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Compressed Air Efficiency: A Case Study Combining Variable Speed Control with Electronic Inlet Valve Modulation

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ABSTRACT

This paper discusses an energy efficient compressed air system at an industrial automation components manufacturing facility. The authors performed and energy assessment as part of the DOE's Industrial Assessment Center program and followed up with additional investigations on the compressed air system.

The compressed air system utilizes an outlet pressure transducer to a microcontroller to adjust system capacity by changing motor speed and modulating an electric proportional inlet valve. This control system allows reduced modulation of operating pressure and a lower operating set point, when compared to either system alone, and avoids thermal overloads when the VFD attempts to operate at low frequencies. The control system will be examined and discussed with respect to operation, energy savings, installation costs, and payback.

INTRODUCTION

Energy consumption represents approximately 80% of the total life cycle cost for compressed air [1]. That means the choice of a control scheme must be made wisely. This is primarily due to significant differences in performance broadly with regard to compressor types or manufacturers. In an ideal case, the compressor's full capacity could be precisely matched to its air consumption, for example, by carefully choosing the gearbox's transmission ratio [2].

The ultimate goal of having such a good control scheme is to switch off unneeded compressors or delay transporting on additional compressed air until needed. In addition, good control schemes must maintain lower average pressure without going below minimum system requirements and are designed to match the compressor output with the system demand.

Methods for modeling the relationships between the power consumption in compressor and air output have been studied to develop criteria that estimate the energy savings by combining two control schemes; inlet modulation and variable frequency drive (VFD), in order to adjust air system capacity, as a result, input power. This control system allows minimized modulation of operating pressure while maintaining the critical minimum operating set point.

In order to be conservative and not limit facility productivity, compressed air systems are often designed with excess capacity. Therefore, since demand is unlikely to match compressor output, a capacity control system is essential to mitigate operating costs.

This facility manufactures electric, pneumatic and hydraulic industrial automation actuators, designed to help companies across all industries optimize their manufacturing processes. The plant is 83,000 square feet with four walled off separate areas; office, shipping and receiving, compressor room, and manufacturing floor. The facility has two 60-hp rotary screw compressors with a capacity of 244 cfm at 125 psi. The standard features include a Microprocessor based control system, premium instrument panel, air-to-air 2-stage after cooler, sealed direct drive gear train, total positive lubrication system with spin-on filter; self-supporting steel skid base. Each compressor has a VFD and a butterfly valve for inlet modulation. However, only one compressor is running continuously while the other serves as a back-up unit. The compressors have pressure transducers on the outlet line sensing demand from the plant. The butterfly valve is controlled by an air cylinder that is actuated by a differential pressure valve. Before the addition of the butterfly valves and the VFDs, the pressure set point of the compressor was 105 psi. Initially, the VFD was installed and intended to operate alone. Instead, it had lowered the motor operating point down to such a point that the motor would trip on thermal overload. In addition, the compressor was loading and unloading frequently because of periods of very low demand from the plant. Hence, the maintenance installed a butterfly valve on the inlet to control the amount of air the compressor could draw. The butterfly valve is controlled by a differential pressure valve that uses a tapped line from the outlet of the compressor to actuate an air cylinder controlling the percent opening of the butterfly valve. The inlet modulation control scheme does not allow for more than 70% capacity because the compressor is oversized. This was done on purpose because at the time of purchase 50 hp compressors were belt driven and a direct drive unit was desired, therefore, 60 hp units were purchased. After running the air compressor on the new control system, the pressure set point on the compressor is in the range of 96 to 98 psi.

THEORITICAL BACKGROUND

Inlet Modulation (throttling) Control

In inlet modulation control scheme, the inlet air valve position is controlled from fully open to fully close in response to compressor output pressure [3]. The inlet valve modulates continuously and responds immediately to any change in the sensed system pressure. Consequently, flow capacity is controlled by restricting air intake. This control holds a constant system pressure with minimal valve movement at any given steady system demand; maintaining the system pressure within a smaller pressure range than load/unload control, reducing fluctuations in system pressure. [4]. Inlet modulation mode is not preferable if extended low load periods are expected; at loads below 60%, and a relatively inefficient output air control [4]. Therefore, backpressure must be overcome in order to reach full capacity because the instant response may make the compressor back down and unload, even when flow is needed for the base load. Sensitivity and rapid reaction make correct piping and backpressure control necessary for optimum operation [4].

Variable Frequency Drive (VFD) Control

Variable frequency drives (VFDs) convert the entering AC power to DC and then back to a quasi-sinusoidal AC power using an inverter switching circuit. The benefit of VFDs is to take advantages of reducing power cost, reducing power surges (from starting AC motors), and delivering more constant pressure, as well as, the ability to start and stop as often as desired. That provides “soft-start” and incurs the lowest required inrush current [4].

Note that a compressor that runs at full load will require more energy if a variable speed drive is used [3]. Usually, when there are multiple air compressors at a facility, one or more fixed speed compressors should supply the base load and a VSD compressor should be used to supply the fluctuating or trim load [3].

In this particular case; where it is a rotary compressor, the capacity is directly proportional to the rotational speed of the input shaft. Though, with constant output pressure, if efficiency remained constant over the speed range, the input torque requirement would remain constant as well. The actual efficiency also may fall at a lower speed which requires an increase in input torque. Electric motors and controllers currently are available to satisfy these needs, but their efficiency and power factor at reduced speeds must be taken into consideration [5].

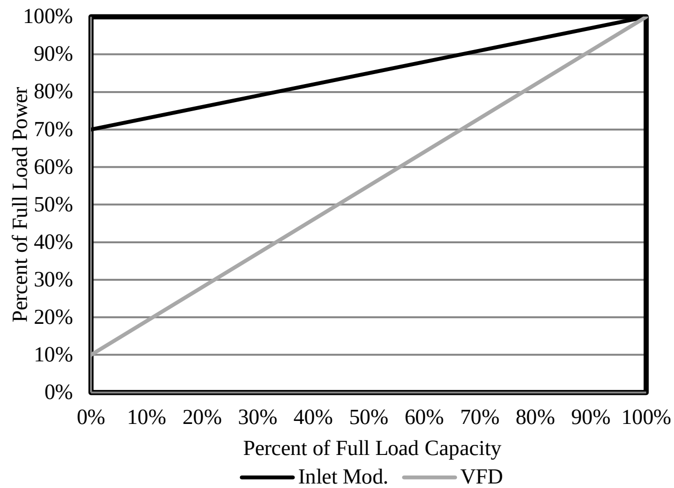

Figure 1. Illustration of power percentage vs. capacity percentage for inlet modulation and VFD control schemes.

Based on Figure 1, inlet modulation control has an inefficient power draw at low capacities; less than 70%, while VFD controls works more efficiently at low loads; 10% down to 70% of full capacity.

Inlet Modulation and VFD Control

Theoretically, VFD control scheme seems to be more efficient to operate than inlet modulation scheme in terms of power draw. However, two penalties will be faced in the VFD control scheme at the facility discussed in this paper. First, at full load capacity the power draw would be higher than inlet modulation scheme due to the potential needed power to run the VFD. Second, at low capacities, running the motor at less than 50% of the full speed would cause the motor to trip on thermal overload which is not desirable. Therefore inlet modulation control was introduced to resolve these issues, and also to maintain tight pressure control and reduce pressure fluctuations throughout the system to protect specific testing application equipment. The outcome of combining inlet modulation and VFD control at the facility is a steady discharge pressure at a minimum set point with a small fluctuation from 96 psi to 98 psi. If pressure dropped below that range, testing equipment must be recalibrated.

Modeling Inlet Modulation and VFD Control Scheme Relationships

To quantify the fraction of full load compressed air output (Capacity Percentage) as a function of fraction of full-load brake power (Power Percentage) for each control scheme separately, Chris and Kelly [4] derived a relationship for different control modes. Equation (1) is corresponded to the inlet modulation control and Equation (2) is corresponding to VFD control:

Inlet Modulation control:

$$Capacity\ \%_{mod} = \frac{Power\ \% - 70\%}{30\%} \qquad (1)$$

Variable Frequency Drive control:

$$Capacity\ \%_{VFD} = \frac{Power\ \% - 10\%}{90\%} \qquad (2)$$

The fractional power is the ratio between the actual and maximum power output from the compressor motor. The actual power output from the motor, P, is the product of the input power, P_{in}, and the motor efficiency, η, as follows:

$$P = P_{in} \times \eta \qquad (3)$$

For this control system, at full load to 70% of the capacity, the compressor is regulated by the inlet modulation scheme to avoid the losses if VFD was used. Therefore, Equation 1 is valid for the capacity range 70% - 100%. Practically, the system is running in the capacity range of 50% - 70%. In this range, the compressor is regulated by the VFD to take advantage of reducing the power required if inlet modulation was used. Below 50% load capacity, the system is again regulated by inlet modulation control to avoid the penalty of heat overload. This new control scheme is summarized in Figure 2.

The total power of this particular case would be as follow:

$$Power\% = \begin{cases} (30\% \times Capacity\%) + 70\% & if \quad Capacity \geq 70\% \\ (90\% \times Capacity\%) + 10\%, & if \quad 50\% \leq Capacity \leq 70\% \\ (30\% \times Capacity\%) + 70\% & if \quad Capacity < 50\% \end{cases}$$

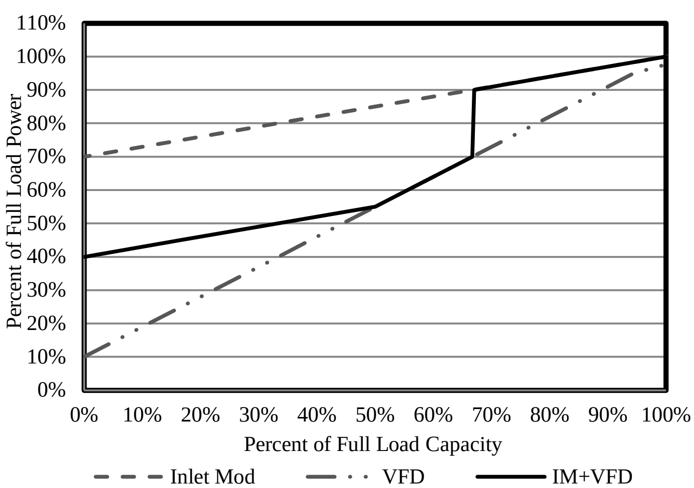

Figure 2. Illustration of Full Load Power vs. Percent of Full Load Capacity.

METHODOLOGY

The data was collected from 9:40 AM, August 9, 2012 to 2:00 PM, August 10, 2012. Critical pressure readings were taken at inlet and several discharge locations using 0 – 500 psig Ashcroft calibrated pressure transducer. The first pressure transducer was placed as close as possible to the air compressors. The second was placed after their largest compressed air consumer, the Mazak Vertical Center Nexus 510C equipped with 28 cfm air blast. The second transducer was then moved from the first location to a second location on the second day, which was after their second largest compressed air consumer, the Mazak PFH 4800 equipped with 19.6 cfm air blast. This location in the plant was also the furthest away from the compressor. Input and output current and input voltage to the VFD measurements were taken using a Fluke 1735 Power Logger and 0 – 100 amp Onset Current Transducer CTV-C connected to a 4 channel Hobo Data Logger. Data was then analyzed using Microsoft Excel.

System Hardware

There are two 60 hp Ingersoll Rand oil-lubricated rotary screw compressors, which are operated in primary/backup mode. Two VFDs; Altivar 71 from Schneider Electric, are used on each compressor. The inlet modulation is controlled on each compressor by an electronic proportional pressure controller. The proportional pressure controller (PPC), model number LCP035A-AAA-GAGA-B, is from MAC Valves. The PPC controls the butterfly valve at air inlet. The system has two 500 gallon storage tanks, one wet and one dry. The piping of the system utilizes Transair, smooth walled aluminum pipe.

Operation

This case study describes the compressed air system at a leading manufacturer of electric, pneumatic and hydraulic industrial automation actuators, designed to help companies across all industries optimize their manufacturing processes. Their products consist of a full line of cylinders, escapements, grippers, linear slides, rotary actuators, clamps, multi-motion actuators, switches and sensors. They also make unique solutions that require a high degree of precision, such as medical equipment.

During operation, pressure was supplied to many points in the plant. Below is a sample of a 50 minute window of data, shown in Figure 3. The black plot is the pressure nearest to the compressor while the gray plot is the pressure next to the largest compressed air consumer; Mazak 510C CNC. This graph illustrates that there was very little pressure drop in the system, which is due to very few and small air leaks as well as low friction piping. This is significant because it allows the company to operate at a minimum pressure in the facility. The company uses high precision compressed air regulators that need a 5 psi minimum pressure drop to operate at 87 psi. They need this high precision because they have test stands that work on medical equipment that require precise pressure to maintain calibration. Due to the small pressure drop the compressor can operate at 96 – 98 psi without concern for the critical minimum pressure required by the test regulators.

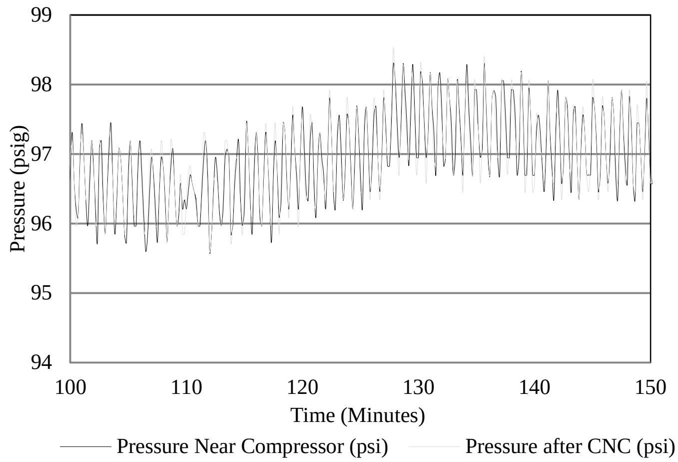

Figure 3. Illustration of pressure drop with 50 minutes of data logging for two points in the facility; near-compressor and after CNC.

Figure 4 below illustrates the operation of the compressor comparing full load power vs. full load capacity. As previously discussed, the compressor was oversized when purchased; the capacity was initially adjusted by the hard limits on the inlet valve to a maximum of 70%. From there the VFD operates between 60 Hz and 30 Hz. This means the VFD controls from 42 hp to 30 hp. The VFD adjusted the power draw of the motor depending on the demand signal it gets from a pressure transducer in the compressor.

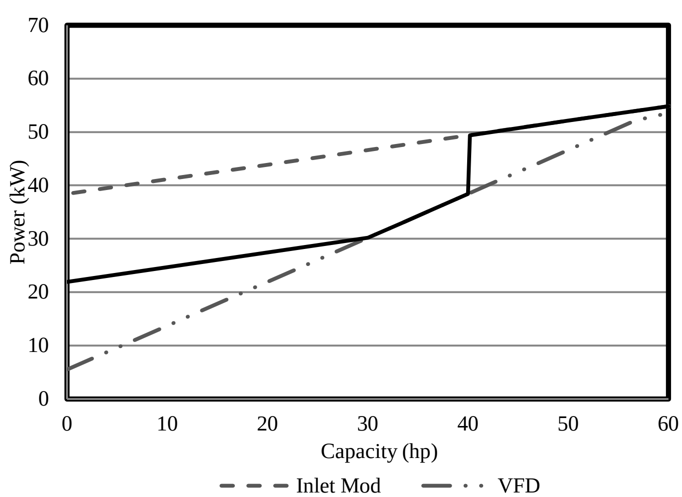

Figure 4. Illustration of Full Load Power vs. Percent of Full Load Capacity.

In this case study current draw was logged for a period of 28 hours on the 60 hp compressor using inlet modulation and VFD control. Figure 5 illustrates the lowest current draw from that time when the plant went on break. The power draw characteristics are indicative of inlet modulation and VFD control, at the lowest it is modulated down to 42% of full load power and at the highest the VFD controls it to 67% of full load power.

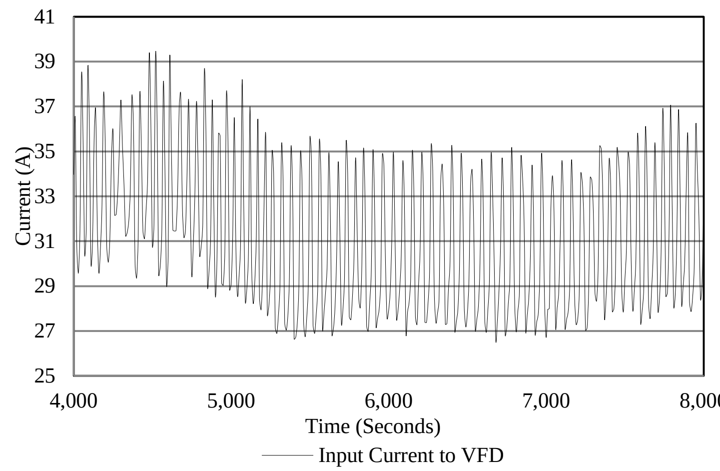

Figure 5. Illustration of current draw of one of the 60 hp compressors.

ECONOMICS

The company reported spending approximately $15,000 on the modifications, VFD and inlet modulation. The company also reported a simple payback period for the project of approximately 1.5 years. Before the addition of the VFD and inlet modulation the pressure was set to 105 psi. The system, with the new control scheme, now requires 96 psi. The reason for the 105 psi setting was due to the pressure fluctuation from 105 to 96 psi. After the VFD and inlet modulation were added, the system can now be set to 98 psi with an approximate 2 psi drop. The associated savings due to operating at a reduced pressure are as follows.

On average during the two day case study the average power draw was 29 hp (21.67 kW), which is 48.4% of full load power. Using Figure 2 this correlates to 33% of full load capacity. Before the installation of the VFD the inlet modulation would have used 80% of full load power to get 33% of the full load capacity. Knowing this the average power draw would be 48 hp (35.808 kW). Thus we can calculate the demand and energy savings as follows:

$$Demand\ Savings = Demand_{Inlet} - Demand_{Inlet\ and\ VFD} \quad (4)$$
$$= 35.81\ kW - 21.67\ kW$$
$$= 14.14\ kW$$

The compressor is operation all the time, so Utilization Factor would be 100%.

$Annual\ Demand\ Cost\ Savings =$

$$Demand\ Savings \times \frac{\$}{kW} \times 12\ months \quad (5)$$

$$= 14.14\ kW \times \frac{\$8.50}{kW} \times 12\ months$$
$$= \$1{,}442$$

$Annual\ Energy\ Cost\ Savings =$

$$Demand\ Savings \times Operating\ Hours \times \frac{\$}{kWh} \quad (6)$$
$$= 14.14\ kW \times 4{,}000\ hours \times \frac{\$0.0729}{kWh}$$
$$= \$4{,}122$$

Another benefit from using Inlet and VFD control is having tight control over the operating pressure, so the plant can reduce from105 to 98 psi max pressure. The cost penalty for operating at a high system pressure is found using fractional savings. The fractional savings for operating at a reduced upper activation pressure, P_{l2}, compared to a high upper activation pressure, P_{h2}, when the inlet air pressure is P_1 is about:

$\boldsymbol{Fraction\ Savings} =$

$$\frac{\left(\frac{P_{h2}}{P_1}\right)^{0.286} - \left(\frac{P_{l2}}{P_1}\right)^{0.286}}{\left(\frac{P_{h2}}{P_1}\right)^{0.286} - 1} \times 100\% \quad (7)$$

$$= \frac{\left(\frac{105}{14.7}\right)^{0.286} - \left(\frac{98}{14.7}\right)^{0.286}}{\left(\frac{105}{14.7}\right)^{0.286} - 1} \times 100\%$$

$$= 4.54\ \%$$

$$Demand\ Savings = 21.67 - (21.67\ kW \times (1 - 0.0454))$$

$$= 0.983\ kW$$

$Annual\ Energy\ Savings =$

$$0.938\ kW \times 4{,}000 \frac{hours}{year} \times 100\%$$
$$= 3{,}935 \frac{kWh}{year}$$

$Annual\ Energy\ Cost\ Savings =$

$$Annual\ Energy\ Savings \times \frac{\$}{kWh} \quad (8)$$

$$= 3{,}935 \frac{kWh}{year} \times \frac{\$0.0729}{kWh}$$
$$= \$286$$

$Total\ Savings =$

$$\$4{,}122 + \$1{,}442 + \$286$$
$$= \$5{,}850$$

These calculations can only validate \$5,850 of the reported \$10,000 savings that the company experienced by adding a VFD to the Inlet Modulation control and from reducing the minimum required pressure.

Figure 6 indicates the two areas of savings. Area 1 represents the savings from adding the VFD. Area 2 represents additional savings from inlet modulation when the VFD can no longer reduce capacity.

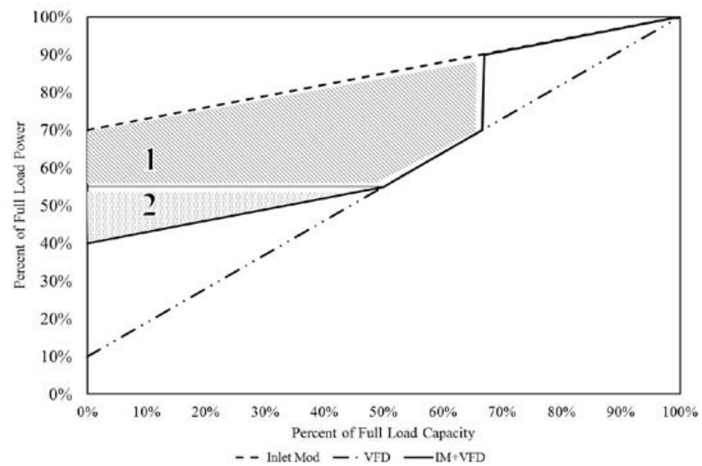

Figure 6. Areas of Savings from Inlet Modulation and VFD System

FUTURE IMPROVEMENTS

Future improvements for this compressed air system that can be recommended are few since the company is already doing many best practices. The company has already implemented low friction piping, reduced required pressure to near minimum, uses waste heat to heat the plant, pulls outside air when it is more efficient, and has adequate air storage. The company currently has a control system that is efficient, but can be improved. The company could utilize the VFD more by upgrading their compressor motor to one that is made for VFD operation, which would allow the motor to avoid thermal overload. This control system would allow the VFD to continue operating below 55% of full load capacity saving more energy, while maintaining the control that inlet modulation allows.

SUMMARY

The plant developed a novel compressed air control scheme, which combines both Inlet Modulation and VFD control; given the constraints that 1) tight pressure control is required and 2) the existing compressor motor is not matched for VFD operation. The new control system saves considerable amount of energy and money, but can be improved by adding an appropriate compressor motor.

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