ULTRA-EFFICIENT COOLING with Demand-Based Control

The value and methods of applying direct-coupled network control to building-energy-system design

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Imagine operating a chilled-water plant without controlling the chilled-water temperature and operating a variable-flow chilled-water distribution network without a differential-pressure setpoint. Why would you operate a cooling system this way? The reasons may surprise you. First, operating plants without directly controlling the temperature or pressure of their outputs can be much more efficient. Second, temperature and pressure control is considerably more complex and less stable than are control strategies that combine more direct control and optimization.

Through a new approach to HVAC control called "demand-based control," building systems are operated using the network capacity of modern building control systems. Combining variable-speed-drive equipment with network-enabled demand-based-control technologies can make simpler, smaller, and lower-cost building energy systems operate as much as 30- to 50-percent more efficiently than conventional system configurations with the same basic HVAC-component efficiencies can. Also, demand-based control enhances the comfort of buildings and provides a platform for individual control and other valuable occupant amenities.

HOW CONVENTIONAL CONTROL WASTES ENERGY

Conventional HVAC controls employ pressure- or temperature-setpoint control to isolate (or decouple) one system element from another. Figure 1 shows basic control modules for a typical HVAC system. The cooling towers, chillers, distribution pumps, and supply fans are controlled independently with temperature or pressure setpoints that ensure the surrounding equipment also can operate independently over a wide range of loading requirements. Although a network-capable direct-digital-control (DDC) system may be employed for control, the network typically is used only to collect information for monitoring. In many systems, additional isolation is provided with primary-secondary pumping, bypasses, decoupling lines, and valves or dampers that have large pressure drops.

Direct-coupled control can reduce the size and complexity of both controls and system components.

This focus on independent equipment operation wastes energy. Normally, the chillers in Figure 1 are operated at a fixed chilled-water temperature. At low loads, the compressor operates at higher-than-needed head (and lower efficiency) to provide colder-than-required chilled water, which is distributed at a higher-than-necessary pressure. To ensure stable and independent chilled-water coil operation under these conditions, the valves are selected for high pressure drops. All of these equipment-isolation measures reduce overall system efficiency.

If current HVAC-control practices were applied

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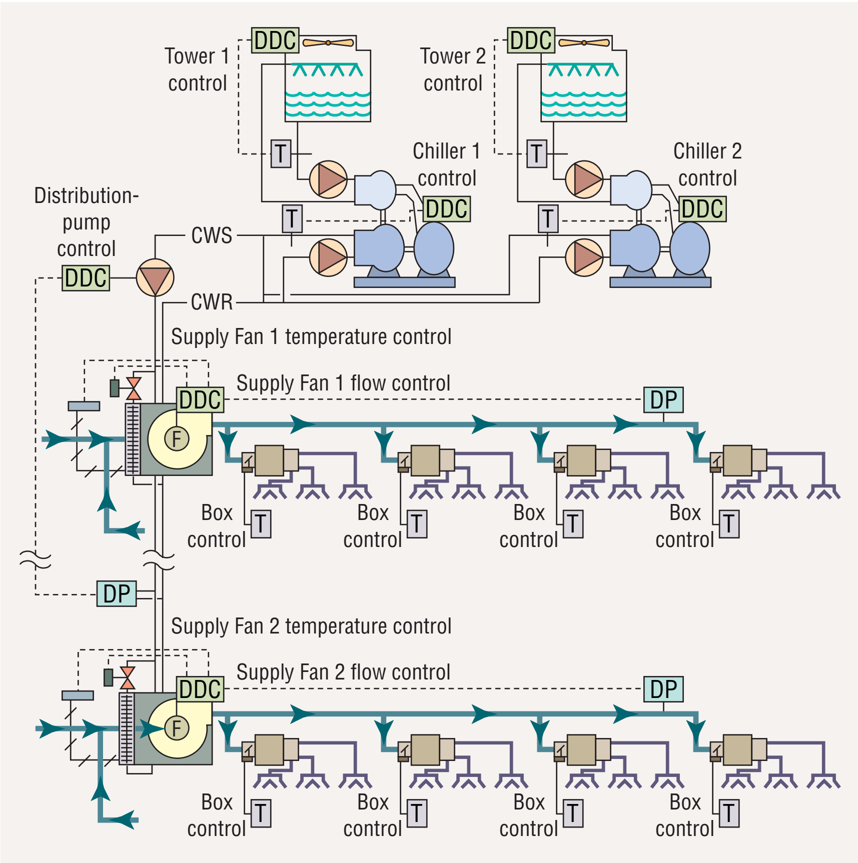

FIGURE 1. A conventional HVAC system in which each piece of equipment is operated with an independent control loop that maintains a temperature or pressure setpoint regardless of the end-use requirements.

to automobile operation, drivers would be taught to control the accelerator to maintain a fixed engine rpm, operate the clutch to provide a specific torque, and use the brake to control the vehicle's speed. Consider what this would do to a car's average miles per gallon!

Traditional optimization approaches cannot overcome the built-in inefficiencies of conventional HVAC control. Instead, they typically create one or more additional layers of software that reset the various setpoints to marginally improve operating efficiency as conditions change. These optimization approaches add complexity to the controls and are limited in their ability to reduce energy consumption.

Direct-coupled control, on the other hand, can reduce the size and complexity of both controls and system components. However, a basic change in how the system is operated must be made first.

DEMAND-BASED CONTROL: A NETWORK-CONTROL SOLUTION

Demand-based control is a method of applying direct-coupled network control. It is based on the idea that a building HVAC system is a single system the energy efficiency and comfort performance of which are optimized when the operation of all components is coordinated to meet actual needs in the spaces served.

Demand-based control is intended to fill the vacuum in controls technologies created by the development of variable-frequency drives (VFDs) for HVAC equipment. Prior to the introduction of VFDs, coordinating the operation of HVAC equipment mattered little because equipment efficiency remained almost constant over ranges in loading. Now, with VFD modulation, the efficiency of HVAC components can change dramatically as load conditions vary. Although coordinated operation is essential to maximizing overall energy efficiency today, most conventional control schemes operate VFD equipment as they do mechanically modulated equipment. Demand-based control can solve this problem; however, applying it effectively requires new thinking about how VFD equipment operates most efficiently.

HOW DEMAND-BASED CONTROL WORKS

With conventional control strategies, little if any information concerning upstream or downstream loading/operating conditions is employed to adjust the operation of equipment. Typically, HVAC components operate to maintain a single temperature or pressure setpoint. If a number of spaces in a building were to begin to overheat, most central systems would not self-adjust to provide more cooling and, once the spaces were satisfied, readjust to meet the reduced load with greater efficiency. Accomplishing this would require a network-control scheme that communicates with the loads being served.

Network-enabled demand-based control is very cost-effective because, in most cases, it does not require additional equipment or controls. In fact, when properly applied, demand-based control

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requires less equipment and often employs a simpler configuration than the conventional system and control it replaces.

Although demand-based control ties the operation of all equipment to end-use requirements—actual space requirements in single-building HVAC applications—this does not mean that chillers and cooling towers operate directly from space-temperature sensors. Rather, as in automobile operation, demand-based control optimizes an HVAC configuration by directly coupling the operation of all components so they operate as a single system in meeting the actual needs of spaces. This single-system approach generally is not considered because HVAC designers are too used to ensuring that their designs isolate the operation of HVAC components to give an alternative a thought. For example, while low delta T is a serious problem in many chiller plants, designers continue to employ decoupling or bypass lines that permit direct mixing of supply and return chilled water.

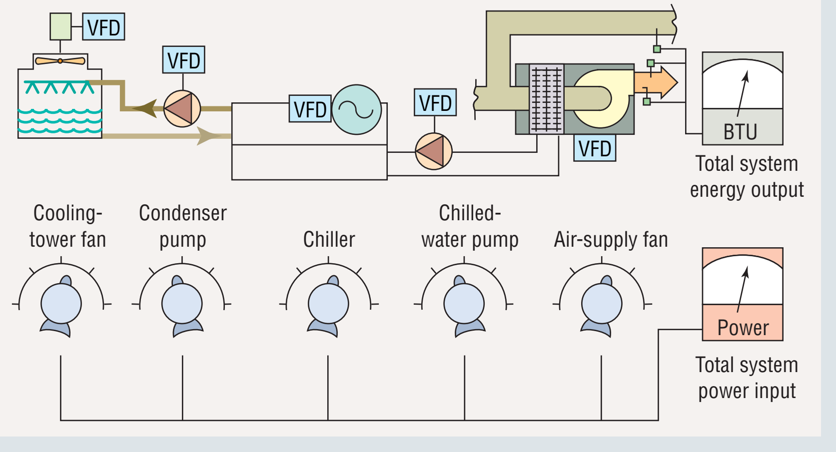
With variable-speed equipment and network-control capabilities, the long-standing dictum that equipment must be decoupled to operate effectively has been reversed. Direct coupling leads to simpler, more-efficient operation. It is intuitive that coordinating the operation of a chiller plant and chilled-water distribution network is required to achieve the highest overall cooling-system efficiency. The question is how does one control these together so they can be operated most efficiently.

The answer is to consider all equipment involved in cooling a building as a single system instead of a series of systems. When cooling needs to be adjusted in response to space conditions, demand-based control coordinates the operation of all elements to provide cooling where it is needed according to predefined efficiency relationships.

We know that coordinating the operation of two identical pumps in a direct-coupled parallel or series circuit based on power or speed is the most straightforward method of optimizing the pumps' overall efficiency. But what if the pumps (or other type of equipment) are not identical? In a similar fashion, one or more power-based relationships can be developed using the Equal Marginal Performance Principle (see sidebar) and employed to optimize the pumps under all loading conditions. The operation of a circuit consisting of cooling towers, chillers, pumps, and conditioning fans with variable-speed drives also can be optimized in this fashion. Like dissimilar pumps, these components can be directly coupled and controlled using demand-based control to operate the circuit as a

Equal Marginal Performance

Formulated more than a decade ago, when variable-speed drives were first applied to pumps and fans, the Equal Marginal Performance Principle (EMPP) states that the operation of a system comprised of multiple modulating components (in series or parallel) is optimized when the marginal system output divided by the marginal system input is the same for all components. To better visualize how the EMPP is applied to an entire cooling system, consider the schematic below.



Imagine that the knobs below each piece of equipment in this schematic adjust the capacity of that element by changing its speed or by some other means. Assume that instrumentation for measuring the system output and system input is provided. How would you optimize this system at its current point of operation? According to the EMPP, it could be done by making small adjustments to the capacity of each element and noting the changes in system output and input. Then, system efficiency could be improved by: (1) reducing the capacity setting of elements that show relatively small marginal-system capacity change per unit input change and (2) increasing the capacity setting of elements that show larger changes in capacity per unit power change so that the total system output remains at its current point of operation. These processes of testing each element and resetting the system would be repeated until all elements had exactly the same marginal output per unit change in power input. At that point, the system would be optimized.

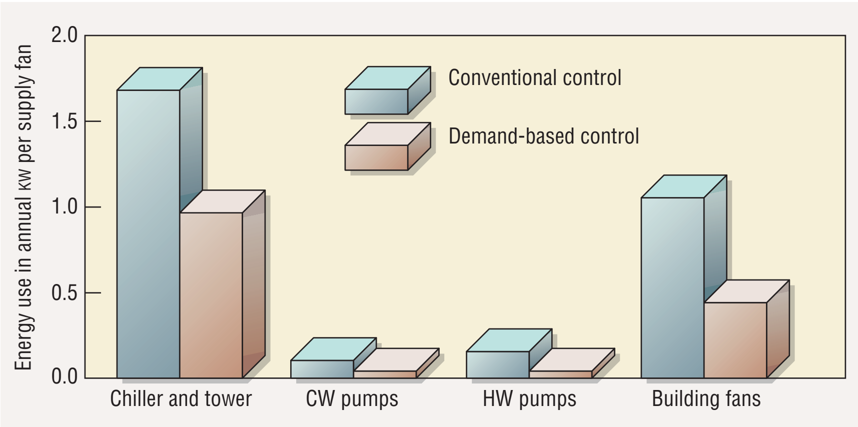


FIGURE 2. A comparison of the annual energy use with conventional optimized HVAC systems and equipment of the same basic configuration and efficiencies except operated with demand-based control of a new mid-rise office building in Denver.

single system and provide the cooling capacity required. Such coordinated control is the simplest method of obtaining the highest overall operating efficiency. Thus, with demand-based control, equipment is coordinated to operate according to power (kilowatt) setpoints, which is simpler, more stable, and much more efficient than the use of temperature or pressure setpoints is. Furthermore, because demand-based control is network-based, enhancing system performance by making system adjustments that focus on meeting exceptional space-conditioning requirements that occur from time to time is very easy.

ENERGY-REDUCTION IMPLICATIONS OF DEMAND-BASED CONTROL

By directly coupling HVAC components into a single system with network communication and acting on end-use requirements in setting system capacity, demand-based-control strategies can improve building comfort, environmental quality, and energy performance. While the assessment of comfort and environmental quality usually is subjective, the energy savings attributable to demand-based control can be accurately determined through hourly simulation. The simulation results for the electric portion of the HVAC system in a new mid-rise office building in Denver are shown in Figure 2. The building was designed to use less than 50,000 Btu per sq ft annually. Note that despite the initial low-energy design, the network-based control further reduced the electric-energy use of the chiller plant and HVAC distribution system by nearly 50 percent. At the same time, the networked control resulted in a more comfortable building and a higher level of indoor environmental quality.

CASE STUDY

Bellevue Corporate Plaza is a multi-tenant mid-rise office building in Bellevue, Wash. It is an all-electric building that employs variable-air-volume (VAV) air systems with fan-powered perimeter boxes and electric reheat. The chiller plant consists of two air-cooled centrifugal chillers and a constant-flow primary-only distribution system. In 1993, an integrated lighting and terminal-regulated-air-volume (TRAV) controls retrofit was ordered. TRAV was the first demand-based-control strategy developed, and its application reduced total building energy use from about 80,000 Btu per sq ft annually to about 50,000 Btu per sq ft. Seven years later, it was time to upgrade the chiller plant. The plant employed a phased-out refrigerant, and the chillers were near the end of their useful life, as evidenced by a dramatic increase in maintenance and numerous failures. Furthermore, the plant lacked the capacity to meet growing tenant internal heat loads at peak conditions.

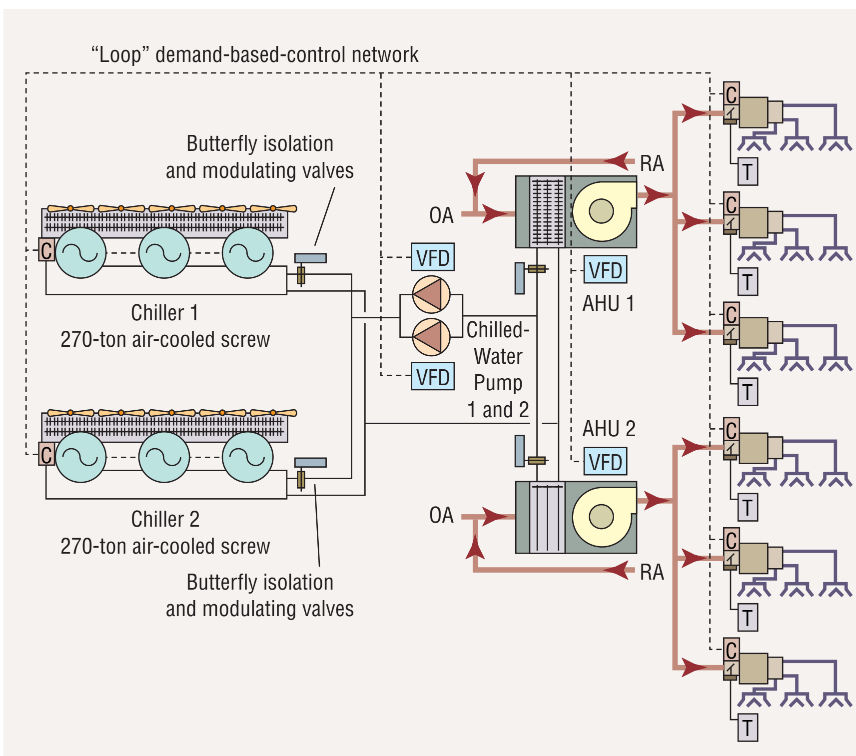


FIGURE 3. The new Bellevue Corporate Plaza cooling system. The Loop demand-based-control network is shown schematically. Its purpose is to connect equipment to the network for coordinated operation rather than to maintain temperature or pressure setpoints.

After exploring several replacement options, the building owner, Hallwood Commercial Real Estate, adopted an upgrade approach that employed the new Loop demand-based-control-sequence package.

The Hartman Co. helped implement Loop ultra-efficient demand-based-control sequences and bring the new system on line. The Loop control sequences were installed in the building's existing DDC system without the need for additional control equipment, save some input/output devices. The resulting cooling system provided additional capacity with a lower design chilled-water temperature, allowing the existing cooling coils to be used.

The Loop demand-based-control technologies significantly improved the chiller plant's operating efficiency by using the control network to coordinate cooling supply with the actual cooling demand. All balancing valves were removed, and the three-way modulating-flow control valves on the cooling coils were changed to two-way line-sized modulating valves. Variable-speed drives were added to the pumps. The distribution system was reconfigured to variable primary flow without a bypass valve.

Direct coupling leads to simpler, more-efficient operation.

The chiller-plant components are now controlled at optimal levels of relative power use rather than to maintain a specific chilled-water temperature or distribution-pressure setpoint. When cooling is called for, the chiller plant, distribution pumps, and fans are optimally operated together. Under normal operations, there is no direct control of chilled-water temperature or distribution pressure. At low-load conditions, chilled-water temperature floats upward, and pump-head requirements for the distribution system fall, resulting in very stable operation and low power requirements. Even at full loading, the chilled-water temperature often remains above the design minimum, and pumping head is only half of what it was before the retrofit.

The operation of the chillers, distribution pumps, and main supply/return fans is coordinated for the highest overall cooling and distribution efficiency at all times. This automatic network optimization is especially useful during periods of demand limiting. In conventional systems, demand limiting may be applied only to chillers. The chilled-water-distribution pumps and air-distribution fans speed up during demand limiting because their loads are not met when the chillers reduce their loading. This results in greater power use by pumps and fans, which reduces the demand-limiting function of the chillers. At Bellevue Corporate Plaza, the Loop demand-based-control sequences coordinate the operation of all equipment and provide more-effective demand limiting with less impact on occupants because system efficiency increases during demand limiting so that the cooling effect remains high.

Despite a larger cooling system and lower design operating temperatures, the building's summer peak electrical demand has been reduced by about 20 percent. And as a result of extending demand-based control to the cooling system, the building's daily energy use during cooling-system operation has been reduced by about 22 percent.

The building is using 50-cents-per-square-foot less energy annually than it would be if the demand-based-control program, which began with the TRAV retrofit, had not been undertaken. In addition, the building's occupants report being much more comfortable.

When demand-based control is installed throughout most typical HVAC systems, one can expect a 30- to 50-percent annual electrical-energy reduction.

Before this project, most of those involved had never seen Loop demand-based-control technologies applied. To their credit, however, they worked cooperatively to ensure the project's success.

SUMMARY AND CONCLUSION

Energy efficiency and comfort can be improved substantially by applying network-enabled demand-based-control strategies to operate building HVAC equipment. The enormous electric-energy reductions possible from the application of demand-based-control strategies are such that this change in building-control technology should be considered as part of national energy policies. When demand-based control is installed throughout most typical HVAC systems, one can expect a 30- to 50-percent annual electrical-energy reduction. Equipment configurations require only slight modifications to be operated in accordance with demand-based control in place of conventional optimized control. Furthermore, a system specifically configured for demand-based control can be less expensive to design, install, and maintain than a conventional system.