Simulating the Effects of Air Compressor Controls and Sequencing Strategies in Variable Air Demand Environments

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ABSTRACT

Compressed air is one of the most expensive and least efficient uses of energy in manufacturing facilities. It is estimated to be responsible for over 10% of industrial energy usage in the United States. Air compressors are typically less than 15% efficient, rendering optimal operation critical for energy conservation. Two of the most important factors affecting compressor performance are the type of compressor control and correct compressor sequencing.

In this paper, we run a simulation model to determine the potential energy savings from correctly sequencing a two-compressor system. The model introduces three popular control types (inlet modulation, load/unload, and variable frequency drive (VFD)) and runs nine scenarios to display the effect of compressor controls on energy performance. The model is set up to use pressure band control (cascading) for compressor sequencing. The model then introduces two additional scenarios using automatic sequencing control to display the effect of using more a sophisticated sequencing strategy on energy performance. The facility's dynamic air demand and pressure setpoints are kept the same for all 11 scenarios, and the model only changes the compressor control types and sequencing strategy, allowing it to isolate the effects on compressor control and sequencing on energy performance.

The resulting energy savings from optimized compressor controls and sequencing strategies are significant, resulting in savings between 5% and 32% depending on the selected control and sequencing strategy.

The author also discusses some barriers to implementing optimal compressor and sequencing controls in manufacturing facilities.

Introduction

Compressed air generation is energy-intensive and highly inefficient, yet it is used in most manufacturing facilities because it is safe, reliable, and easy to maintain (Saidur et al., 2010). Most manufacturers rely on compressed air for their daily production needs (Cerci et al., 1995; DOE, 2014; Rollins, 1961; Zahlan and Asfour, 2015). A combination of excellent control, availability, long lifespan, instantaneous torque, and simplicity of mechanisms all make pneumatic tools and switches an attractive choice in industry (Harris et al., 2013; Saidur et al., 2010).

Although the use of air compressors is abundant, there is a vacuum of information on energy efficiency measures that can improve compressor efficiency as well as on correct operation of compressed air systems (Holdsworth, 1997; Joseph, 2004; Risi, 1995). Air is free, however the electricity used to compress air is not, and air compressor systems are only 11%-13% efficient, making them one of the most inefficient systems in a manufacturing facility (Foss, 2005). Compressed air is responsible for over 10% of industrial energy consumption in the United States (Berkeley, 1999; Senniappan, 2004; XENERGY, 2001).

Per the Manufacturing Consumption Survey published by the Energy Information Administration (EIA), in 2010, 17% of all electrical energy to machine drives (motors, pumps, fans, etc.) was used by compressed air systems (EIA, 2010). This equates to 341 TBtu of energy used, of which 299 TBtu was lost to inefficiencies in the compressor systems (EIA, 2010). This translates to a staggering 87.7% loss in total energy use, or close to $5 billion annually (using current price per MMBtu (EIA, 2015)).

The above observation illustrates the importance of correct and efficient air compressor operations. Reducing leaks, setting correct pressure setpoints, and matching air supply with demand all contribute to an optimal air compressor system, along with correct piping design, correct compressor sizing, and location, (McKane, 2008; Zahlan and Asfour, 2015).

Correct air compressor control and sequencing is critical for improved energy efficiency. In fact, per Saidur et al. (2010), "two of the most important factors influencing the cost of compressed air are the type of compressor control and the proper compressor sizing. Oversized compressors and compressors operating in inefficient control modes have the highest unit energy and the highest annual operating costs." In this paper, we run a simulation model to determine the potential energy savings from correctly sequencing a two-compressor system. The model introduces three popular control types (inlet modulation, load/unload, and variable frequency drive (VFD)) and runs nine scenarios to display the effect of compressor controls on energy performance. The model is set up to use pressure band control (cascading) for compressor sequencing. The model then introduces two additional scenarios using automatic sequencing control to display the effect of using more a sophisticated sequencing strategy on energy performance. The facility's dynamic air demand and pressure setpoints are kept the same for all 11 scenarios, and the model only changes the compressor control types and sequencing strategy, allowing it to isolate the effects on compressor control and sequencing on energy performance.

The resulting energy savings from optimized compressor controls and sequencing strategies are significant and will be discussed in the subsequent sections. The paper also discusses some barriers to implementing optimal compressor and sequencing control strategies.

Model Structure and Assumptions

This section discusses the inputs, variables, and assumptions used to calculate the energy performance of the 11 sequencing scenarios presented. Air compressor performance and facility air demand are the two key elements considered in the simulation analysis.

Air Compressor Performance

The key characteristic affecting air compressor performance curves is the control type. Figure 1 from a study by Scales et al in 2013 illustrates the percent load versus power required for each control strategy in a standard screw air compressor system. As displayed, the partial load performance of an air compressor depends considerably on the type of control strategy used by the facility. Using VFDs to control the screw compressors at partial load results in the most efficient strategy, with compressors experiencing minimal losses. This is discussed in findings by Nadel et al. (2001) and Saidur et al. (2012), which indicate that VFDs can save over 30% in compressor applications.

As shown below, the higher the average load of the air compressor, the more efficiently it runs. This demonstrates the importance of selecting the correct controls in a multi-compressor system. The goal is to size the baseline compressor to always maintain a high load, reducing any losses from partial loading. The trim compressor should be selected for efficient part load performance. As can be seen in Figure 1, all control types perform well at loads above 90%.

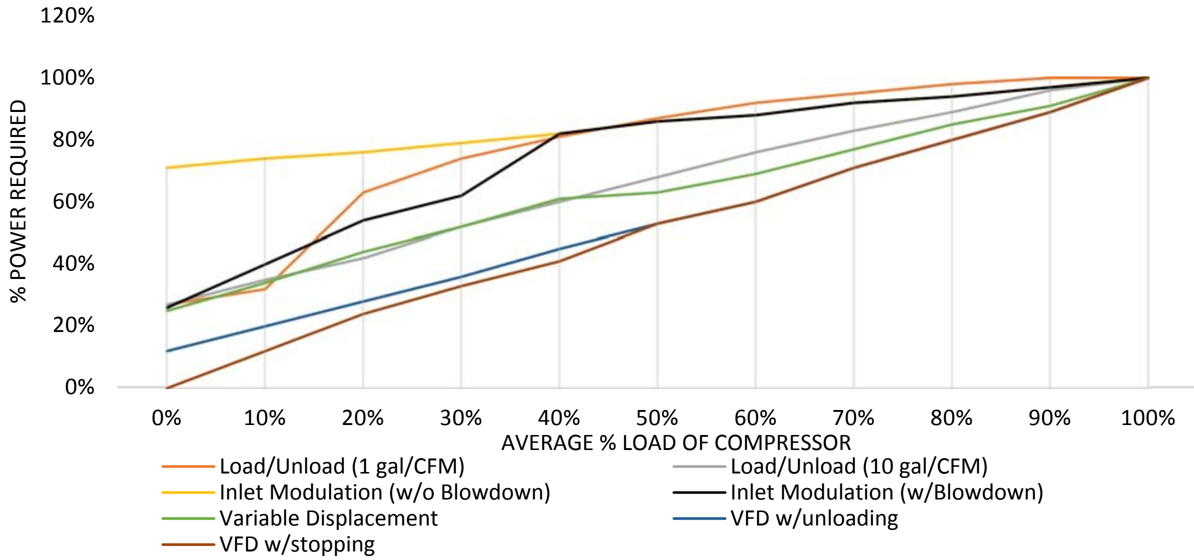

Figure 1. Effect of air compressor control strategy on screw compressor power. *Source:* Scales et al., 2013.

Using power and load data from the Scales et al. study, polynomial performance curves are derived for each control type (inlet modulation with blowdown, load/unload with 10 gal/cfm, and VFDs). These equations are used in the simulation analysis to generate the kilowatt (kW) required to meet facility demand (CFM). Figure 2 illustrates the performance curves for the three selected control types.

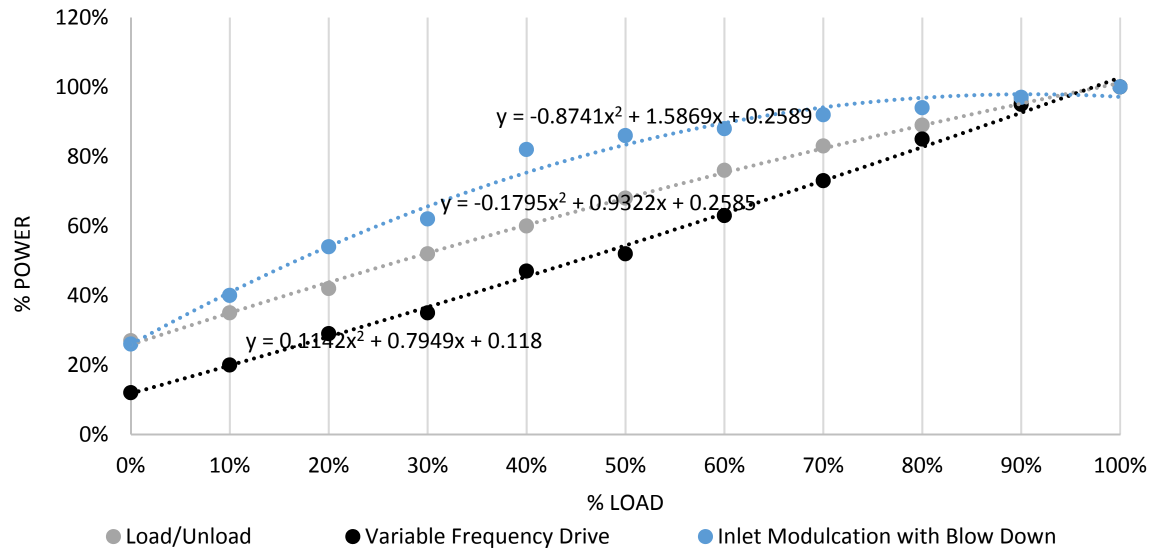

Figure 2. Screw Compressor performance curves and associated equations.

As discussed above, we use the curve equations to model the compressor performance for each control strategy. The input (x) in the curve equation is the cubic feet per minute (cfm) of air required at any given time by the facility. The output (y) is the resulting kW required to meet air demand. As displayed in Figure 2 the developed polynomial closely traces each power versus load point introduced by Scales et al. We estimate the error resulting from the use of the polynomial curves as less than 2%.

Facility Air Demand

Facility air demand is the next determinant of air compressor system performance. In a two-compressor sequencing strategy, the primary compressor or baseload compressor operates most of the time, meeting air demand as needed. During periods of high demand, a second air compressor is brought online to act as a trim compressor. The trim compressor provides any additional air required above the amount used by the baseload compressor to meet demand. Trim compressors generally operate at part load, making the controls on the trim compressor critical for improved air compressor performance.

One week of cfm demand monitored at 15 second intervals at a wood processing facility is used to test the 11 scenarios. This set of data was selected because it provides a dynamic environment with decent fluctuations in cfm, typical of a five-day-a-week production process. The maximum air demand in the facility was 869 cfm. Figure 3 illustrates the air demand used in the simulation model.

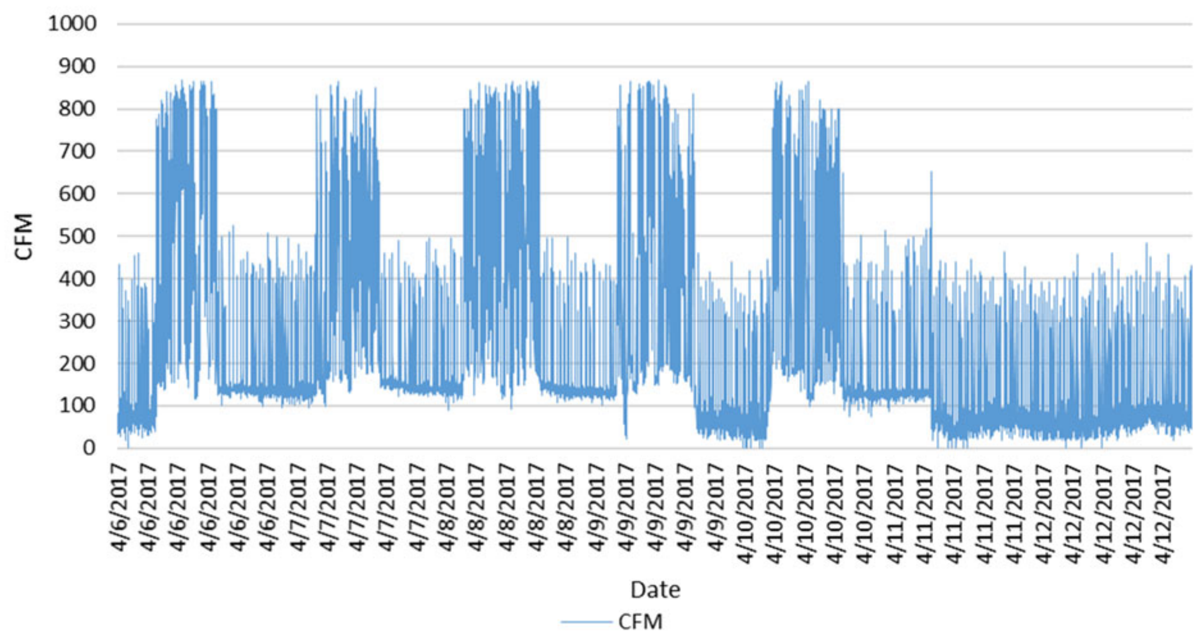

Figure 3. CFM demand profile.

As shown in the figure, cfm demand drops significantly during the weekend days and non-production hours, allowing the simulation model to test the part load efficiency of the baseload compressor. During peak production periods, cfm demand increases significantly, causing the second compressor to start and load, allowing the model to test the second compressor's part load efficiency. The subsequent sections discuss the assumptions and the 11 sequencing scenarios tested.

Assumptions

As described above, the performance of air compressors is based on the performance curves generated using data from Scales et al. (2013). The equations in Scales et al. are also cited in the Air Compressor Evaluation Protocol published by the Department of Energy's National Renewable Energy Lab (NREL) (Benton, 2014). We use these generally accepted performance curves because they are representative of a wide range of compressors. We acknowledge that air compressor performance characteristics vary depending on several factors. In cases where the compressor type and model is known, unique compressor curves published by the Compressed Air and Gas Institute (CAGI) can be used to model performance.

In this study, two 100-kW screw compressors (one for baseload (Lead) and the second for trimming (Lag)) with 500 cfm capacity each is used to model performance. This results in a total max capacity of 1000 cfm at 125psi. The efficiency of the selected compressors at full load is 20kW/cfm. Performance characteristics for these two compressors are generated using the performance curves discussed earlier. The 100-kW screw compressors were selected because they are readily available through a host of compressor manufacturers. Since the maximum air demand recorded on site was 869 cfm, the authors also felt like the two 100-kW compressors capable of producing 1000 cfm would also be a realistic solution to meeting air demand at the modeled facility.

Air pressure, air storage, blowdowns and compressor piping are assumed to be the same for all eleven scenarios. The piping layout for the monitored facility was set up in a loop with minimal dead ends. Substantial storage of approximately 10 gallons per cfm is assumed to be available for all simulation cases to run a compressor system more efficiently. This storage was representative of the actual scenario at the facility.

Last, we assume that the cfm data are representative of a typical facility. We understand that all facilities have different demand profiles; however, we selected cfm data that are realistic for many facilities that operate five days per week and one or two shifts per day. If air demand in a facility is steady throughout the week, savings from sequencing and compressor controls can be significantly less.

Simulation-Based Analysis of Compressor Performance

A simulation-based approach is used to investigate the energy performance of the 11 scenarios. The simulation considers two different sequencing strategies (cascading and automatic sequencing) and three different compressor control types (modulation with blowdown, load/unload, and VFD). The sequencing strategies, compressor scenarios, and the simulation analysis are discussed in the corresponding sections.

Sequencing Strategy

The first and most common sequencing control strategy considered is cascading, also known as pressure band control. The second sequencing strategy is automatic sequencing, which uses more sophisticated controls for improved sequencing performance.

Cascading is the simplest and most popular form of compressor sequencing. It involves loading and unloading compressors based on rising and falling pressure. This sequencing strategy has minimal cost. Simply put, compressors in a system are each programmed to run at different desirable pressure ranges. As pressure in a system drops, the next compressor starts and loads to maintain the desired plant pressure. As the system pressure rises back up, the reverse happens and the compressors go offline once desired pressure is met. Once pressure stabilizes, the last operating compressor in the system acts as the trim compressor and operates at part load to maintain the desired pressure. In a cascading sequencing strategy, the pressure bands are preprogrammed into the logic board of the compressor. This means the order of compressor sequencing cannot be changed. Therefore, when the performance of a two-compressor system in a cascading control environment is simulated, the trim compressor will always remain the second compressor inline and will not move to the baseload load even in low demand situations where it could perform more efficiently.

Automatic sequencing uses a more advanced processor and algorithm to automatically control the sequencing order of air compressors in a system. In this control strategy, the optimal number of air compressors operate at any given time, in optimal order. The algorithm selects the most efficient group of compressors required to meet demand. This sequencing strategy is very effective, especially when there are several compressors in a system with different performance characteristics.

The section below discusses the compressor controls and scenarios used in the simulation analysis.

Compressor Controls and Sequencing Scenarios

The 11 different two-compressor scenarios evaluated in this study are shown in Table 1. Nine scenarios use the cascading sequencing strategy. Two additional scenarios use the automatic sequencing strategy. The objective for modeling the nine cascading scenarios is to compare the effectiveness of different combinations of the three selected compressor control types. Two identical scenarios from the initial 9 (load/unload/VFD and modulation with blowdown/VFD) are then re-run using the automatic sequencing strategy. This allows comparison of the effectiveness of the two sequencing strategies, described in the following section.

Table 1. Eleven scenarios for simulation analysis.

Scenario #	Lead Compressor	Lag Compressor	Sequencing Control
1	VFD	VFD	Cascading
2	Load/Unload	Load/Unload	Cascading
3	Modulation w/ Blowdown	Modulation w/ Blowdown	Cascading
4	VFD	Load/Unload	Cascading
5	VFD	Modulation w/ Blowdown	Cascading
6	Load/Unload	VFD	Cascading
7	Modulation w/ Blowdown	VFD	Cascading
8	Load/Unload	Modulation w/ Blowdown	Cascading
9	Modulation w/ Blowdown	Load/Unload	Cascading
10	Load/Unload	VFD	Automatic Sequencing
11	Modulation w/ Blowdown	VFD	Automatic Sequencing

In Table 1, the lead compressor is designated as the baseload compressor and the lag compressor is designated as the trim compressor for scenarios 1 to 9. As discussed earlier, because scenarios 1 to 9 have cascading sequencing controls, the position of the lead and lag compressor does not change during the model run. In scenarios 10 and 11, the position of the lead and lag compressor changes based on the cfm demand at the facility. Automatic sequencing allows the optimal air compressor in the system to run at any given time.

Simulation Analysis and Results

We developed and implemented the simulation framework using MS Excel and VBA due to ease of use, availability, and effectiveness. The goal of the simulation analysis is to test the two-compressor system energy performance for the 11 scenarios.

The model calculates energy performance of the compressors using the compressor performance curves for each control type, the cfm demand of the facility, and the sequencing control attributes. The model registers facility air demand and simulates switching on the baseload compressor. If demand rises above the capacity of the baseload compressor, the second compressor is started and loaded. As discussed previously, compressor positions are fixed for the cascading control strategy. In the automatic sequencing scenarios, the model uses the performance curves to determine which compressor or order of compressors is most efficient to meet demand. In this case the positions of the compressors are not fixed and can change depending on facility air demand.

To make the model more realistic we model several additional considerations. To reflect the inefficiencies of wide pressure band settings in the cascading control strategy, the model starts and loads the trim compressor once the baseload reaches 90% of its capacity. The model also assumes that each compressor in the system has an automatic shutoff timer; therefore, unloaded or idle trim compressors are shut down after 10 minutes of no operation. The timer shutoff consideration allows the model to be more conservative in calculating energy savings. Note that without automatic shutoffs, unloaded compressors draw between 12% and 27% of energy, depending on control type.

Figure 4 below illustrates the energy performance of the two-compressor system in each of the nine cascading sequencing scenarios (Scenarios 1-9).

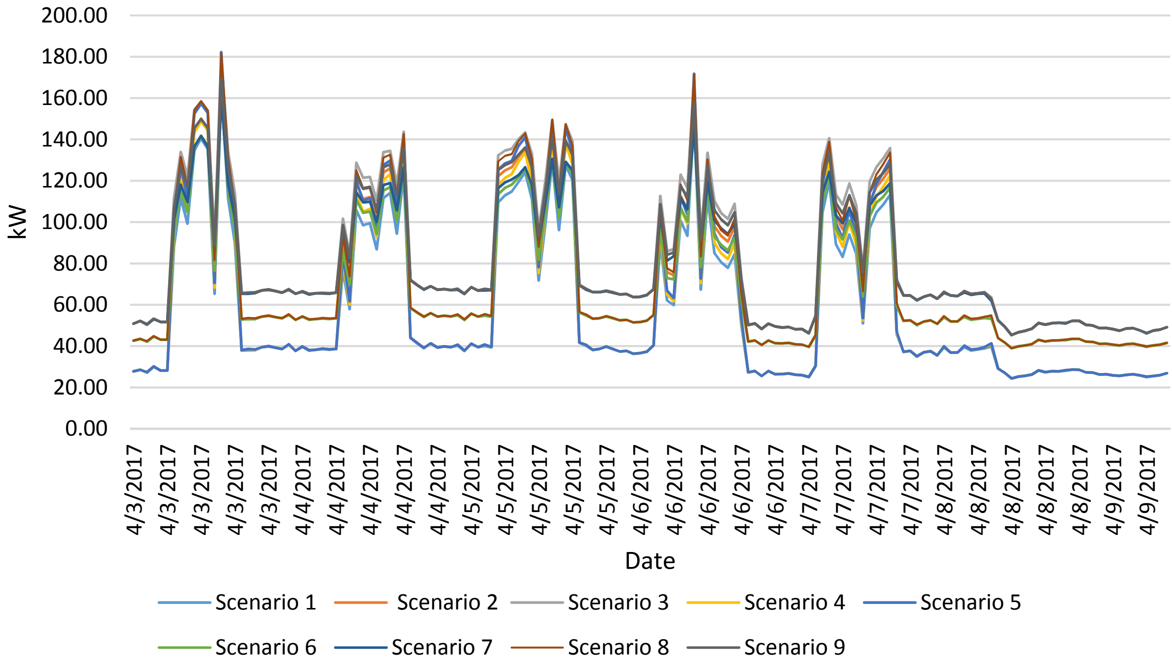

Figure 4. Compressor energy performance for each scenario using cascading sequencing controls.

As shown in Figure 4, the air compressors perform similarly at high load. The effects of compressor controls are seen during lower load periods, where the part-load performance is tested. Scenarios 1, 4, and 5, with VFD controls on the baseload compressors, are shown to be most efficient. This is because the VFD compressors can handle low cfm demand during nights and weekends more effectively. The trim compressor was calculated to only operate 15% of the week, meaning the negative energy impact from inefficient trim compressors is exceeded by the part load performance of the baseload compressors with VFDs. Results are discussed further in Table 2.

Figure 5 illustrates the performance of scenarios 6, 7, 10, and 11. Scenarios 6 and 10 have load/unload and VFD controls, while scenarios 7 and 11 have inlet modulation and VFD controls. The cascading sequencing strategy is applied to scenarios 6 and 7, and the automatic sequencing strategy is applied to scenarios 10 and 11. This figure illustrates the potential energy savings from using automatic sequencing versus cascading.

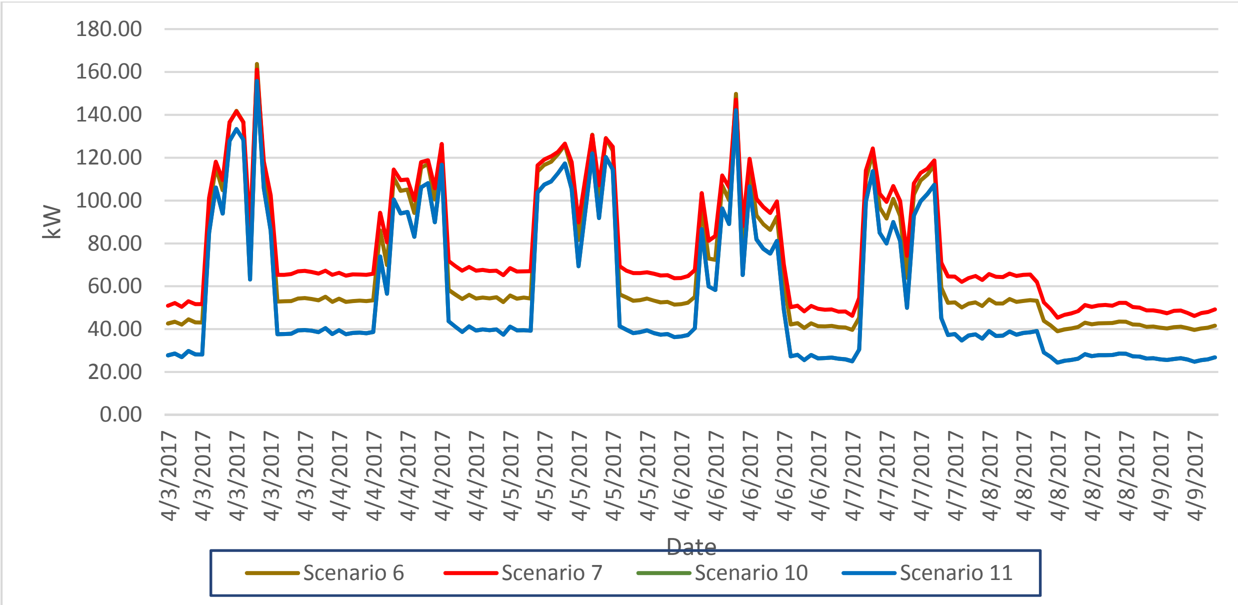

Figure 5. Compressor energy performance for cascading versus automatic sequencing controls.

Although all four scenarios start off with VFD-controlled compressors as the trim, the scenarios using automatic sequencing change the position of the VFD compressors to handle baseloads during low demand periods. This results in a much higher system efficiency during nights and weekends. Additional savings are achieved through tighter pressure control bands. When cascading compressors are used, there is no interaction between the two compressors in the system. Wide pressure bands are set to ensure that compressors start and load with sufficient time to meet demand. With automatic sequencing, pressure bands are tightened, saving additional energy. Figure 5 also suggests that scenarios 10 and 11 are operating identically hence only three plots visually illustrated. This is because the VFD compressor in both scenarios is the same. The automatic sequencing strategy allows only the load/unload compressor in scenario 10 and the modulating compressor in scenario 11 to operate at full load. Since the performance curves provided by Scales et al for-load unload and modulating are identical at full load, we see no difference in the compressor performance of both scenarios.

Table 2 displays the results of the compressor controls and sequencing strategies on the 11 scenarios. Note that the compressors modeled in each of these scenarios are the same. Efficiency improvement and power savings are the result of improved controls and sequencing strategy. The power savings (kW) and improved efficiency (%) are calculated comparing the performance of each scenario against the worst-performing scenario. For example, in a cascading sequencing environment, using two compressors with VFD controls (scenario 1) will result in a 30% improvement in energy efficiency over two compressors controlled by inlet modulation with blowdown (scenario 3).

Table 2. Results of compressor performance on eleven scenarios.

Scenario #	Average Power (kW)	Power Savings (kW)	Yearly Power Savings (kWh)*	Percent Improved Efficiency (%)	Estimated Cost Savings ($)**
1	55.44	24.23	212,297	30%	21,230
2	69.54	10.14	88,839	13%	8,884
3	79.68	-	-	0%	-
4	57.74	21.93	192,140	28%	19,214
5	59.60	20.08	175,875	25%	17,587
6	67.23	12.44	108,996	16%	10,900
7	75.52	4.16	36,422	5%	3,642
8	71.39	8.28	72,574	10%	7,257
9	77.82	1.86	16,265	2%	1,627
10	53.84	25.84	226,372	32%	22,637
11	53.84	25.84	226,372	32%	22,637

*Yearly kWh savings are calculated using 8,760 hours per year. Estimated cost savings are calculated using 0.10 cents per kWh.

There are some very interesting observations that can be gleaned from Table 2. We notice that the most efficient air compressor operation occurs in scenarios 10 and 11. Using automatic sequencing controls versus cascading controls for the same compressor control setup will result in a 16% efficiency improvement for scenario 10 versus 6, and a 27% efficiency improvement for scenario 11 versus 7. This is mainly attributed to the automatic sequencer switching the VFD to serve as the baseload compressor during low demand periods such as nights and weekends. What is more interesting is the 2% improved efficiency of both scenarios 10 and 11 over scenario 1, which consists of two VFD compressors. This improvement is attributed to the tighter pressure bands resulting from use of the automatic sequencer.

Savings in compressor performance in scenarios 10 and 11 are highest because, although the full load performance of all control types is similar (as shown in Figure 2), the automatic sequencer runs the VFD compressor in the system as the baseload compressor during low demand, improving the part load of the compressor. Once the air demand in the facility rises above 95% of the VFD compressor capacity, the sequencer switches the load/unload or inlet modulation with blowdown compressor to serve as the baseload and uses the VFD as the trim. This essentially means that the load/unload and modulating compressors only operate at full load or close to full load in the system, resulting in increased system performance and efficiency. This also explains the equal savings potential of both scenarios 10 and 11.

In an actual condition, savings will slightly differ because we do not expect the performance of all compressors to be equal at full load. The compressors' performance will be based on individual compressor performance curves provided by CAGI.

Barriers to Implementing Optimal Compressor and Sequencing Controls

There are several barriers to implementing ideal sequencing controls and more efficient compressor controls. Based on the 2013 California Building Energy Efficiency Standards, the incremental capital and labor cost of installing a VFD compressor versus a load/unload compressor is between $2,000 and $16,000, depending on the size of the air compressor (C&S,

2013). For a 100-kW compressor like the one modeled in this study, the incremental capital and labor cost for a VFD is estimated at $12,000, which typically results in less than a 2-year payback period. Even with the short payback period, this initial cost to a VFD compressor and program it still acts as a large deterrent to implementing VFD compressor use in facilities. However, many utilities such as Entergy, Dayton Power and Light, PPL, PacifiCorp, and Energy Trust offer incentives and rebates on VFD upgrades and the resulting kWh savings from installing VFD compressors, and costs typically drop significantly once discounts are factored in.

Similarly, an automatic sequencing controller is significantly more expensive than the pressure band or cascading controller. In some cases, a study of the facility demand profile and additional power and pressure sensors are required to correctly set up an automatic sequencer. Automatic sequencers can have a capital cost between $10,000 and $25,000 before facility-specific customization (Dugan, 2017).

It should be noted that automatic sequencing controllers and VFD controls save a significant amount of energy over the life of the air compressor. The initial capital investment in an air compressor only accounts for approximately 16% of the total cost of running the compressor over its effective useful life (Radgen 2006). This, along with potential for high energy savings, suggests that investing an additional 10% to 20% to install the right compressor and sequencing controls can save a significant amount of money, resulting in typical payback periods of less than two years.

Another important barrier is the lack awareness on the part of the facility. As mentioned earlier, compressed air is very inefficient and a costly system to operate. Most facilities do not have dedicated energy managers, and are unaware of potential savings resulting from improved controls and sequencing. Facilities also tend to prefer simpler controls, that can be repaired and adjusted onsite without hiring an outside contractor. This extends to maintenance personnel who might prefer the simplicity of having two identical compressors with the same control strategy, allowing them to rotate between the lead and lag units to even out wear-and-tear and reduce cost of stocking compressor parts. Raising awareness and highlighting potential savings and short payback periods will encourage facilities to improve their compressed air systems. Recourses such as CAGI and the Compressed Air Challenge are critical to raising awareness.

Lastly, changes and improvements to sub-systems such as compressed air and HVAC are not typically investigated unless a system goes down or is unable to meet facility demand. The air compressors work in the background and are generally not noticed. Attention and investments are normally focused on improving the primary production process rather than the air compressors supporting the process.

Conclusions and Future Work

This study shows that significant energy savings can be achieved through improved compressor control and improved sequencing control. Based on the tested scenarios, the most efficient control for compressors using a cascading sequencing strategy is two VFD compressors. This compressor set-up can save up to 30% over two inlet-modulation compressors. Furthermore, the same compressor control setup for automatic sequencing vs. cascading results in a 16% efficiency improvement for scenario 10 versus 6, and a 27% efficiency improvement for scenario 11 versus 7. Also interesting is the 2% improved efficiency of both scenarios 10 and 11 over scenario 1, which is a compressor setup in the cascading sequencing strategy with two VFD controls. These results show that with an automatic sequencing strategy, only one compressor in the system needs to be a VFD. This will result in initial cost savings.

This paper also identifies cost as the largest barrier to implementing better compressor and sequencing controls. Still, in considering the initial cost of the compressor versus the lifetime cost of energy use and maintenance, upgrading to better controls is beneficial, with typical payback periods of less than two years. The cost factor also highlights the importance of air compressor education. Facility personnel can benefit from understanding the lifetime cost of running air compressors and the energy-intensive process of producing compressed air. Air is free, but compressed air is not, and understanding the potential energy savings from upgraded controls will guide facilities in their decision-making.

There are several areas for improvement and expansion of this study. Future work could include increasing the number of compressors to three or four, allowing for a better understanding of larger systems. Also, running the simulation for several hundred iterations of varying air demand could give more accurate and representative savings results. Finally, performing actual case studies using currently installed compressor systems would help benchmark and support results from the simulation.

Despite the need for these additional areas of investigation, the current model clearly shows that significant energy savings can be achieved through better air compressor and sequencing controls.

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