to raise the pressure from the lower to the upper activation pressures. The compressor would generate no compressed air output as the system pressure falls back to the lower activation pressure.

Similarly, an algorithm for modulation and variable speed control modes can be written to maintain system pressure between the lower and upper activation pressures, P_l and P_h, respectively, using a variant of proportional control. AirSim does this by relating the compressed air output and the system pressure, P, such that the compressed air output is the product of the full rated capacity and FC, where FC is defined as:

$$FC = 1 - (P - P_l) / (P_h - P_l) \quad (9)$$

The primary differences between AirSim and the popular AirMaster+ software [17] is the time interval for the simulation and the automatic sequencer control logic. AirSim allows the user to define a time interval appropriate for the system being considered, where AirMaster+ operates on a fixed time interval of one hour. Thus, in AirSim the time interval can be defined short enough to model actual load/unload, blowdown, or modulation events, which typically occur on the order of seconds or minutes. This feature makes calibration easy, allows the user to develop a better understanding of the dynamic behavior of the system, and allows AirSim to consider savings opportunities, such as automatic shut off, which cannot be modeled using AirMaster+.

Additionally, AirSim allows the user to simulate a compressed air system with multiple compressors using automatic sequencer control. AirSim uses basic control logic, to be discussed in the next section, to automatically determine which compressors operate based on the variable plant air demand. AirMaster+ requires the user to specify the staging order of compressors for each hour of plant air demand.

SIMULATING MULTIPLE AIR COMPRESSOR PERFORMANCE

Multiple-compressor system controls coordinate how individual compressors operate and how multiple compressors interact to deliver the required pressure and volume of air to the facility in the most reliable and efficient manner. The three main types of multiple-compressor control strategies are: pressure band control, network sequencer control, and automatic sequencer control (also referred to as system master control). In the past, compressors were typically staged by cascading the pressure bands of the compressors in the system, the most basic type of pressure band control. The next advancement was network sequencer controls, which tied multiple compressors together to operate as a strategic unit, rather than independently. Modern automatic sequencers now enable much more intelligent and efficient staging of air compressors by fully utilizing VSD trim compressors [13].

Pressure Band Control

The lease sophisticated multiple-compressor control strategy is pressure band control. Pressure band control is a strategy for operating individual compressors without communication between compressors. Each compressor continues to operate with a distinct control type (i.e. modulation, load/unload, variable speed) and makes control decisions based solely on the pressure at the outlet of the compressor. Traditionally, pressure band control has been used to stage load/unload compressors in cascading pressure band, as shown in the Figure 2. Pressure bands for load/unload compressors typically span 10 psig with individual compressors overlapping every 5 psig.

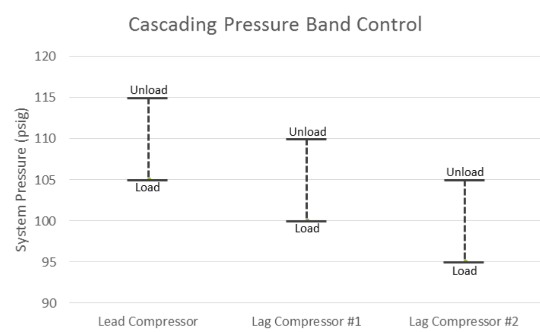

Figure 2. Cascading Pressure Band Control Strategy

For the set-points shown in Figure 2, if plant demand is low, only the lead compressor will operate between 105-115 psig. When the plant air demand increases, the lead compressor will become fully loaded. If the lead compressor cannot keep up with demand, the system pressure will drop and eventually hit 100 psig. At this point the first lag compressor will sense the plant air pressure at its activation pressure, 100 psig, and it will load.

Now if the plant air demand remains fairly constant the system will stabilize with the lead compressor running fully loaded and the first lag compressor operating at part-load between load and unload. The plant pressure will be in the 100-110 psig band. Since the pressure never reaches 115, the lead compressor will not unload.

Finally, if the plant air demand increases further beyond the capacity of both the lead and first lag compressor combined, the system pressure will drop below the lower band of the first lag compressor to the activation pressure of the second lag compressor, 95 psig. At this higher plant air demand both the lead and first lag compressors will operate fully loaded, while the second lag compressor loads and unloads between 95-105 psig. If additional plant air demand were to occur beyond the capacity of these three compressors an additional lag compressor would need to be cascaded at a lower pressure band. When plant air demand decreases and the system pressure increases, the compressor operating partially loaded will unload and typically automatically shut off after a certain time period. Once the system pressure reaches the unload pressure of the previously cascaded compressor, this compressor will unload/load and become the partially loaded compressor.

This control strategy allows only one compressor to operate at part-load at a time, thus limiting the quick cycling of load/unload compressors. However, since the lower band of the last cascaded compressor must still provide high enough pressure to meet plant demand, the lead and lag #1 compressors operate inefficiently at excessively high pressures. This control strategy also results in very high pressure fluctuations throughout the compressed air system as the system cascades between pressure bands. Furthermore, depending on plant demand, any one of the three compressors could be operating at part-load with a cascading pressure band control strategy.

Figure 3 shows a simple compressed air demand profile over time. The operation of lead and lag compressors with varying demand is shown for cascading pressure band control and network sequencer control (discussed in the next section). As described previously, the lead compressor always meets the first amount of compressed air demand, followed by each of the lag compressors based on their cascading pressure set-points.

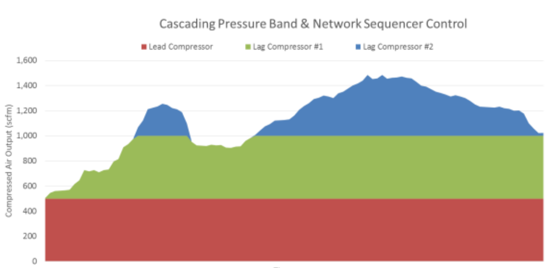

Figure 3. Cascading Pressure Band and Network Sequencer Control Demand Profile

More complicated control strategies can be achieved if a modulating or variable speed compressor is included in a pressure band controlled system. Figure 4 shows one such pressure band strategy with a VSD compressor staged in such a way as to maximize the operation of the VSD compressor at part-load rather than the load/unload compressors. This strategy achieves energy savings due to VSD compressors operating at higher part-load efficiencies and an overall reduction is the system pressure band compared to the cascading pressure band strategy shown in Figure 2.

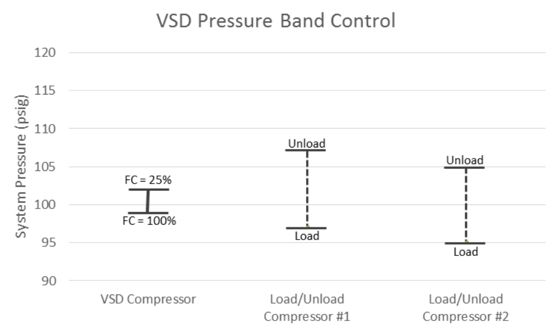

Figure 4. VSD Pressure Band Control Strategy

The VSD pressure band strategy shown in Figure 4 would operate in the following way as plant air demand changes. Initially assume that the plant air demand is low enough to be met by the VSD compressor alone. The compressor speeds up and slows down within the pressure band of 99-102 psig with a control algorithm similar to Equation 9. If the plant air demand increases beyond the capacity of the VSD compressor, the system pressure will drop below 99 psig to the activation pressure of the first load/unload compressor. This constant speed drive (CSD) compressor will load at 97 psig and cause the system pressure to increase. As the system pressure increases back within the VSD compressor's pressure band, the VSD compressor slows down until the system pressure stabilizes. Since the system pressure did not increase to the first load/unload compressor's unload pressure, this compressor will remain fully loaded while the VSD compressor will operate at part-load.

If the plant air demand increases further, the pressure will drop causing the VSD compressor to fully load and the first load/unload compressor will remain fully loaded. The pressure will drop to the second load/unload compressor's activation pressure, 95 psig, causing it to load. As the system pressure increases back within the VSD compressor's pressure band, the VSD compressor slows down until the system pressure stabilizes. Now the two load/unload compressor are operating fully loaded and the VSD compressor is operating at part-load.

If the plant air demand decreases from this point, the system pressure will increase through the VSD compressor pressure band causing it to eventually shut off. The pressure may continue to rise to the second load/unload compressor's unload pressure set-point, 105 psig, causing this compressor to unload. With the second load/unload compressor unloaded, the system pressure will decrease back into the VSD pressure band. If the system demand stabilizes, the first load/unload compressor remains fully loaded and the VSD compressor operates at part-load.

A potential issue when operating a VSD compressor in such a manner as shown in Figure 4 is having a system control gap. Control gaps can be avoided by properly sizing the capacity range of the VSD compressor to be greater than the full-load capacity of the largest base compressor. Control gaps will be discussed further in the automatic sequencer section.

The VSD pressure band control strategy is much more efficient than the cascading pressure band control strategy with all load/unload compressors. However, the main disadvantages of both include: large pressure swings throughout the plant, decreased compression efficiency due to excessively high pressure bands, and limited compressor response time. This last issue, compressor response time, often results in some "ideal" pressure band control strategies being unrealistic due to significant response times of individual compressors not tied to a central controller. If the individual compressor's pressure bands are too small or if compressors' unload or load set-points are too near each other, compressors could short-cycle, excessive pressure swings could occur, and the system will likely not operate as intended [16]. Thus, communication between individual compressors is key to reduce large pressure swings and operate the system most efficiently.

AirSim allows for the staging of multiple compressors of various individual controls with pressure band system control [9]. This control strategy idealizes systems to have immediate response times and exactly the same system pressure sensed at each compressor. Thus, simulating pressure band control in AirSim should be done with caution.

<u>Network Sequencer Control</u>

Network sequencer control adds a level of sophistication by allowing individual compressor to communicate with one another. This typically occurs by linking the compressors' microprocessors together, with one compressor designated as the lead compressor and all other compressors subordinate, lag compressors. Network sequencer control allows the lead compressor to decide which compressors operate based on which compressors are currently operating and a single reading of system pressure. This single pressure reading reduces the variance which often occurs in pressure band control where different compressors sense different system pressure depending on where they are located throughout the system [16].

Although the system still makes decisions based primarily on the system pressure, the additional data points of which compressors are operating allows for tighter overall system pressure control. An example of a network sequencer control strategy is shown in Figure 5.

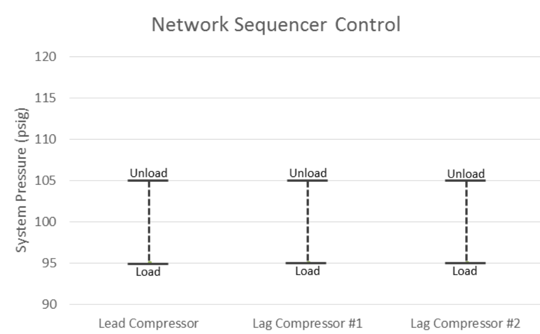

Figure 5. Network Sequencer Control Strategy

In this network sequencer control strategy, three load/unload compressors are operating within a common pressure band. This is possible by classifying their sequence of operation based on their lead/lag position. The lead compressor will operate first within the 95-105 psig range. If the system demand exceeds the lead compressor's capacity, the network sequencer will sense the system pressure dropping below the lower pressure set-point, determine which compressors are currently operating, and turn on the next appropriate compressor (lag compressor #1). Now the first lag compressor will operate at part-load while the lead compressor will remain fully loaded. If plant demand continues to increase and system pressure drops below the lower pressure set-point, the second lag compressor will operate at part-load with the first two compressors fully loaded. Conversely, if the plant air demand decreased and the pressure rises above the upper pressure set-point, the network sequencer will know which compressors are operating and determine which compressor to shut-off (lag compressor #2) and which compressor to run at part-load (lag compressor #1).

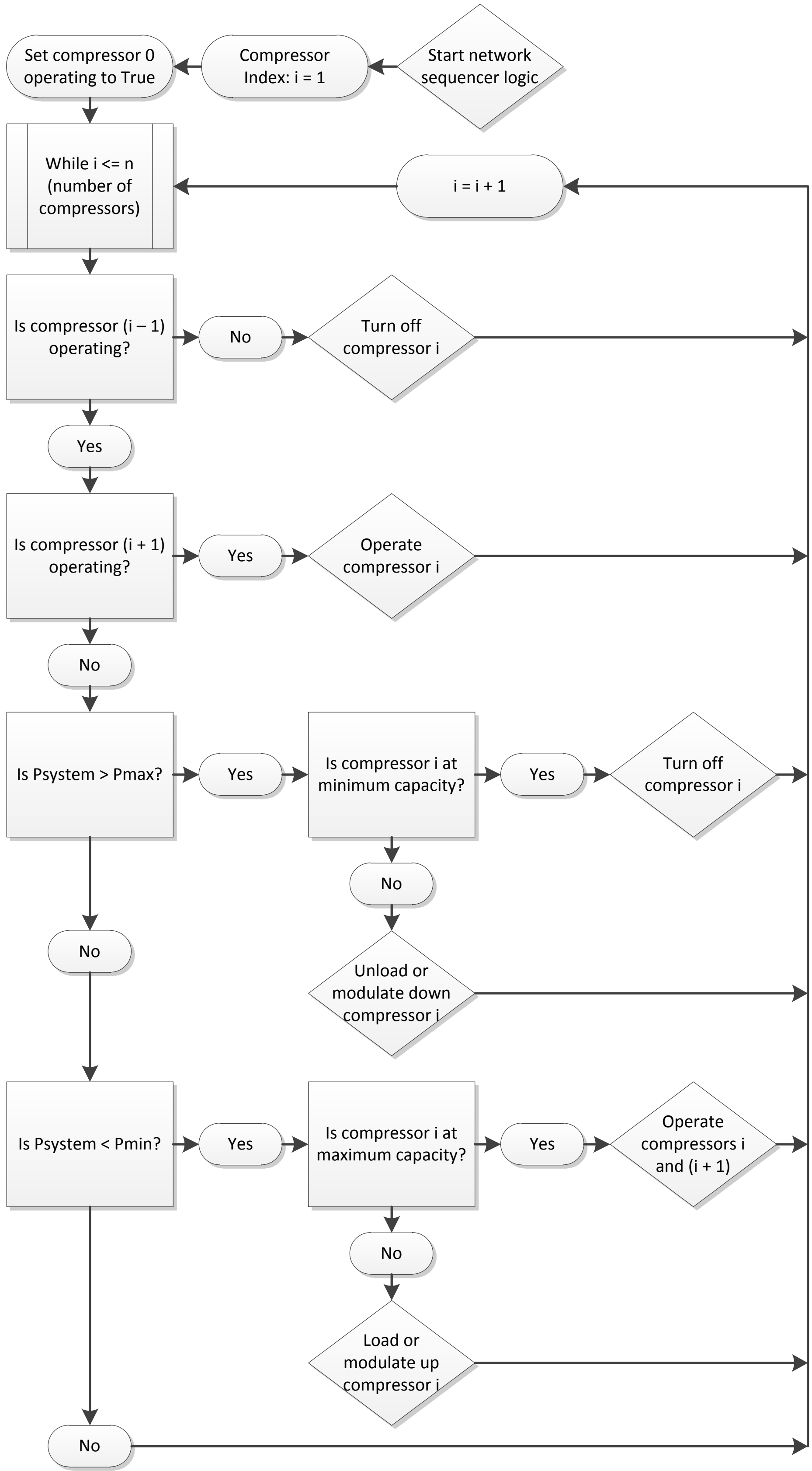

Figure 6. Network Sequencer Control Logic

This multiple-compressor control strategy is currently not explicitly available in AirSim, however, the pressure band control strategy can be used to simulate network sequencer control. Rather than a 5 psig span between cascading compressors, to simulate network sequencer control enter a 1 psig or even a 0.1 psig gap between sequenced compressors. As always, AirSim models should be carefully calibrated with each use.

Figure 6 details the control logic which could be expected for network sequencer control. In application, compressors contain timers to prevent them from short-cycling on/off too frequently. Thus, the compressors will typically idle for 5-10 minutes before automatically turning off.

While network sequencer control achieves a tighter system pressure band resulting in increased compression efficiency, it still is not an ideal control strategy. As shown in Figure 3, any of the compressors could operate partially loaded, regardless of their individual part-load efficiency. Ideally, only one compressor in a multiple-compressor system should operate at part-load, with all other compressors either fully loaded or off. Automatic sequencer control achieves this objective and is, therefore, the most efficient multiple-compressor control strategy.

<u>Automatic Sequencer (System Master) Control</u>

Automatic sequencer control (also referred to as system master control) ties compressors together at a central controller which operates the system at the highest efficiency at any plant air demand. This is the most sophisticated multiple-compressor control strategy and also the most efficient. In addition to measuring system pressure, central controllers typically monitor the rate of change of system pressure, plant air demand, and individual compressor's output and power draw. Rather than being responsive to system pressure changes, an automatic sequenced system proactively makes adjustments based on all of these incoming data. Furthermore, more holistic central controllers could measure drier performance, pressure drop across filters, and include the ability to trend historic data. These additional data provide added value for preventative maintenance programs on compressed air system components [13].

The main disadvantage of both pressure band and network sequencer control is that any of the compressors in the system could be operating at part-load depending on the plant air demand. Automatic sequencer control eliminates this problem by designating one compressor the "trim" compressor, which is the only compressor in the system to operate at part-load. Thus, the trim compressor should have a very high part-load efficiency and fast response time to changing air demand. Trim compressors are typically VSD compressors.

Similar to network sequencer control, automatic sequencer control operates compressors within a common pressure band. However, the sequencer order is not predefined, as it is in network sequencer control. The automatic sequencer determines the combination of compressors at any given plant air demand which will produce the require amount of air within the required pressure band at the highest system efficiency. Typically this results in base compressors either fully loaded or automatically shut-off, with a trim VSD compressor meeting the part-load air demand. The same sample demand profile from Figure 3 is shown in Figure 7 with automatic sequencer control.

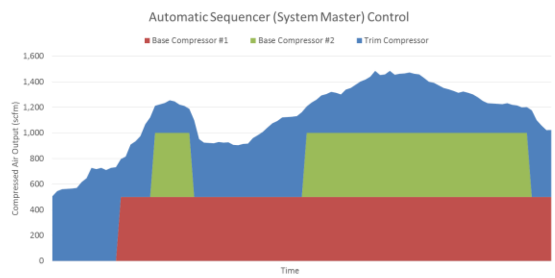

Figure 7. Automatic Sequencer Control Demand Profile

The trim compressor is vital to the successful operation of an automatically sequenced system. If the trim compressor is incorrectly sized, control gaps can occur at various plant air demands. A control gap occurs when the plant air demand cannot be met by some combination of fully-loaded base compressors and a partially-loaded trim compressor. This results in a base compressor cycling between loaded and unloaded or modulating at an inefficient part-load. To avoid control gaps, the trim compressor should be at least the same size as the base compressors [11]. Control gaps can also occur on pressure band controlled systems with VSD compressors, such as the one described in Figure 4. Similar precautions should be taken when sizing VSD compressors in these systems [14].

Additional consideration should be given if the trim compressor is a variable speed compressor controlled with a variable frequency drive (VFD), which is often the case. VFDs can typically only reduce electrical frequency down to about 15 Hz, corresponding to motor speeds of about 25%. Thus, the effective capacity range of most VSD

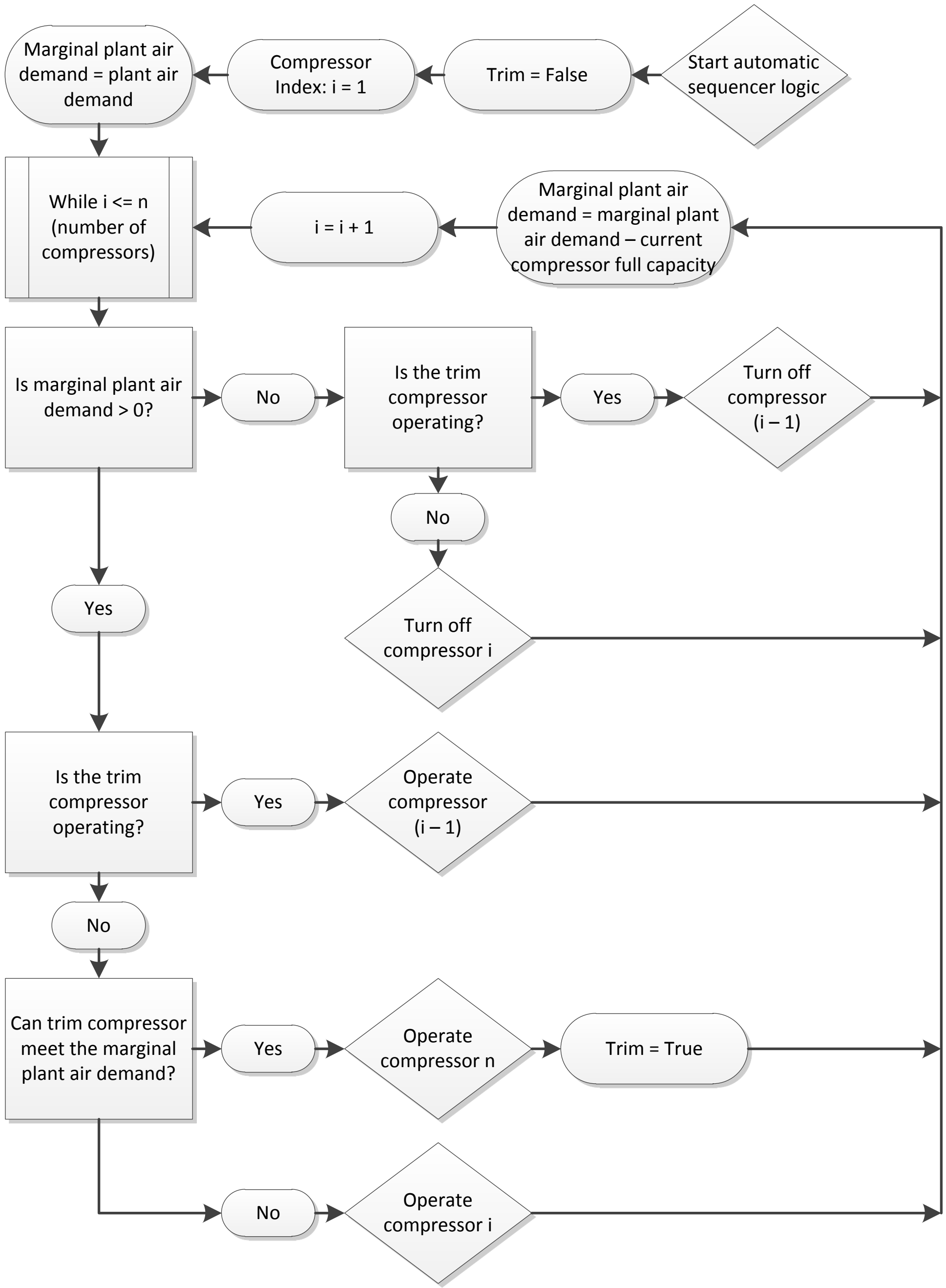

Figure 8. AirSim Automatic Sequencer Control Logic

Compressors is only about 75% of their full-load capacity. This is the motivation behind the 2013 California Building Energy Efficiency Standard requiring VFD compressors to be at least 1.25 greater than the next largest compressor [8].

Compressors controlled with VSDs operate more efficiently at part-load than full-load. Another advantage of automatic sequencers is determining the specific part-load efficiency relationships for all compressors in the system and making sequencing adjustments accordingly. The linear FP vs FC relationships shown in Figure 1 are simplifications which depend on many factors from system storage to operating pressure.

AirSim allows users to specify a trim compressor and the sequence order of the base compressors for automatically controlled systems [9]. The automatic sequencer control logic built into AirSim operates the base compressors at full-load or no-load and operates the trim compressor to meet any part-load demand.

This is the main advantage of AirSim over AirMaster+, as AirMaster+ does not have the capability to automatically sequence air compressors [17]. Users must manually choose the percent load of each compressor for each hour of operation based on the plant air demand profile. While it is feasible to simulate automatically sequenced system in this manner [4], it is a very time intensive process requiring in-depth knowledge about compressed air systems.

The AirSim automatic sequencer control strategy is controlled by the following logic. The automatic sequencer allows for only one trim compressor. If more than one trim compressor is present in a system, consider modeling the multiple trim compressors as one larger trim compressor. All other compressors are designated as base-load compressors. The highest numbered compressor (i.e. '4' in a 4-compressor system) is designated as the trim compressor, and all other compressors are designated as base-load compressors. Base-load compressors are staged in an ascending order following their defined sequence position (i.e. compressor '1' loads first before compressor '2' loads). The automatic sequencer determines which compressors operate based on the plant air demand and the capacity of the available compressors with the logic diagram shown in Figure 8.

CASE STUDY

The following case study uses AirSim to simulate a multiple-compressor compressed air system and calculate the energy use from various system controls. Additional and updated examples of energy saving opportunities modelled with AirSim are available in the University of Dayton Industrial Assessment Center (UD-IAC) Energy Efficiency Guidebook [15]. The Energy Efficiency Guidebook is available for download free of charge on the UD-IAC website: http://www.udayton.edu/engineering/industrial_assessment/.

During an UD-IAC energy assessment, the following compressed air system was investigated. Two 100-hp, air-cooled, oil-injected, rotary-screw, CSD compressors were operating in load/unload control. One 125-hp, air-cooled, oil-injected, rotary-screw, VSD compressor was operating in VSD control. The compressed air system contained 1,860 gallons of primary compressed air storage and was controlled with an automatic sequencer between 110-115 psig. The VSD compressor operated as the trim compressor, and the two CSD compressors operated as base compressors. Trend power, output, and pressure data was provided for each compressor and the system, as seen in Figures 9 and 10.

Using these power and load profiles and the air compressor datasheets from the Compressed Air & Gas Institute (CAGI), AirSim was used to model the current system [5]. AirSim was calibrated against the logged system data to accurately simulate the actual compressed air system. Figures 11 and 12 show the inputs and outputs for the base case automatically sequenced compressed air system.

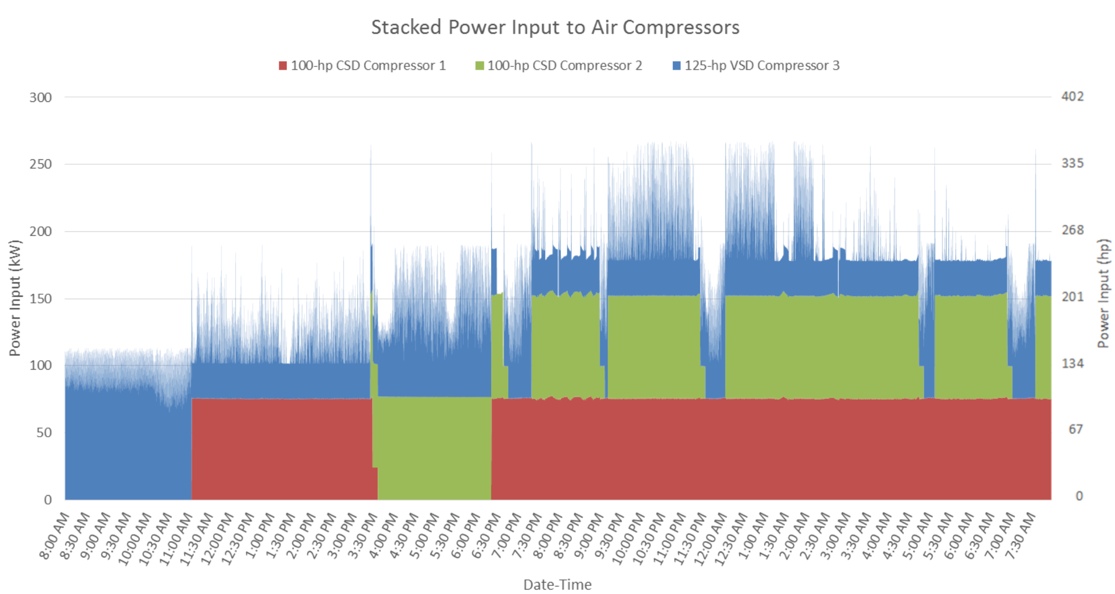

Figure 9. Stacked Individual Compressor Input Power for 24-hours

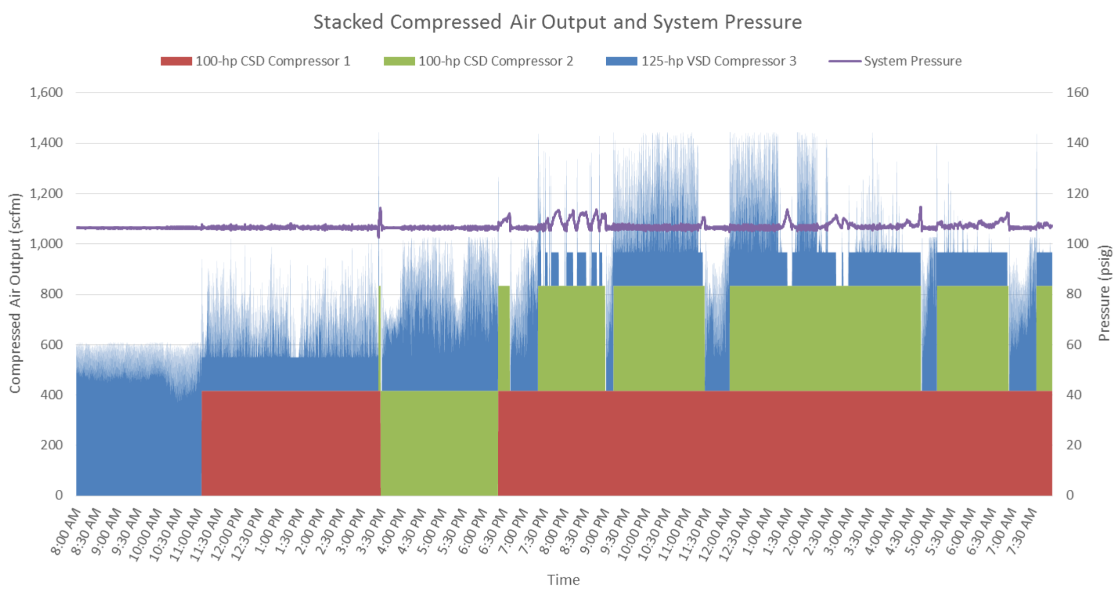

Figure 10. Stacked Individual Compressor Air Output and System Pressure for 24-hours

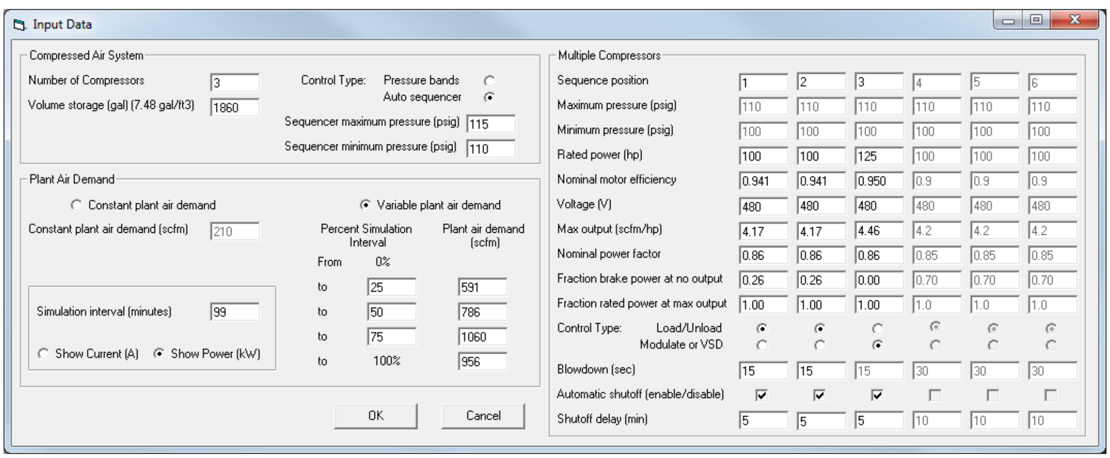

Figure 11. AirSim Inputs for Base Case Automatically Sequenced System

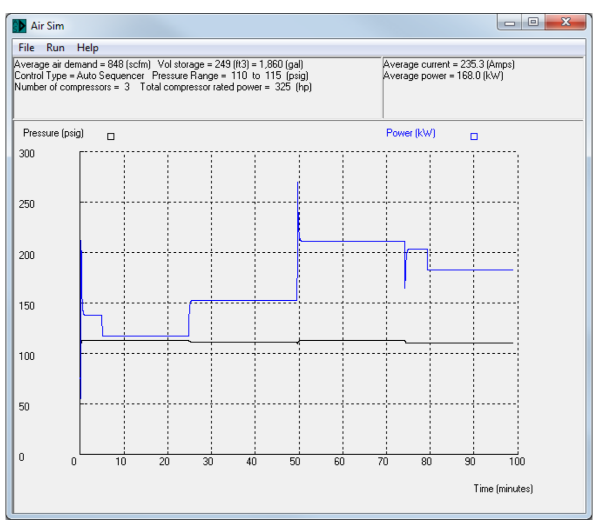

Figure 12. AirSim Outputs for Base Case Automatically Sequenced System

As described in previous papers by Schmidt and Kissock and Abels and Kissock, AirSim can be used to simulate a variety of compressed air system changes including: reduced pressure set-points, increased storage, decreased plant air demand, and various control and compressor changes [3] [2]. AirSim now has the capability to simulate multiple-compressor compressed air systems and investigate total system power from changing system control parameters.

Maintaining the same demand profile with the same compressors used to establish the base case in Figures 11 and 12 above, various pressure band and network sequencer system controls were simulated in AirSim. A summary of these control strategies and resulting system power are shown in Table 1.

The current automatically sequenced system is the most energy efficient, when compared to cascading pressure band, VSD trim pressure band, and network sequencer controls. Cascading pressure band control is the least efficient alternative, while pressure band control with the VSD compressor staged as the trim compressor is the most efficient alternative. It is important to keep in mind that AirSim allows for instantaneous compressor response with all compressors sensing the exact same system pressure. This is not true in most facilities and piping arrangements, thus the tight and overlapping pressure bands in some of the alternative cases are likely not practical without a central controller.

Further analysis was done with the same demand profile and three CSD compressors, rather than two CSD and one VSD compressor. Automatic sequencer, cascading pressure band, and network sequencer controls were simulated for this system with the inputs and output power shown in Table 2.

Without a VSD compressor, the total system power draw is significantly increased. In all three cases, the average power increased by at least 10%, in addition to increased system pressure swings without a VSD compressor. These energy savings for systems with and without a central controller and a VSD trim compressor are comparable to those calculated by the California Utilities Statewide Codes and Standards Team [4].

CONCLUSIONS AND FUTURE WORK

Multiple compressor systems without a VSD compressor or an automatic sequencer can benefit from both. Energy savings on the order of 10% could be realized for systems without VSD compressors. While energy savings between 2-7% could be realized for systems with VSD compressors but without automatic sequencer control. Compressed air systems are very complicated and detailed analysis should be conducted before upgrading system components or controls. However, AirSim allows individuals to quickly and accurately simulate current and proposed compressed air systems. By making modifications to the base case, the proposed systems can estimate the energy savings and pressure swing reductions expected from hardware and/or software controls upgrades.

Furthermore, the ability of AirSim to simulate pressure band control and automatic sequencer control allows individual system operators and policy makers to simulate energy efficient compressed air systems. As more states begin to follow California's leading role in energy efficiency, VSD trim compressors and automatic sequencers will become the norm, not the exception, in compressed air systems. AirSim allows users to quickly and accurately model automatically sequenced systems, where AirMaster+ lacks this capability.

Despite the many improvements made to AirSim, additional advancements are always

Table 1. Various Control Strategies with a VSD Compressor Simulated with AirSim

Control Strategy with VSD	100-hp CSD #1	100-hp CSD #2	125-hp VSD #3	Avg. Power hp (kW)	Percent Difference from Base Case
Automatic Sequencer - Base Case	Base #1	Base #2	Trim	225.3 (168.0)	0.0%
Pressure Band (Cascading)	115-125 psig	110-120 psig	120-130 psig	240.2 (179.1)	6.6%
Pressure Band (Cascading)	120-130 psig	115-125 psig	110-120 psig	235.2 (175.4)	4.4%
Pressure Band (VSD trim)	112-122 psig	110-120 psig	114-117 psig	230.1 (171.6)	2.1%
Pressure Band (VSD trim)	111-116 psig	110-115 psig	112-114 psig	227.4 (169.6)	1.0%
Network Sequencer	Lag #1	Lag #2	Lead	232.7 (173.5)	3.3%
Network Sequencer	Lead	Lag #1	Lag #2	230.4 (171.8)	2.3%

Table 2. Various Control Strategies without a VSD Compressor Simulated with AirSim

Control Strategy without VSD	100-hp CSD #1	100-hp CSD #2	100-hp CSD #3	Avg. Power hp (kW)	Percent Difference from Base Case
Automatic Sequencer	Base #1	Base #2	Trim	252.4 (188.2)	12.0%
Pressure Band (Cascading)	120-130 psig	115-125 psig	110-120 psig	249.6 (186.1)	10.8%
Network Sequencer	Lead	Lag #1	Lag #2	248.0 (184.9)	10.1%

available. With the capability to simulate multiple compressors, better output visualization is needed to differentiate individual compressors in a system. Output load profile plots, similar to those in Figures 3 and 7, would increase the understanding of how compressors are interacting and help identify potential system inefficiencies.

Future work should also add additional individual compressor control options, such as auto-dual control, and refine current control options. For example, the relationship between power and capacity becomes non-linear for VSD compressors operating at very low loads, and most VSD compressors can only reduce to about 25% fraction capacity. Furthermore, AirSim is currently based on linear generalizations for individual compressor control; future work should allow for custom development of the performance function based on measured data or manufacturer data. Manufacturer automatic sequencer control algorithms consider these non-linear part-load efficiencies with added complexity to multiple-compressor control logic.

Additional areas for improvement within AirSim include the ability to model the influence on compressed air storage volume on dampening system pressure swings. Also, secondary effects such as pressure drop from friction through dryers and the compressed air distribution system could be incorporated into AirSim in the future. Finally, increased demand profile resolution would increase the accuracy of AirSim, especially when simulating different multiple-compressor compressed air system.

Despite these limitations, AirSim is an effective tool to quickly and accurately simulate compressed air systems. It allows users to easily calibrate a simulation to the current system and simulate proposed changes to the system. The pressure band and automatic sequencer control logic built into AirSim can simulate multiple-compressor control strategies with VSD compressors, which are certain to become more prominent in future compressed air systems.

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