White Paper

The benefits of variable speed drives for high-load chiller operations

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Introduction

This paper demonstrates the extent to which variable speed drives (VSDs) reduce the energy consumption of chillers compared to constant speed drives (CSDs), even in applications where chillers are running continuously at high loads – for example, data centers, factories that require process cooling for equipment, and district cooling facilities. This paper also shows a system designer how to optimize the efficiency of chilled water systems using VSDs. It supplies the metrics that support each claim and provides recommendations on how to evaluate the impact of off-design operation.

Terminology

To clearly illustrate the points in this paper, it is important to clarify the definitions of commonly used terms:

- **Power** refers to the instantaneous rate of doing work, which is often measured in joules per second, or watts. This paper will reference kilowatts (kW).
- **Energy** refers to the amount of work done over time, which is often measured in joules or watt-hours. This paper will reference kilowatt-hours (kWh).
- **Specific Power Input** refers to the amount of power that is required to do work for a specific set of conditions. This paper will reference kW/Ton.

Overview

Water-cooled chiller plants have three major components that consume electricity: the chiller, the condenser and evaporator pumps, and the cooling tower fan. The chiller consumes the highest amount of total plant room energy. In certain applications, the energy consumption of a chiller is very significant. For example, in district energy applications, chillers may consume more than 75 percent of the facility's total energy.

Energy consumption by chiller plant components

For the designers, owners, and operators of chiller plants, it is important to understand what causes a chiller to consume power and what strategies can be implemented to optimize power consumption during high loads. This is particularly true for district cooling plants, where chillers generally operate at higher loads to achieve their objectives.

It is important to establish the metrics to accurately illustrate the correct way to optimize the efficiency of chilled water systems. These metrics inform all recommendations about the evaluation of the impact of off-design operation.

A common misconception in chiller performance evaluation is that design full-load kW/Ton is directly indicative of chiller efficiency. Reducing the chiller selection process to full-load efficiency does not account for a more representative and impactful metric: off-design energy efficiency or annual energy efficiency.

If owners and operators of chiller plants only consider full loads, it can result in unexpected energy use consequences. One of the best ways to improve annual efficiency levels is to employ a VSD for the chiller compressor motor. VSDs are powered devices, which means they negatively impact the full-load performance of chillers, but they are an excellent way to reduce operating costs and improve annual efficiency.

VSDs reduce the energy consumption of chillers, especially compared to CSDs, even in applications where chillers run at continuously high loads. To prove this, a new metric is proposed. This metric is a more accurate alignment of specific power input to expected annual energy consumption.

The validity of the newly proposed metric is corroborated by the case study presented in this paper. Finally, this paper does not address the electrical design and topology of a VSD, but rather a VSD's impact on the compressor of a chiller and – by extension – overall energy performance.

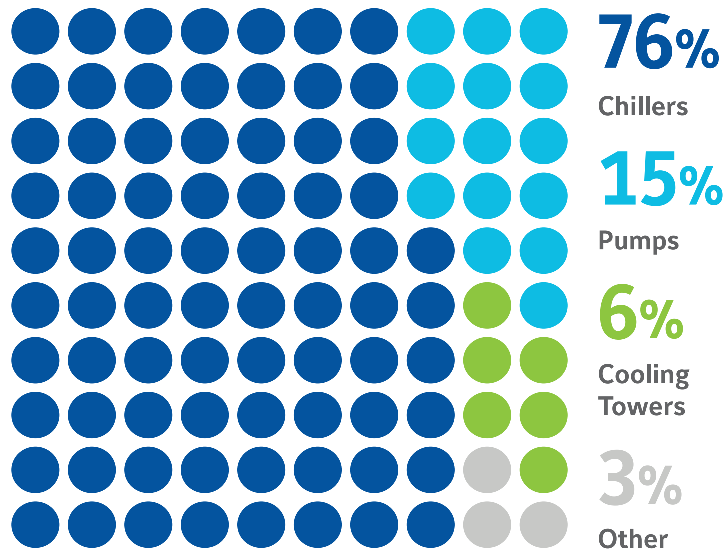

Figure 1 Energy consumption by chiller plant components

VSD impact on chiller power consumption

System designers will specify that a chiller be designed to operate at the most severe condition (the design condition) to avoid insufficient cooling on the most important days. The design condition is used to calculate the maximum instantaneous power consumption. This is then used to size critical electrical components, such as circuit breakers, wires, and generators.

However, chillers run at design conditions for less than 10 percent of the year. Therefore, off-design performance is more important to the overall evaluation of a chilled water system. This is particularly true for applications where chillers run at high loads throughout the year – for example, plant rooms in data centers and other facilities that require process cooling. In these facilities, the chilling duty does not change.

A water-cooled chiller's instantaneous power consumption varies because of two dynamics. The first is the variation in the capacity required by the system, and the second is the amount of compression required. This is illustrated in Figure 2.

Figure 2 is a graph that gives the example of a 2,500 Ton of Refrigeration (TR) water-cooled centrifugal chiller. Figure 2 isolates and compares the impact of changing loads and varying condenser water inlet temperature on a chiller's power consumption. The solid lines represent the performance of the VSD. The dashed lines denote the performance of the CSD.

At the design point, the full load kW/Ton is greater for the VSD chiller than the CSD chiller because of the losses from the electronics in the VSD. However, as conditions change, the improvement of the VSD chiller offsets the losses at the full load and delivers a net improvement over the life cycle of the chiller.

The key insight from the graph is that specific input power consumption is reduced as the Entering Condenser Water Temperature (ECWT) goes down. However, two important observations must also be made.

1. At a given ECWT for a chiller using a CSD, the specific consumption is at its optimum closer to full-load (100 percent) conditions. However, for a chiller using a VSD, the specific consumption improves as the load is reduced.

2. Even at full-load conditions, the specific consumption of a chiller using a VSD is superior to a chiller using a CSD. This yields a net reduction in power consumption and operating costs for the chiller using a VSD.

These results prompt an interesting question: how and why does a VSD improve the performance of a chiller?

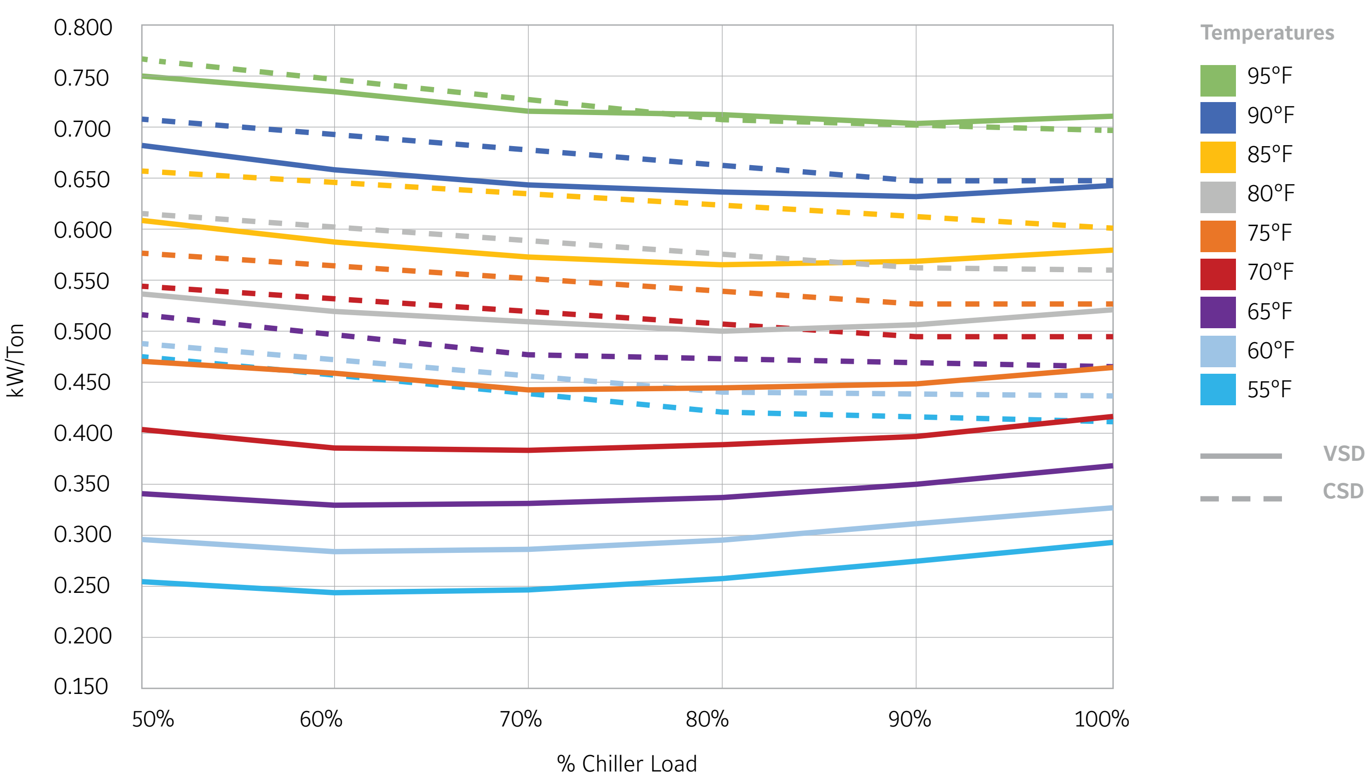

Figure 2 Effect of variation in ECWT and percentage load on the efficiency of a chiller

To understand how VSDs improve the performance of chillers when they are not at peak capacity and design ECWT, one must continue with the same example of a 2,500 TR centrifugal chiller (see Table 1a and 1b). By analyzing the two dynamics that determine power consumption in a chiller, one can assign measurable units to these dynamics.

The first unit in each table, Tonnage, denotes the amount of refrigerant that a compressor needs to complete its work, which is directly related to a cooling load in tons (see column 1). The second unit, ECWT, denotes the amount of work that must be done to a refrigerant, which is directly related to the differential in evaporator and condenser pressure – this is denoted as lift (column 3 and 4).

As the load drops from 2,500 TR to 750 TR, power consumption drops to nearly 40 percent of peak power. However, in both cases, the specific input power of the chiller deteriorates from 0.698kW/Ton to 0.861 kW/Ton. In this case, the changing load reduces energy consumption.

When one compares chillers using CSDs with those using VSDs, the key driver for the difference in specific power input is that the VSD reduces a chiller's load by reducing the impeller revolutions per minute (RPM) by nine percent, while the chiller using a CSD uses its inlet guide vanes to throttle the refrigerant flow entering the compressor. This translates to reduced efficiency in the performance of a chiller using a CSD because throttling imparts frictional losses.

This loss of efficiency relates to the performance of the inlet condenser water temperature. When the inlet condenser water temperature drops, lift – expressed in pounds per square inch differential – is significantly reduced, even at a constant load.

In a centrifugal compressor, the compressor's ability to develop lift depends directly on the tip speed of the impeller. However, as the demand for lift increases, the required tip speed of the impeller decreases, which allows for a reduction in motor speed.

It is important to note that, even at a constant load, the impeller RPM in a chiller using a VSD is reduced by 18 percent. This results in a specific power input reduction of almost 55 percent. This is considerably better than a chiller that uses a CSD, which can only achieve a 38 percent reduction.

The affinity laws for centrifugal equipment prove that changes in the amount of power drawn by a compressor are proportional to the cube of the impeller's speed. As the VSD reduces the speed of the compressor's impeller by 18 percent, rotating at 82 percent of RPM, the power consumption would theoretically be 82^3 percent. This equates to approximately 55 percent of design power, which aligns closely with the observed results.

For a chiller using a CSD, impeller speed does not vary and is constant for all the load conditions. This necessitates throttling, which gives rise to the observed 17 percent loss in specific power consumption, along with the specific power input improvements for full-load cooling from an ECWT of 85°F (29.4°C) and lower. This amounts to a significant number of operational hours for facilities with large chilled water systems.

Tonnage	ECWT	Lift in psid		Job kW		kW/Ton		Impeller RPM	
2,500	95	100.49	100.48	1,778	1,745	0.711	0.698	11,497	11,539
2,500	90	89.22	89.33	1,608	1,616	0.646	0.6465	11,215	11,539
2,500	85	78.63	78.79	1,447	1,501	0.579	0.6004	20,852	11,539
2,500	80	68.69	68.89	1,306	1,401	0.511	0.5605	10,496	11,539
2,500	75	59.33	59.58	1,159	1,312	0.464	0.5248	10,220	11,539
2,500	70	50.54	50.85	1,034	1,231	0.414	0.4925	9,941	11,539
2,500	65	42.31	42.66	917	1,157	0.367	0.4628	9,651	11,539
2,500	60	34.61	34.99	814	1,088	0.325	0.4351	9,348	11,539

Table 1a: Varying Entering Condenser Water Temperature Impacts

Tonnage	ECWT	Lift in psid		Job kW		kW/Ton		Impeller RPM	
2,500	95	100.49	100.48	1,778	1,745	0.711	0.698	11,497	11,539
2,250	95	97.66	97.75	1,584	1,571	0.704	0.698	11,194	11,539
2,000	95	94.6	94.71	1,424	1,405	0.712	0.703	10,854	11,539
1,750	95	92.04	92.17	1,253	1,264	0.716	0.722	10,775	11,539
1,500	95	89.56	89.68	1,103	1,111	0.735	0.741	10,599	11,539
1,250	95	87.1	87.23	939	958	0.751	0.766	10,526	11,539
1,000	95	84.57	84.67	807	803	0.807	0.803	10,456	11,539
750	95	82.23	82.32	656	646	0.874	0.861	10,424	11,539

Table 1b: Constant Entering Condenser Water Temperature Impacts

VSD

CSD

Annual Specific Power Input (ASPI)

Capacity	ECWT in Deg F°	% hours in year	Number of hours in year	Performance of the chiller
Design Point Load (Full Load)	95	10	876	A
	85	25	2,190	B
	75	30	2,628	C
	65	25	2,190	D
	60	10	876	E

$$\text{Annual Specific Power Input (ASPI)} = \frac{A+876 + B \times 2190 + C \times 2628 + D \times 2190 + E \times 876}{8760}$$

Reducing lift, as opposed to the load, reduces the specific power consumption of a chiller. Once this is clearly understood, the question is simple: how do system designers accurately evaluate the performance of different equipment against each other?

To answer this question correctly, the performance data of the equipment must be converted into a metric that will consider real-world annual energy consumption.

It is very important that the system designer specifies a chiller at its peak condition. This ensures that the chiller delivers cooling on the hottest day in a given facility, especially when downtime or missed capacity is not an option – in district cooling plants, for example.

However, the majority of other days in a given facility allow for cooler ECWTs because of the variation in ambient temperature or, more specifically, the wet-bulb temperature. Although the maximum capacity at this point is critical to system design to avoid a shortage of cooling during peak demand, the specific power input does not give an accurate representation of energy consumption by the chiller as it operates throughout the year.

Therefore, to effectively compare the energy consumption of two chillers that are expected to operate at nearly full loads for the majority of their operating hours, it is also important to analyze the performance of the chillers at conditions of reduced entering condenser water temperatures. These reflect actual weather patterns.

The ASPI is a weighted average of a chiller's specific power input at peak power with off-design, full-load operating points where the ECWT is lower.

The ASPI of a chiller is defined as the weighted average of the full-load efficiency of that chiller for one year.

The table and equation above can be explained in the following way: 8,760 is the total number of hours in a year. The table refers to the tabulated values used in the definition of the ASPI. The weighted average of specific power input should be taken by considering the variation of ECWT throughout the year. The weighted average yields the final average efficiency number to reflect the relative importance of variation in ECWT.

Comparison of ASPI using a fixed speed versus a variable speed chiller

The same example of a 2,500 TR centrifugal chiller can be used to demonstrate the variation in the full-load efficiency of a variable speed centrifugal chiller and a constant speed centrifugal chiller. The design conditions for the selection of these chillers are an Evaporator Inlet/Outlet of 56/30°F (13.3/-1.1°C), an ECWT of 95°F (35°C), and the capacity requirement at these conditions, which is 2,500 TR.

By considering continuous full load operations all year round, the chiller is rated for a full load at varying ECWT. Table 2 below shows the chiller operating hours for the given ECWT for climatic conditions in Dubai. The electricity tariff for Dubai is assumed to be $0.12/kWh. Though the chiller is designed for and selected at 95°F (35°C) ECWT, the chiller will spend most hours operating with between 85 and 65°F (29.4 and 18.3°C) ECWT.

At the design point, the peak kW/Ton for a chiller using a VSD is higher than that of a chiller using a CSD. This is because of the electronic losses of the VSD. However, the kW/Ton of a chiller using a VSD starts to reduce below 65°F (18.3°C) and the accompanying efficiency improvements can be as high as 26 percent. This can even be seen at a constant full load of 2,500 TR compared to a chiller using the CSD.

The ASPI of a chiller using a VSD is 0.479 kW/Ton, which is approximately 11 percent lower than the 0.537 kW/Ton of a chiller using a CSD. This indicates a significant reduction in annual energy consumption. Energy costs can be achieved with the employment of a chiller using a VSD, even for an application where the chiller operates at very high loads. The example outlined in Table 2 shows that 1,257,498 kWh savings can be achieved over one year with the use of a VSD. This amounts to $150,900 in annual savings.

Cooling load in TR	ECWT in DegF	Running time in year (%)	Running hours in year	kW/Ton (Constant Speed Chiller)	kW/Ton (VSD Chiller)	Energy consumption in CSD (KWh)	Energy consumption in VSD (KWh)
2,500	95	10	876	0.698	0.7113	1,528,620	1,557,747
2,500	85	25	2,190	0.6004	0.5787	3,287,190	3,168,383
2,500	75	30	2,628	0.5248	0.4637	3,447,936	3,046,509
2,500	65	25	2,190	0.4628	0.3667	2,533,830	2,007,683
2,500	60	10	876	0.4351	0.3254	952,869	712,626
Annual specific power input (ASPI)				0.537	0.479		
Total energy consumption in one year (kWh)						11,750,445	10,492,947
Annual energy cost (AEC) with $0.12/kWh						$1,410,053	$1,259,154
Savings in kWh with VSD chiller in one year						1,257,498	
Savings in annual energy cost using ASPI with $0.12/kWh						$150,900	

Table 2 Operating hours of a chiller for the given ECWT under climatic conditions in Dubai

Conclusions

1. Between the load and the ECWT, ECWT has a higher impact on the efficiency of a chiller. An internal building load variation is a less significant parameter from an efficiency perspective.

2. As a result of the available variation in the ECWT due to annual weather patterns, the VSD dramatically improves the performance of a chiller. The improvement offered by the VSD is 25 to 30 percent better than a CSD. This conclusively shows that a VSD provides higher performance improvements with changes in the ECWT (lift) than the CSD.

3. The analysis of a water-cooled centrifugal chiller during a continuous full-load operation demonstrates that a CSD shows relatively little benefit: two to three percent on the design point. By contrast, the ASPI of a chiller using a VSD is greater by 11 percent.

4. As seen in the case study example, for a 2,500 TR centrifugal chiller running continuously on a full load throughout the year, the annual energy saving is 1,257,498 kWh, which results in cost savings of $150,900. This is all achieved by using a VSD on a centrifugal chiller.

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