SPEED CONTROL IN INDUSTRIAL REFRIGERATION: THEORY, APPLICATION & CASE STUDIES

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ABSTRACT
It is often standard practice in the field of industrial refrigeration to design and operate systems with little regard toward part-load performance. This approach is understandable, whether viewed from the standpoint of the design engineer, plant manager or chief operator. As long a space temperature and production rates are maintained during peak periods, the refrigeration system is viewed as operating "correctly".

The truth is, most refrigeration systems spend some, if not most operating hours at reduced capacity. Screw compressors back off slide valves, evaporator coils utilize back-pressure regulators (BPRs) or liquid solenoids, and condensers cycle fans. Unfortunately, these control methods do not provide the maximum attainable reduction in brake horsepower (BHP) as refrigeration capacity is reduced.

This paper will discuss the application of variable speed drive (VSD, also called "variable frequency drive", "adjustable speed drive", "inverter", or simply "freq. drive") technology to capacity control of screw compressors, evaporator fans, and condenser fans. As shown through theory and case study, speed control of these components provides maximum flexibility, control and energy efficiency.

SPEED CONTROL BACKGROUND
In standard system design, electric motors are intended to operate at a fixed speed. This speed is determined by the frequency of power supplied by the utility and motor design (number of poles). The shaft load on the motor is determined by the product of shaft speed and torque. With a fixed speed, motor power is determined by the torque of the load. With a change in speed, motor load will not only benefit from the speed reduction, but also any reduction in torque with speed. Two types of motor loads exist; constant torque and variable torque.

Positive displacement compressors (e.g., screw, reciprocating, rotary vane) are constant torque devices. That is, the twisting force required to turn the shaft is constant, regardless of speed. Therefore, the shaft power is determined by operating conditions (pressures) and method of capacity control, which both affect torque. In general, a reduction in speed (e.g., to 50%) would provide a proportional reduction in shaft power (e.g., also 50%).

Fans are variable torque devices. That is, the twisting force required to turn the shaft is not constant, but rather a squared function of shaft speed. This means that shaft power, which is the product of speed and torque, will vary as the cube of speed. This is quite important, since a reduction in speed (e.g., to 50%) will provide a dramatic cubic reduction in power (e.g., $50\%^3$, or 12.5%)

Unless some means of speed control is made available, speed will be held constant for compressors and fans. Fortunately, the advent of VSDs enables most existing motors to vary speed while supplying full-load torque at all speeds. A VSD receives standard 60 Hz, 3-phase power, and outputs a user selectable frequency (typically 0 to 72 Hz). With this additional equipment, speed control can be implemented in refrigeration systems.

GENERAL VSD APPLICATIONS
Why utilize speed for capacity control when a variety of alternative control strategies exist? The general answer is improved control and efficiency, whether for compressors or fans.

There are several incentives for speed control on screw compressors:

- Speed control will reduce the power penalty associated with slide valve capacity control. On compressors with no capacity control, speed control will eliminate other poor control strategies.
- Speed control will reduce wear and tear associated with slide valve action.
- Speed control allows a precise suction pressure to be maintained.

For evaporator fans, several incentives exist for speed control:

- Speed control provides dramatic fan power reductions at reduced speed. This also translates into reduced motor heat loads in refrigerated spaces.
- Speed control provides outstanding space temperature control.

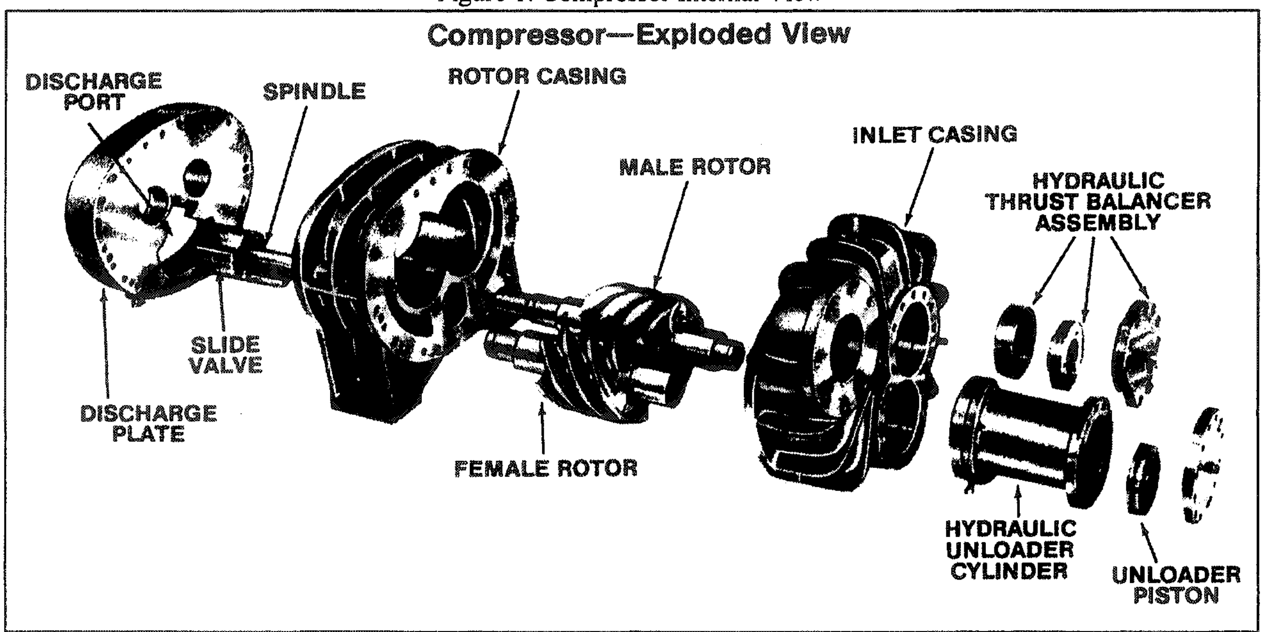
Similar to evaporator fans, several incentives favor speed control on condenser fans:

- Speed control provides dramatic fan power savings relative to fan cycling.
- All condenser fans can be ramped together in speed, rather than staged by familiar Penn or Mercoid switches over a range of condensing pressures. Not only does this allow maximum use of coil surface area relative to fan power, but ensures that all condenser fans can operate to minimize condensing pressure when possible.
- A wet-bulb approach feature can be used to match delivered condenser capacity to actual heat rejection requirements, regardless of ambient conditions. This prevents possible "over-condensing" while maintaining the lowest possible condensing pressure.

SCREW COMPRESSOR OPERATION

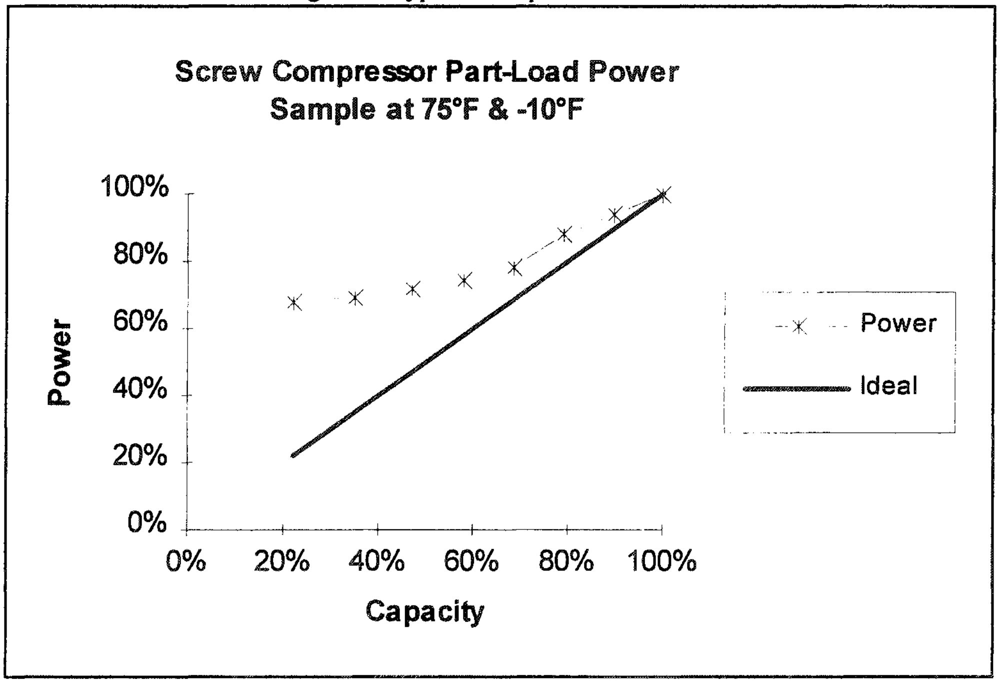
Nearly all rotary screw compressors utilize a slide valve for unloading. The slide valve moves along the length of the rotors, reducing the compression length within the rotors. An internal view of a screw compressor is shown in Figure 1.

Figure 1: Compressor Internal View



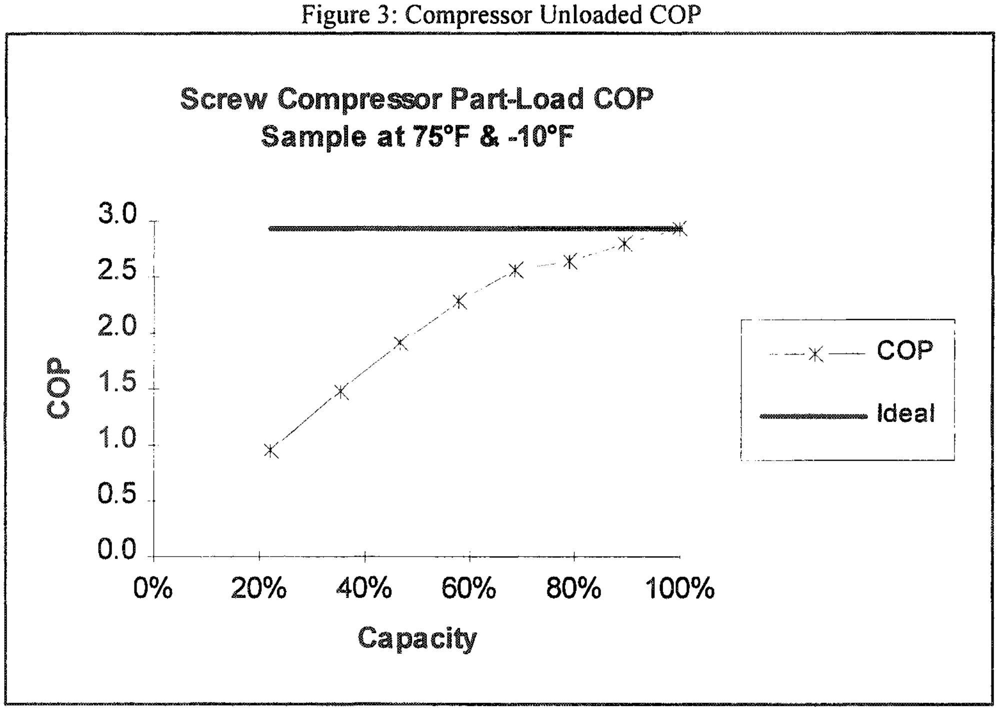
Although this method of control is infinitely adjustable and provides reasonable suction pressure control, there can be a substantial power penalty associated with slide valve control. As the compressor unloads, there is not a proportional reduction in power. A typical screw compressor part-load curve is shown in Figure 2.

Figure 2: Typical Compressor Part-Load



This capacity reduction system results in a lower Coefficient of Performance (COP=Output/Input) and higher BHP/TR at reduced load, and hence the operator is paying more for each unit of refrigeration. The associated unloaded COP is shown in Figure 3

Figure 3: Compressor Unloaded COP



In general, part-load performance degrades with deeper suction or higher discharge pressure. Also, economized compressors typically lose economizer operation at approximately 75% slide position. Below this position, the compressor operates non-economized, adding to the performance penalty.

Most screw compressors can operate down to 50% speed, as rated by the factory. Below 50% speed, the slide valve must be used for further capacity reduction. The improved part-load power curve is shown in Figure 4, and the improved COP curve for the same screw compressor is shown in Figure 5.

Figure 4: Improved Capacity Curve

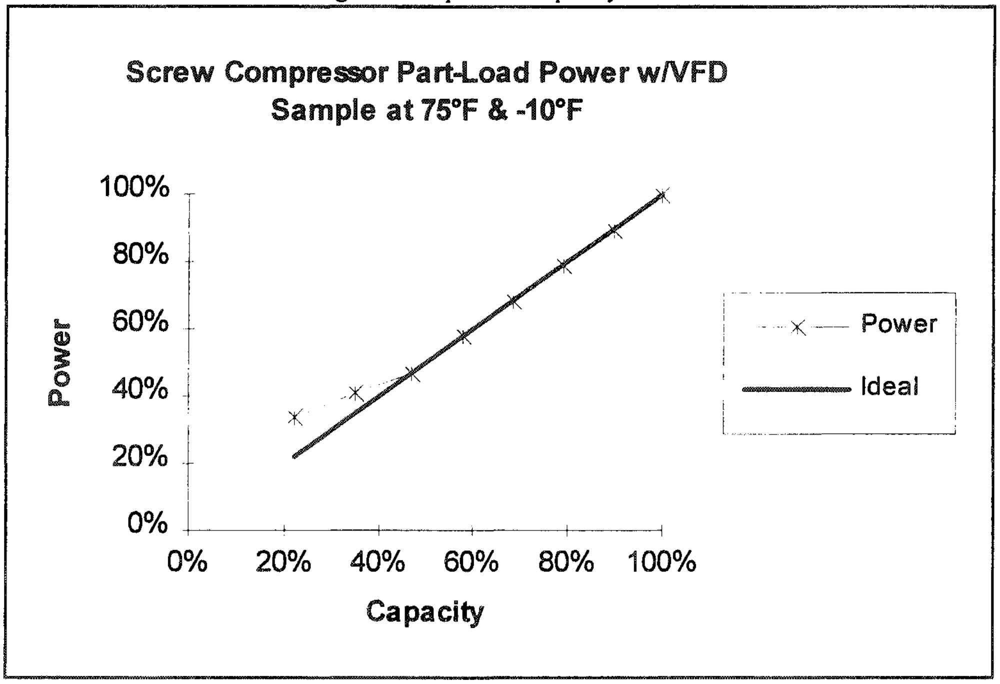
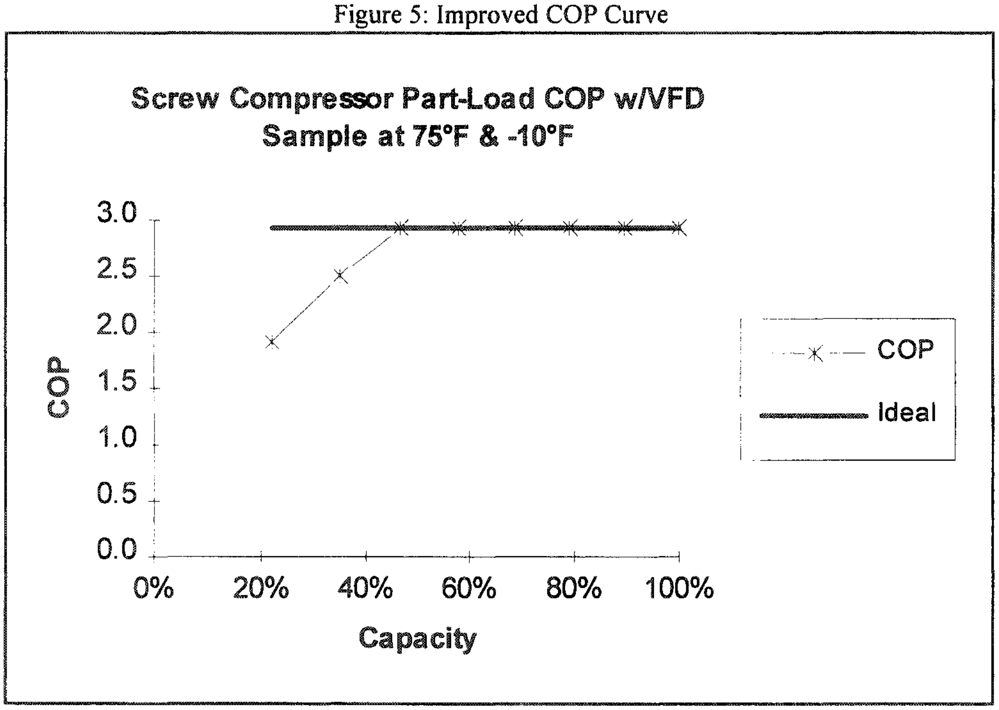


Figure 5: Improved COP Curve



Note the substantial improvement in compressor performance, throughout the entire range of loads.

SCREW COMPRESSOR VSD APPLICATION

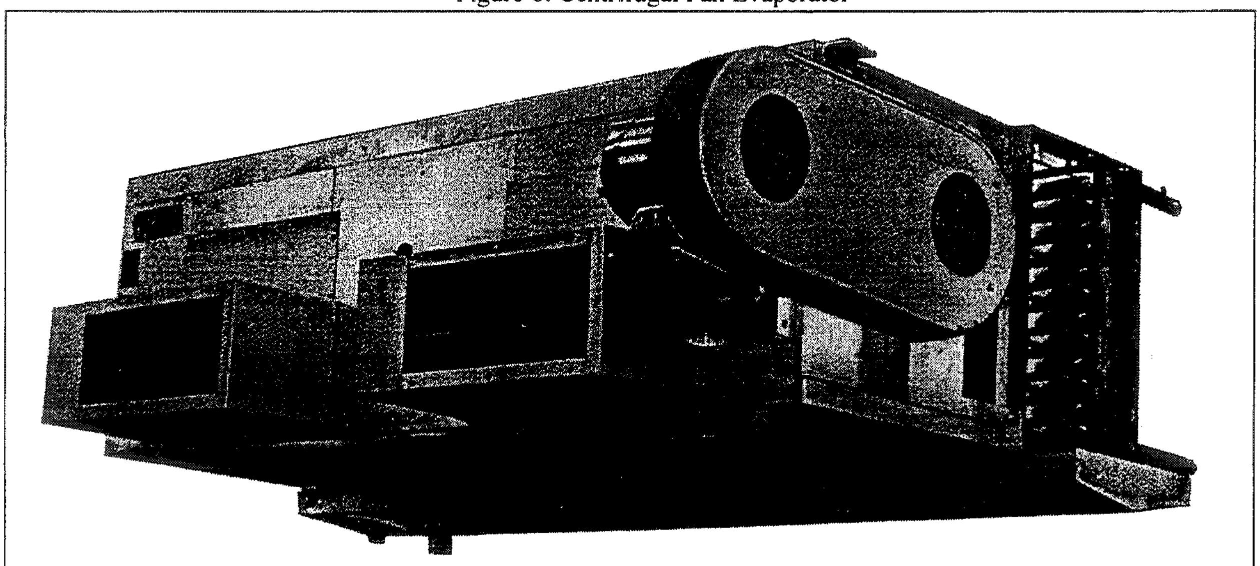
Before installation of a VSD on a screw compressor, several issues should be researched or examined. These include:

- **Compressor Minimum Speed:** Check with the factory to verify the authorized minimum speed. Often this will be 50% of full speed (typically 1800 of 3600 rpm).
- **Motor Capabilities:** Check with the motor manufacturer to ensure that the motor can operate with a constant torque load at 50% speed. Motor cooling is typically the limiting factor. Applications may work with existing open-drip-proof or totally-enclosed fan-cooled motors.
- **Constant Torque VSD:** Ensure that the VSD is a capable of constant torque output. Many VSD vendors have two model lines of drives, rated for either variable (fans) or constant torque loads (compressors).
- **Trim Compressor:** In installations with more than one compressor, savings are maximized by always using the compressor with a VSD to perform all capacity trimming. It will rarely be necessary or economically prudent to install more than one compressor VSD.
- **Method of Control:** Two facets of control are important. First, the control system must ensure that speed control is used exclusively down to 50% speed, with the slide valve completely open. At 50% speed, the compressor speed must be maintained and continued capacity reduction performed with the slide valve. Second, a refrigeration system control system must be sophisticated enough to sequence compressors in such a way that trimming is always performed with the compressor utilizing VSD control.

EVAPORATOR COIL OPERATION

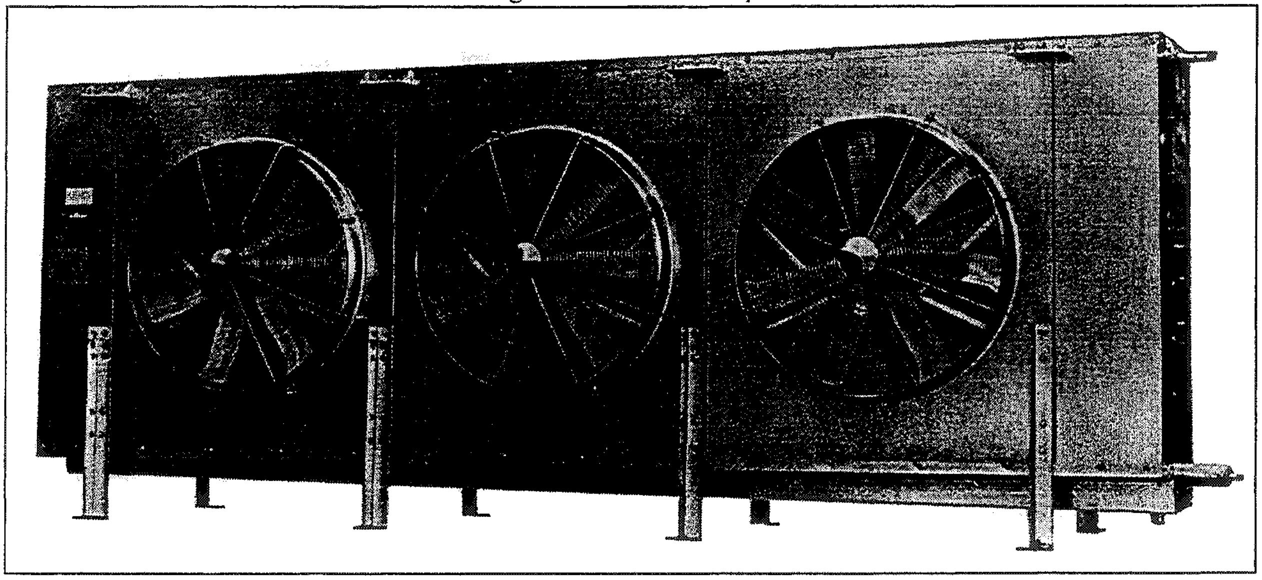
Virtually all cold storage facilities use air-coil evaporators for space refrigeration. Each coil has one or more fans, of either centrifugal or axial type. A typical centrifugal evaporator coil is shown in Figure 6.

Figure 6: Centrifugal Fan Evaporator



Most modern applications utilize axial fan coils. A typical axial fan evaporator coil is shown in Figure 7.

Figure 7: Axial Fan Evaporator



The number of fans can vary from one to six per coil, and typically range in size from 1/3 hp to 10 hp or larger. Since these motors operate in a cold environment, they are often sized to operate well into their service factor. These motors not only use electricity, but all energy used by the motors must be removed from the space as a refrigeration load. In some facilities, evaporator fans are not only a large energy user, but a primary contributor to refrigeration load.

Evaporator coils may employ any of a variety of capacity control methods, including:

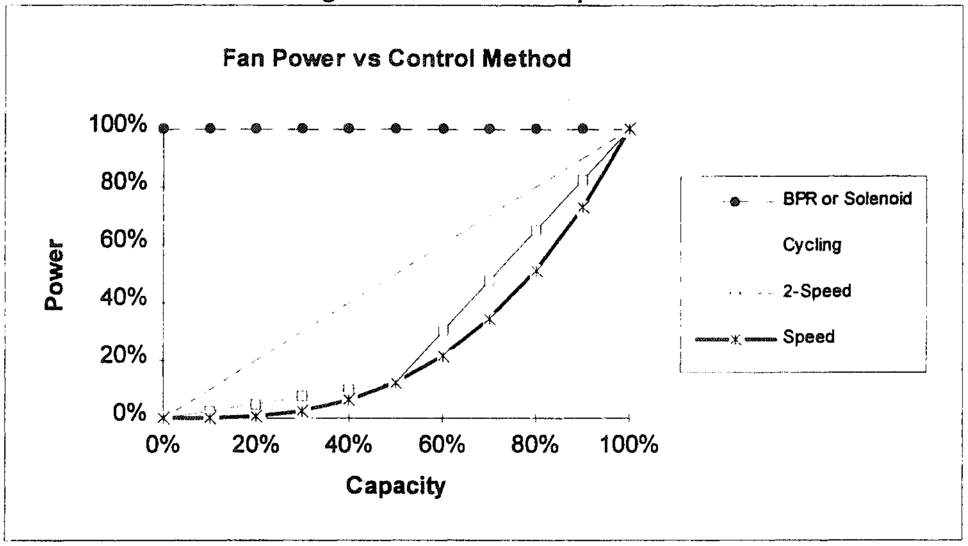
1. Solenoid for liquid refrigerant interruption.
2. Fan cycling or manual fan control.
3. Back-pressure regulators to change refrigerant pressure in coil.
4. Two-speed fan motors.
5. Mechanical (variable sheave) or electro-magnetic (eddy-current clutch).
6. Engine room suction pressure.
7. No control. Room temperature and refrigeration system reach equilibrium.

The most common methods of control in cold storages include liquid solenoids, fan cycling (manual or automatic) and back-pressure regulators (BPRs). Unfortunately, only fan cycling provides energy savings. Many, if not most, facilities operate fans non-stop.

As mentioned earlier, fans power benefits from a cubic reduction as speed is reduced. A comparison of power requirements for the most common control methods are shown in Figure 8.

Evident from Figure 8, full-range speed control provides the maximum energy savings and flexibility. Although 2-speed motors can provide excellent savings, flexibility is limited to two operating speeds. Fan cycling can provide dramatic savings as well, although some applications will not allow fully-reduced air flow.

Figure 8: Fan Power Comparisons



EVAPORATOR FAN VSD APPLICATION

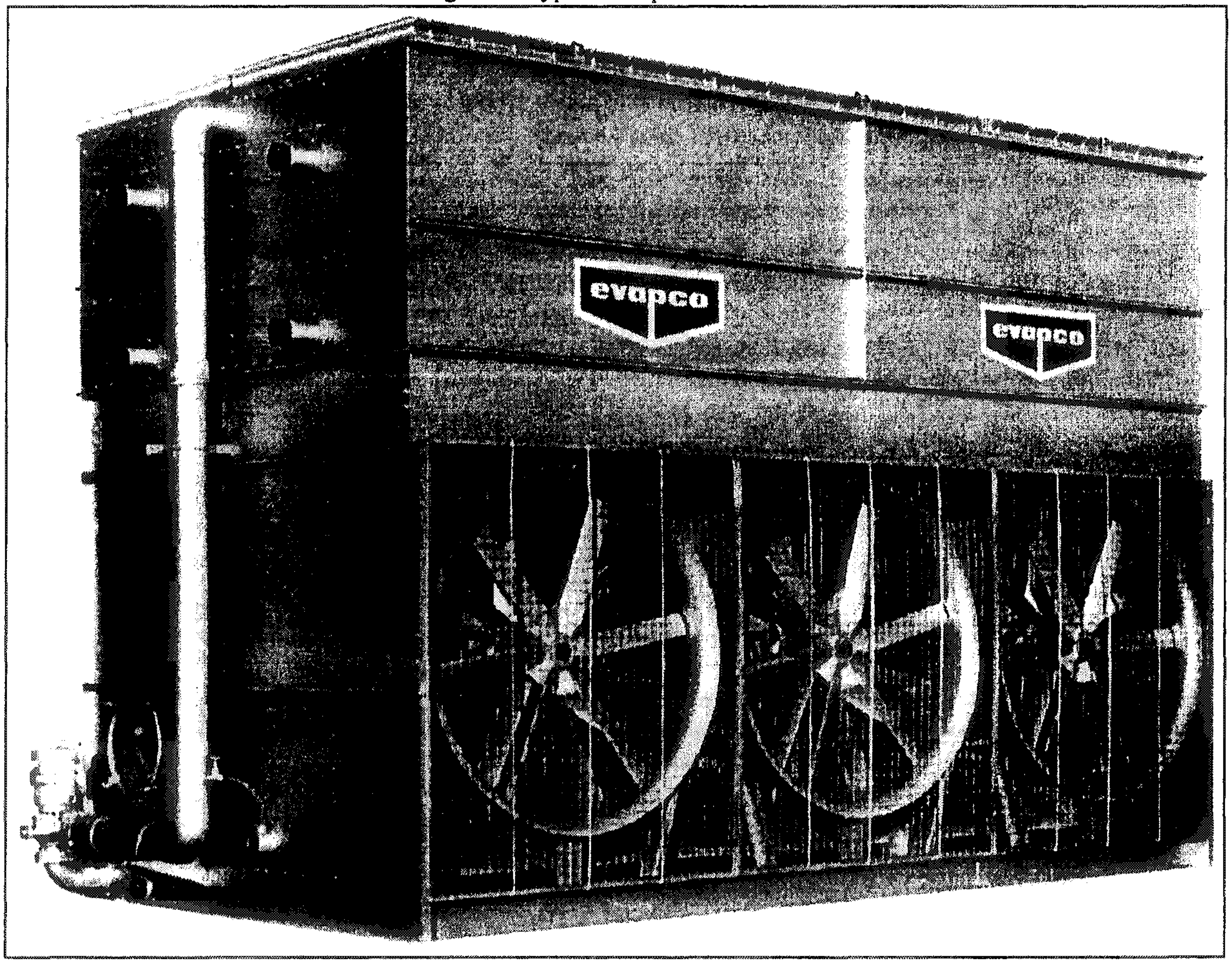
When using VSD technology for evaporator coil capacity control, several items must be considered:

- **Coil Zoning:** Evaporator coils are typically arranged in zones for cooling duty and defrost. A particular coil or group of coils may be located over a doorway which provides a large infiltration load, or in an area where hot product is placed for cool-down. In addition, several coils may be grouped for defrost. In any case, careful consideration should be given to how many motors and/or coils are controlled by a single VSD.
- **Minimum Speed:** The minimum acceptable speed will be determined by the room configuration and the need for high air movement. In general, most cold storage can be operated at substantially reduced fan speed with no increase in temperature stratification or appearance of "hot spots". A practical minimum speed of 50% will allow generous energy savings while moving half of full speed air volume.
- **BPR Control Strategy:** In some applications, BPRs can be eliminated as a method of capacity control. In other applications (notably fruit storage), the BPR is not only used for capacity control, but also as a method of reducing coil temperature difference and the associated moisture removal from the air stream. It is important that a method of "teamwork" be implemented between fan speed and BPR control. Often, fan speed can be reduced in direct proportion to BPR position, down to the minimum allowable speed of the fan. Below this point, any additional capacity reduction can be performed with the BPR.
- **DX Coil Application:** Coils utilizing direct-expansion (e.g., thermal-expansion) valves may not respond gracefully to varying air flow. Slow valve activity may result in liquid carry-over. Check with the coil manufacturer prior to VSD control. It may be necessary to convert the coil to flooded or overfeed.
- **Control System & Sensors:** Fan speed control is best implemented with a reasonably sophisticated control system and a well thought-out distribution of temperature sensors throughout each zone. It is important that the VSD be controlled to ensure that all locations in the zone are maintained at an acceptable temperature.

EVAPORATIVE CONDENSER OPERATION

Most industrial refrigeration systems utilize evaporative condensers for heat rejection. Each of these heat rejection devices rely on fans to move ambient air past falling water for evaporative cooling used in the condensing process. A typical evaporative condenser is shown in Figure 9.

Figure 9: Typical Evaporative Condenser



Condensers can have one or more fan motors ranging from 5 to 40 hp, often driving fans with V-belts. Sometimes, a single motor will drive two fans simultaneously.

Since refrigeration systems usually have a minimum allowable condensing pressure, most condensers utilize fan cycling for capacity control. A few condensers are fitted with 2-speed motors for additional flexibility. The most common controls are Penn-type pressure switches or Mercoid switches which cycle fans within a range of pressures. The disadvantages of these control methods relative to speed control are numerous, including staging, fan power and optimized capacity control.

Condenser & Fan Staging

With standard pressure switches, condenser capacity is added in stages as condensing pressure increases. This results in increased compressor power at the higher pressure and further increases the heat load on the condenser. For example, suppose we had three condensers, each with two fans. With a minimum condensing pressure of 100 psig and a minimum pressure switch resolution of 10 psig, the control strategy shown in Table 1 would result.

Table 1: Condenser Fan Example

Capacity Stage	Cycles Off (psig)	Cycles On (psig)
1st Condenser, 1st Fan:	100	110
1st Condenser, 2nd Fan:	105	115
2nd Condenser, 1st Fan:	110	120
2nd Condenser, 2nd Fan:	115	125
3rd Condenser, 1st Fan:	120	130
3rd Condenser, 2nd Fan:	125	135

In this example of cycling and pressure switch control, the condensing pressure must reach 135 psig before total condenser capacity is on-line. This results in excessive condensing pressure, higher compressor power and poor use of available condenser surface area. With speed control, a single target pressure setpoint can be maintained, with all condenser capacity available if necessary.

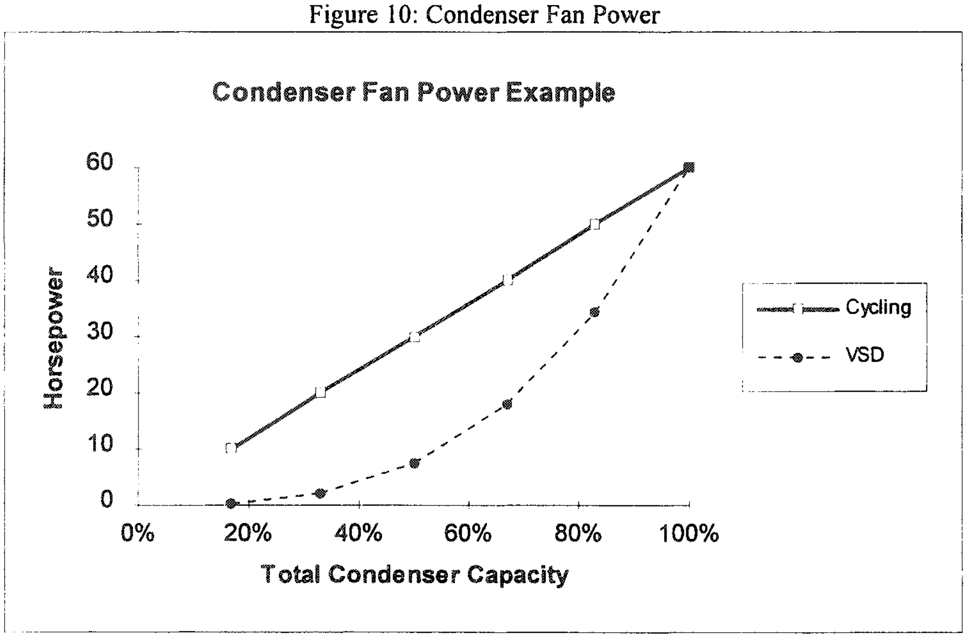
Fan Power

In the previous example, condenser fan power varies directly with capacity contribution. No advantage is taken of the cubic relationship between fan speed and power. As a follow-up, assume that each of the fans in the previous example were 10 hp each. A comparison between fan power associated with cycling control and speed control is shown in Table 2 and graphically in Figure 10.

Table 2: Condenser Fan Power Example

Condensing Capacity Stage	% Cap.	Cycle HP	VSD HP
1st Condenser, 1st Fan:	17%	10	0.3
1st Condenser, 2nd Fan:	33%	20	2.2
2nd Condenser, 1st Fan:	50%	30	7.5
2nd Condenser, 2nd Fan:	67%	40	18.1
3rd Condenser, 1st Fan:	83%	50	34.3
3rd Condenser, 2nd Fan:	100%	60	60.0

Figure 10: Condenser Fan Power



It is clear that speed control offers superior power reduction at all levels of condenser capacity. This, coupled with reduced condensing pressure, can offer substantial compressor and condenser fan savings.

Optimized Capacity Control

A strong incentive exists to operate condenser fans to drive down condensing pressure. The savings in compressor power can be substantial. Unfortunately, pressure switches are simple devices. The condenser fans only know to operate when the condensing pressure reaches a particular setpoint, regardless of actual heat rejection load. This results in "over-condensing", where less than 100% condenser capacity is desirable, but the simple control system cannot match capacity to load.

Often, the compressor energy savings is reduced or even offset by the increased condenser fan power required to drive down the condensing pressure. It is important that some type of optimized condenser capacity control be used to minimize combined compressor/condenser power. VSD control adds the necessary flexibility and fan power savings to fully optimize condenser/compressor interaction.

CONDENSER FAN VSD APPLICATION

Several important VSD application considerations and control features are recommended to ensure maximum energy efficiency when utilizing VSD technology on condenser or cooling tower fans.

- **Fan/Condenser VSD Grouping:** To ensure full energy savings with reasonable control and maintenance abilities, it is often best to install one VSD for each condenser. This provides a balance between flexibility and first cost.
- **Simultaneous Ramping:** It is very important that all condensers be ramped together in speed, not sequentially. This will ensure maximum energy savings and simple control strategies.
- **Wet Bulb Approach:** A wet bulb approach feature should be used to control condensing capacity. That is, condenser fan speed should be varied to maintain a condensing temperature that is held at a user specified temperature difference above the ambient wet bulb. This temperature difference is commonly set between 10°F and 15°F. The setpoint should allow the condenser to spend most operating time in the range of 50% to 80% speed when above the minimum condensing pressure setpoint.
- **Control System:** A control system will provide the best method of condenser fan VSD control, although some systems may work satisfactorily with simple PLCs. The system should handle wet bulb approach, simultaneous ramping, and a user selected minimum condensing pressure setpoint. It may also be necessary to bump condensing pressure up during hot gas defrost.

GENERAL IMPLEMENTATION NOTES

Several items of interest concerning installation of VSDs in refrigeration are listed below:

1. **Harmonics:** All VSDs generate harmonics. The quality and installation of the drive determine the existence and magnitude of harmonic problems. Buy quality drives and have them installed by someone with experience in VSD installations. Often, an isolation transformer may be required to prevent undesirable feedback into the main power system.

2. **Wiring, Line Reactors and Transformers:** Most drive manufacturers recommend separate output and input wiring runs in applications with multiple VSDs. Wiring input and/or output leads from multiple drives in a single gutter or conduit can result in degraded wave form quality and cross-talk. In addition, for installations with multiple small motors on a single drive and/or long wiring runs, it may be necessary to install line reactors close to the motors to eliminate motor wear or failure associated with excessive voltage and "ringing". Finally, it may also be necessary to install a choke on the output of the VSD to protect the drive from the same voltage fluctuations.

3. **Motor Selection or Review:** Most motor manufacturers offer a line of "inverter-duty" motors. Typically, these motors are designed for the high dV/dt and diminished motor cooling experienced with VSD applications. Often, motor manufacturers will suggest premium efficiency motors for inverter duty. In retrofit applications, it may be possible to use existing motors with VSDs, as long as issues of motor insulation and output wave

form quality are addressed. For some retrofit projects using existing motors, operating 460 volt motors at 230 volts with VSDs and line reactors will provide sufficient "cushion" to prevent motor degradation.

4. **VSD/Motor System Design:** It is often prudent to budget for a VSD application specialist to assist in overall system implementation as well as post-installation measurements of performance. A system-wide analysis prior to installation will ensure that all necessary components have been reviewed for compatibility and satisfactory operation.

5. **Manual Override:** Consider providing for manual override in the case of VSD or control system failure. This might include auxiliary starters and pressure switch controls.

6. **2-Speed vs VSD:** Closely examine the cost of 2-speed motors versus VSDs. When including the 2-speed starter and considering the decreasing price of VSDs, there is little reason left to install 2-speed motors. In addition, 2-speed motors have poor efficiencies, even relative to the 95-98% efficiency of a VSD.

7. **Limit of Fan Savings:** There is little reason to reduce fan speed below 50%, since theoretical input power is only 12.5% at this point.

8. **Necessity of Good Controls:** Although some VSD installations may be operated with simple controls or a PLC, it really requires a sophisticated (not necessarily complicated or proprietary) control system to ensure proper operation and maximum savings.

9. **Compressor Selection vs VSD Control:** A VSD may not always be the answer to compressor capacity control. Selecting compressors at proper sizes may allow sequencing for energy savings. Often, a reciprocating compressor can be used for trim, since they have reasonable part-load power curves. Consider cost, savings, maintenance, and space prior to choosing a form of capacity control.

10. **Don't Operate Above 60 Hz:** Although some compressors can operate as high as 4500 rpm (rather than the standard 3600 rpm), avoid the temptation to wring additional performance from the VSD/motor/compressor combination. Also, operating a fan above 60 Hz can burn out a VSD and/or motor due to excessive load. Operating a fan at 65 Hz results in a load increase of nearly 30% over 60 Hz operation.

11. **Select Right Type and Size of VSD:** It can't be emphasized enough that the right VSD must be chosen to match the load (constant or variable torque) and the motor. Some applications (e.g., evaporator fans) are notorious for operating into the motor service factor. Ensure that the electrical contractor or other involved parties are aware of all necessary component operating loads prior to selecting the type and size of a drive.

12. **Check With Manufacturers:** Contact the manufacturer of the compressor, VSD and motor to verify correct operation at reduced speed. Set a minimum operational speed for each component of the project.

CASE STUDIES

Several case studies of VSD technology applied to industrial refrigeration are presented below:

Agripac #8 - Woodburn, Oregon

A 250,000 sq.ft. -10°F freezer and 78,000 sq.ft. repack area at 55°F. Refrigeration systems consists of the following components:

(3) 500 hp screw compressors at -28°F suction.
(1) 125 hp screw compressor at 30°F suction.
(2) Evaporative condensers with 80 hp of fans.
(22) Evaporator coils with 269 hp of fans.

VSDs were installed on the following components:

(1) 500 hp VSD on a screw compressor.
(2) 40 hp VSDs on the evaporative condensers.
(16) VSDs totaling 375 hp on evaporator and O.A. fans.

Sysco - Wilsonville, Oregon

A 80,000 sq.ft. cold storage facility used for food products. Refrigeration system consists of the following components:

(1) 150 hp screw compressor
(2) 125 hp screw compressors
(1) 100 hp screw compressor
(1) Evap. condenser with 30 hp of 2-speed fans.
(26) Evaporator coils with 81 hp of fans.

VSDs were installed on the following components:

(7) VSDs totaling 36 hp on evaporator fans.

Naumes #6, 7 & 8 - Medford, Oregon

A 45,000 sq.ft. storage for bulk, boxed and controlled atmosphere fruit. Refrigeration system consists of the following components:

(2) 250 hp screw compressors
(1) 150 hp screw compressor
(2) Evaporative condensers with 33 hp of fans.
(36) Evaporator coils with 208 hp of fans.

VSDs were installed on the following components:

(1) 150 hp VSD on the 150 hp compressor.
(5) VSDs totaling 180 hp on evaporator fans.

Naumes #1, 3 & 9 - Medford, Oregon

A 38,000 sq.ft. storage for bulk, boxed and controlled atmosphere fruit. Refrigeration system consists of the following components:

(1) 300 hp screw compressor
(1) 150 hp screw compressor
(1) 75 hp screw compressor
(2) Evaporative condensers with 50 hp of fans.
(28) Evaporator coils with 104 hp of fans.

VSDs were installed on the following components:

(2) VSDs totaling 50 hp on condenser fans.
(7) VSDs totaling 120 hp on evaporator fans.

Duckwall-Pooley Fruit Co., - Odell, Oregon

A 156,000 sq.ft. storage for bulk, boxed and controlled atmosphere fruit. Refrigeration system consists of the following components:

(3) Screw compressors totaling 700 hp.
(5) Reciprocating compressors totaling 305 hp.
(6) Evaporative condensers with 77.5 hp of fans.
(110) Evaporator coils with 224 hp of fans.

VSDs were installed on the following components:

(1) 150 hp screw compressor
(28) VSDs totaling 250 hp on all evaporator coils.
(6) VSDs totaling 80 hp on all condenser fans.

Columbia Colstor, - Woodland, Washington

A 105,000 sq.ft. storage and blast facility held at -5°F. Refrigeration system consists of the following components:

(2) 350 hp screw compressors.
(1) 400 hp screw compressor.
(1) 30 hp & (1) 60 hp reciprocating compressor.
(1) Evaporative condenser with 60 hp of fans.
(12) Evaporator coils with 126 hp of fans.

VSDs were installed on the following components:

(1) 60 hp VSD on evaporative condenser.
2-speed fans on all evaporator coils.

Umpqua Dairy - Roseburg, OR

A dairy producing a variety of products, including milk, ice cream, cottage cheese, cream, sour cream and buttermilk. Refrigeration system consists of the following:

(2) 150 hp screw compressors.
(1) 125 hp screw compressor.
(4) 60 hp reciprocating compressors.
(1) 40 hp reciprocating compressor.
(3) Evaporative condensers with 35 hp of fans.
(10) Evaporator coils with 42.5 hp of fans.

VSDs were installed on the following components:

(2) VSDs for all evaporative condenser fans.
(10) VSDs for all evaporator coils.

Several other facilities are currently installing VSDs to control equipment capacity.

RESEARCH

Graduate student research is currently taking place at Oregon State University. A refrigerant flow meter will be used to accurately model economized screw compressor performance at reduced capacity, both with and without speed control. Additional work will be performed on evaporator and condenser VSD installations.