

“Ultra-Efficient” Optimization of Data Center Chilled Water Systems

Abstract

The primary goal of data center cooling design has always been reliability backed up by redundancy. All that mattered is that the cooling equipment maintained the critical ambient conditions – precise temperature and humidity -- regardless of how crudely this was achieved by the existing cooling system strategies. This resulted in unnecessary energy use. Nowhere is this more evident than with CRAC (Computer Room Air Conditioning) units that continue to employ control strategies in which the cooling, humidification and reheat systems fight with one another in order to maintain the critical ambient conditions without concern for the amount of energy that is consumed to do so. Even more energy is wasted when full airflow is supplied at part-load operation by CRAC units. Even when Electronically Commutated EC fan technology is built in, the fans usually are operated in bypass or manual mode at full speeds. Despite these energy inefficiencies, cooling equipment and control strategies that have worked reliably and satisfactorily for over the last twenty years continue to be utilized today in new data center designs. This will soon have to change as the push for data center energy reductions is well underway and will be mandated through legislation.

As a result of the looming legislation, we can see the trend towards more energy efficient data center facilities, with the primary goal to reduce operational costs associated with energy use. Reducing a data center's carbon footprint will become an additional objective when the carbon caps and a carbon trading system will become reality in President Obama's 2010 budget. The cooling system offers the greatest potential to realize substantial energy savings for two reasons: 1) proven energy-efficient chilled water cooling system technology, which uses variable-speed devices and optimized controls, already exists; and 2) the cooling system accounts for over 50 percent of a data center's total power spending and its carbon footprint. As technology and processing power continue to increase heat load densities at a rapid pace -- at approximately 25 to 30 percent annually -- chilled water cooling systems offer the most efficient means of transporting and transferring heat. When all rotating devices within a chilled water cooling system -- including chillers, pumps and fans -- utilize variable speed and an integrated control strategy, never before seen energy savings are realized.

Introduction

This paper will explore the concept behind “Ultra-Efficient” data center chilled water system design and control integration that will see an additional 40 to 60 percent energy savings in today's best-in-class variable-speed chilled water systems. By using a different approach to system design and a more direct control strategy using power-based relational control, variable-speed components can be sequenced and operated to not only substantially reduce energy use, but also to improve performance, reliability, redundancy, expandability, reduced maintenance and to greatly extend the life of the chilled-water cooling system. In order to appreciate the concept of Ultra-Efficient data center chilled water cooling systems we need to understand where and how current design practices and control strategies are lacking so we can fully maximize what is possible.

Body

System Design and Selection

Data center chilled water systems design can take a modular approach of sizing for gradual buildup to match the data center buildup in stages or it can be designed from the start for the full-load that the data center will see when fully utilized. Regardless of the approach, the chilled water system will be oversized in order to future-proof and account for the rapid rate that technology is advancing, which is causing data center equipment heat load densities to increase. These increasing heat load densities result in shorter life cycles of the data center processing and storage equipment, subsequently requiring equipment upgrades every three to five years to utilize existing floor space with more processing power and/or storage capacity. However, the cooling system will have a useful life of over twenty years, so it must be designed to accommodate these equipment changes over its operating life. When the data center cooling system is properly controlled and components selected to work in harmony with each other as part of an integrated system, the functional life of the electrical and mechanical subsystems can be extended by an additional 20 to 30 percent.

Since a data center cooling system will be required to operate over a greater operating design envelope at varying loads, reliability and efficiency will be mostly required at part-load operation. The most effective method to satisfy the continuously varying and critical demands for data center cooling is to utilize all variable-speed components -- chillers, pumps and fans -- and a control strategy specific to the unique operating characteristic of variable-speed devices. There are no exceptions to this, because constant-speed devices cannot solve the challenges of a varying application such as data center cooling.

“Ultra-Efficient” Optimization Of Data Center Chilled Water Systems

Chillers and other subsystems, including piping and CRAC units, will have to be sized to meet current and future cooling demands. Since a data center's cooling systems will spend most of their operating time at part-loads, equipment selections should be based on part-load efficiencies. Variable-speed chillers offer greater part-load efficiencies than constant-speed chillers. This is because constant-speed chillers only achieve their highest efficiencies at full-load, and remain relatively flat when operating anywhere below 100 percent full-load. As a result, constant-speed chillers for data center cooling are selected based on full-load efficiencies even though they will spend most of their time operating at part-load. Therefore, any control strategy is forced to operate constant-speed chillers and all related devices (including chilled water pumps, condenser water pumps, and cooling tower fans) -- that are normally sequenced with the chillers -- at full capacity also. This means that in a multiple chiller cooling system, the control strategy that is most commonly used is “capacity-based sequencing”. This widely used sequencing method uses on/off cycling to ensure that chillers are first operating at full-load capacity -- their most efficient operating level -- before the next chiller in sequence is turned on as the load increases. This capacity-based sequencing of on/off staging has many negative impacts. Equipment life and energy efficiency are two of these negative impacts.

Equipment Life is shortened due to the on/off cycling that is employed to stage equipment to match the cooling system output capacity to the demand requirements of the data center. Motor life is shortened each time a motor is started because of the large amounts of stress the motor windings experience from the inrush current upon each motor start. This inrush current can be as much as 10 times the full-load current of the motor, due to the high torque required to ramp up the motor from idle to full speed. In contrast, variable-frequency drives offer a “soft-start” capability, gradually ramping up a motor to the required operating speed. This lessens mechanical and electrical stresses on the motor and can reduce maintenance and repair costs while at the same time extending the motor's working life.

Energy Efficiency is not realized with constant-speed devices operating at full speeds during part-load operation -- exactly where a data center will spend most of its operating time. When constant-speed equipment is used in place of variable-speed, mechanical flow controls are used to restrict flow in order to unload devices to reduce output capacity to meet demand during part-load operation. Mechanical flow controls include:

- closing in-let vanes to restrict flow in a compressor,
- pumps to close valves,
- fans to close dampers, and
- resetting the static and differential pressure.

These bandage solutions that remain widely in use today to unload constant-speed devices operating at full speeds during part-load operation can be compared to driving a car with one foot on the gas pedal and the other on the break pedal to control the speed of the car -- not a very effective or efficient control strategy.

Integrated Control Strategy

A new, integrated control method is needed to replace capacity-based sequencing of on/off staging. Variable-speed offers the most effective, reliable energy-saving solution to respond and operate efficiently across a broader operating design envelope to match the continuously varying heat load in data centers. A control strategy that is specifically geared towards the operating characteristic of variable-speed devices is needed to harness all that variable-speed has to offer. In a variable-speed cooling system, the speed of all rotating devices will increase as the load increases and decrease as the load decreases (as opposed to decreasing output with mechanical flow controls as with constant speed devices operating at full- speed during part-load). When a variable frequency drive (VFD) is added to a compressor, pump or fan to improve part-load efficiency, the energy savings potential is huge due to the pump fan laws which state: power is proportional to rotary speed cubed ($P \propto N^3$).

Affinity Laws

Flow rate proportional to rotary speed	$Q \propto N$
Head (pressure) proportional to rotary speed squared	$H \propto N^2$
Power proportional to rotary speed cubed	$P \propto N^3$

If a rotating device is allowed the flexibility to operate along its “Natural Curve”, a 50% reduction in flow would be equivalent to $(.5^3)$ or 12.5% nameplate power draw. This would equate to $50\% / 12.5\% = 400\%$ increase in operating efficiencies. This efficiency is only possible if the pump fan law relationship between pressure and rotary speed, along the “Natural Curve”, are maintained at the decreased speed. A 50% reduction in flow would be equal $(.5^2)$ or a 25% reduction in pressure.

“Ultra-Efficient” Optimization Of Data Center Chilled Water Systems

In order for these devices to operate at their highest efficiencies, they require the freedom to maintain the relationship between flow and pressure for all load conditions and to be allowed to operate along their ideal operating curve, as illustrated in *Figure 1 – Natural Curve for Pump Operation*, below. Traditional control practices will maintain a fixed or minimum differential pressure (DP) across the pump supply and return headers. The pump will operate along the fixed differential pressure curve, as seen in *Figure 1*. This means that the pump will require much more power than necessary to maintain the DP set point and will not have the freedom to operate along its Natural Curve or “sweet point”. Ideally, the pressure differential sensor should be placed at the CRAC unit where the pressure is more critical, allowing the pump to follow and maintain the ideal flow and pressure relationship at varying speeds/flows and head pressures.

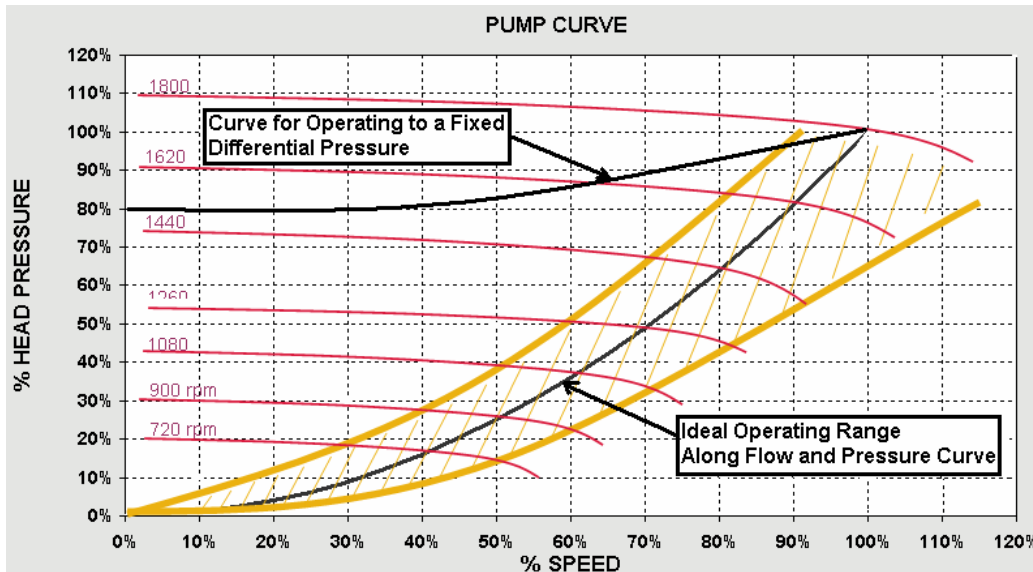


Figure 1. Natural Curve for Pump Operation

The Natural Curve Sequencing will sequence variable-speed chillers to operate along their natural curve for all load conditions. There is an ideal point on a chiller's loading curve for a specific chilled water supply and entering condenser water temperature where that chiller will be operating at its optimum efficiency. The natural curve for a chiller is developed by finding these ideal points for the four entering condenser water temperatures for a specific supply chilled water temperature. This point will be the lowest point (lowest kw/ton) on each of the four condenser water temperature curves. The natural curve is then developed by drawing a line that intersects the four points as illustrated in *Figure 2 – Natural Curve for Chiller Operation*, below. The chiller will be operated only along its Natural Curve for all operating scenarios, ensuring optimum efficiency at all loads.

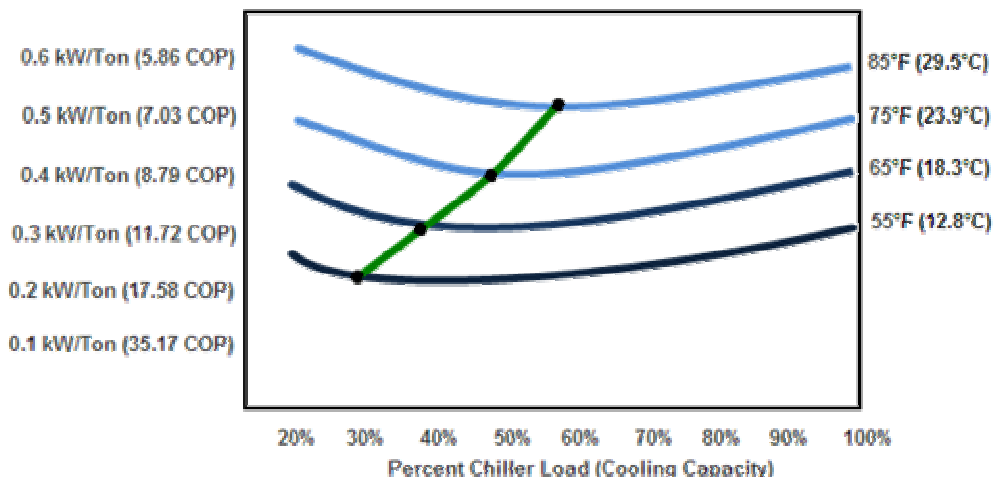


Figure 2. Natural Curve for Chiller Operation

It was mentioned that peak efficiency of chilled water data center cooling systems is achieved when: (1) variable-speed devices are utilized; and (2) the optimization of all the subsystems is controlled in response to data center heat loads served by the cooling systems. When the operation of variable-speed chillers, pumps, and cooling tower fans are harmonized with the operation of chilled water CRAC units with EC fan technology, the cooling system efficiency is dramatically improved. Present-day data center chilled water cooling systems are operated as four sub-systems, each with their own standalone proportional-integral-derivative (PID) feedback loop:

1. CRAC Units,
2. chillers,
3. condenser water distribution systems, and
4. cooling tower fans.

Each of these four sub-systems operates efficiently on its own. However, this same independence means that the plant, as a whole, does not operate at peak efficiency because the sub-systems are not working in harmony with each other. Integrating these four subsystems with network-based relational control allows for complete optimization of all components and causes them to function as a unit.

PID control has been around for decades and is a very simple, general-purpose control for simple linear processes. PID feedback control loops are able to effectively control a single device, controlling a single variable such as pressure or temperature that is on a single control loop. Any process that has changing conditions would be too complex for PID control. PID control, as part of a network, which is communicating and controlling a number of varying devices, does not have the flexibility to continuously adapt to varying loads that are encountered in HVAC applications. Instead, a different control method is needed to improve chilled water plant performance.

Power-based speed control and power-based sequencing are used to achieve “Ultra-Efficient” optimization of data center chilled water cooling systems. Power-based speed control uses a control methodology called Equal Marginal Performance Principal to calculate and determine the best power relationship between the chiller, condenser pump and tower fan. This control methodology trades off load and efficiency between the three subsystems to achieve the best net system efficiency. Power-based sequencing replaces the traditional, inefficient capacity-based sequencing of running devices at full speeds before the next one is sequenced either on or off to match the varying data center load. Power-based sequencing will sequence components to operate at peak efficiency during part-load operation along their natural curves. Operating loads are satisfied by determining the best net system efficiency and trading off power efficiencies among the system components in relationship to one another. This trade-off may operate a greater number of devices at lower speeds to take advantage of the affinity laws. This results in cubed power savings and utilizes a much larger heat transfer area that is created by operating either two devices at 50 percent, or three devices at 33 percent. This is in contrast to conventional capacity-based sequencing when the load would normally be satisfied by one device operating at 100 percent full speed, which consumes more power unnecessarily.

Conclusion

The technology exists today to greatly improve data center efficiency and reduce its carbon footprint while at the same time improve performance, reliability, redundancy, expandability, reduce maintenance and greatly extend the life of the chilled water cooling system. By taking a new and different approach -- variable-frequency drive technology – integrated with a control strategy that takes advantage of the unique characteristics of variable-speed devices to operate and sequence those devices in relation to one another, offers data center cooling unmatched opportunities for energy savings in addition to offering overall superior performance and reliability. The full benefits of what is currently available have not yet been truly harnessed to fully maximize data center chilled water system efficiencies to Ultra-Efficient levels that would see current energy use reduced by up to 60 per cent.

Reference:

- Hartman, T. PID control: May it rest in peace. HPAC Engineering, Jul-2002
Hartman, T. New “LOOP” Chiller Plant uses Advanced Technologies to Achieve Big Cost Reductions Nov 1999
Erpelding, B Ultra-efficient all-variable-speed chilled-water plants. HPAC Engineering, Mar-2006
Vidovic, M Ultra-Efficient” Optimization of Chilled Water Plants, ACREX India, Feb-2008
ASHRAE TC9.9 Datacom Equipment Power Trends and Cooling Applications 2005