Variable-Speed Pumping

Changing flow and maintaining it smartly, exactly as dictated by demand

By JOHN VASTYAN
Common Ground
Manheim, Pa.

Worldwide, pumping systems account for nearly 20 percent of the energy used by electric motors and 25 to 50 percent of the total electrical energy used by certain industrial facilities. Significant opportunities to reduce pumping-system energy consumption exist, the most popular being through the application of variable-frequency drives (VFDs).[1]

This article will explain why VFDs and their cousins—electronically commutated motors (ECMs)—are a valid and cost-effective means of varying pump speed and identify many downstream benefits of their use.

With variable-speed pumping, savings go well beyond energy and include enhanced performance, improved reliability, and reduced life-cycle cost. For new projects, capital cost is reduced through the elimination of valves, starters, wiring, pneumatic lines, and smaller-diameter piping with bypass lines. Additionally, the use of VFDs permits the use of smaller pumps with lower-horsepower motors, ensuring a tangible bottom-line benefit for building owners.

VFDs Explained

There are several types of variable-speed drives (VSDs). For applications requiring flow or pressure control—particularly systems with high friction loss—the most energy-efficient option is the VFD. The most common form of VFD is the voltage-source, pulse-width-modulated frequency converter (often incorrectly referred to as an inverter). In its simplest form, a converter develops voltage directly proportional to frequency; its job is to control alternating-current-motor speed and torque. For instance, when controlling pump operation for a closed-loop system, a converter compensates for changes in process by changing the power and frequency supplied to the motor and, thus, motor speed.

Variable-speed drives govern the operation of end-suction pumps with high-efficiency, inverter-ready motors coupled with multipurpose valves and suction diffusers. Suction and discharge flanges are connected to piping with elastomeric couplings. The components are mounted on inertia bases.

VFD control of a pump often results in operation at 50 to 75 percent of full speed. As a result, horsepower and current draw are reduced significantly. For example, a 300-hp motor at 60 percent of full speed requires about 20 percent of full load power.

Inherent in VFDs is a soft-start capability that prevents overcurrent and overtorque conditions on startup and avoids pressure spikes (water hammer), reducing the risk of damaged pipes and pumping-system components.

Smart Pumps

Today, manufacturers offer a wide variety of pumps with on-board VFDs and ECMs. Both technologies offer the intelligence for optimal operation, communication between smart devices, process control, and diagnostics.

"Proportional pressure control is prevalent in sensorless ECM smart pumps," Steve Thompson, lead project manager for Taco Inc.'s commercial pump line, said.

According to Thompson: "Energy savings and noise

The president of trade-communications firm Common Ground, John Vastyan is a journalist who has been writing about the plumbing-and-mechanical and HVAC industries for 25 years. He can be reached at 717-664-0535.

reduction are achieved with proportional head regulation that also compensates for varying pressure drops within the system as loads change (Figure 1). In this mode, the pump head changes continuously as the demand for water changes, reducing as the water demand declines and increasing as the water demand rises."

In context

In a pumping system, the objective, in most cases, is to transfer a liquid (e.g., circulate liquid through a piped network as a means of heat transfer). Pressure is needed to make liquid flow at the required rate and overcome losses in the system. Losses are of two types: static head and friction head. Static head, in its simplest form, is the difference in height between the supply and the destination of a liquid or the pressure in a vessel into which a pump discharges, if it is independent of flow rate.

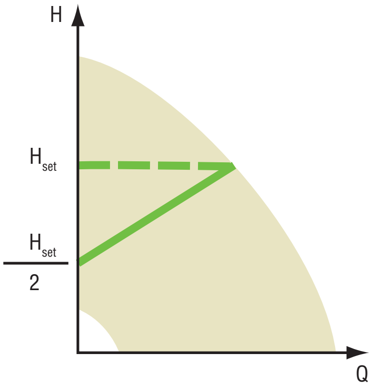

FIGURE 1. Proportional pressure control.

A closed-loop circulating system without a surface open to atmospheric pressure shows only friction losses. Most systems, however, have a combination of static and friction head. The ratio of static head to friction head over the operating range influences the benefits achievable with a VSD. Static head is a characteristic of installation. Reducing static head when possible generally reduces installation and pumping costs. Friction-head losses must be minimized to reduce pumping cost, but after unnecessary pipe fittings and length are eliminated, reduction of friction head requires larger-diameter pipes, which add to installation cost.

"This is the dilemma that most HVAC professionals face: balancing the installed upfront cost against the longer-term life-cycle operating cost," Bryan Payne, PE, Taco's southeastern sales manager, said. "The great news is that drives allow the use of smaller pipe sizes, now pushing design velocities up over traditional constant-speed systems. For many months of the year, it's quite common for piped systems to

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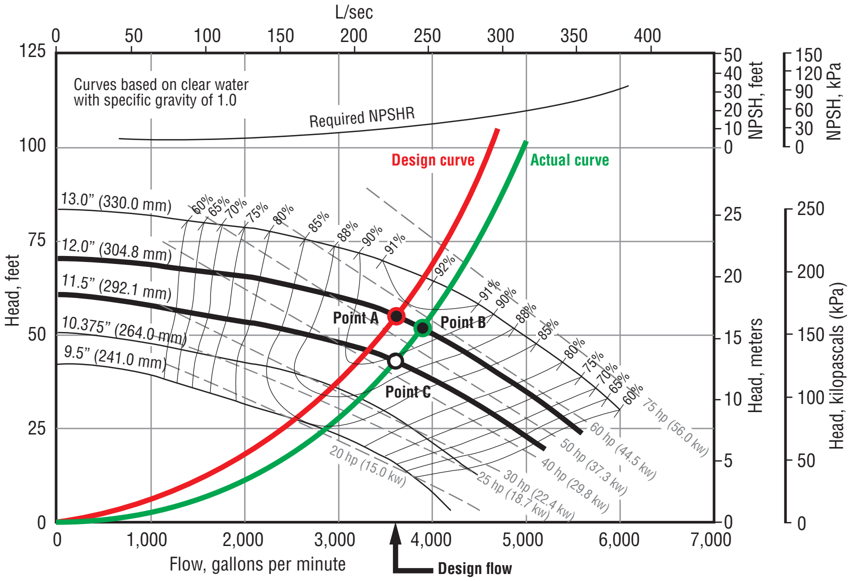

FIGURE 2. The pump with 12-in. impeller tracks down the green system curve as demand in the building is reduced. The savings are significant—a 10-percent reduction in speed yields a 28-percent reduction in horsepower, while a 50-percent reduction in speed yields an 87.5-percent reduction in horsepower.

operate at flow rates that have very low velocities and pressure drops, yielding significant savings to building owners. Designing with drives for all system pumps allows the best of all worlds: lower installed costs and lower operating costs."

When a centrifugal pump is installed in a system, the effect can be illustrated graphically by superimposing pump and system curves. The operating point is where the two curves intersect.

"Many pumping systems require a variation of flow or pressure," Gene Fina, senior product manager for Taco, said. Referring to Figure 2, he added: "Pumps would run at maximum speed on a design day, but this occurs only rarely. A vast majority of the time, the system needs reduced flow and reduced pressure drop. This allows the pump to run at slower speeds and to track the system curve."

According to Fina, either the system curve or the pump curve must be changed to get a different operating point.

Single pumps installed for a range of duties are sized to meet the greatest output demand and, thus, usually are oversized and operate inefficiently for other duties. Consequently, there is an opportunity for energy-cost savings through the use of control methods, such as variable speed, that reduce the power driving the pump during periods of reduced demand.

"Here in Florida, ... new ASHRAE requirements for outside air have increased the need to introduce fresh air, which, 10 months of the year, is very high in moisture, needs to be cooled and reheated," Bill Dalhoff, LEED AP, vice president of Jacksonville, Fla.-based manufacturers' representative Florida Hydronics Inc., said. "Reheat coils and capacity increase, larger boilers are needed, and now there's also greater system flow. Of course, at the high end, with winter design conditions, it's no surprise that we see systems with greatly varying flow needs—say, 10 percent of load to 100 percent—making the use of variable-speed pumps a perfect fit.

"It's now almost expected that secondary-loop building pumps have variable-speed drives," Dalhoff continued. "Now, the quickly building trend is the use of variable drives to balance constant-speed pumps on the primary side for chillers and boilers. This makes so much more sense than to use constant-speed pumps with manual balancing valves that impart false head and require higher-horsepower pumps. Though this ultimately achieves the same thing, the smarter, far-more-cost-effective solution is to use variable-speed technology. Payback to the building owner is amazingly fast. Though a starter may cost $550 and a variable-speed drive perhaps $700 or so, the upcharge can typically be recovered within three or four months."

Mike Kiani, PE, CPD, CIPE, principal mechanical engineer for MK2 Engineers, a Fairfield, Calif.-based consulting engineering firm, said he recommends VFDs for virtually all pumping applications.

"Building owners are now quite open to it and see the value in the minimal upcharge," Kiani said. "Variable-speed pumps and drives that were prohibitively expensive and at the bleeding edge have now become

Motor horsepower	Starter pricing (NEMA 1, hand-off-auto switch, through-door disconnect)					Drive	
	Rep 1	Rep 2	Rep 3	Rep 4	Avg.	Base drive with conduit kit	Drive with bypass
10	$651	$663	$686	$746	$688	$638	$1,091
20	$736	$843	$875	$954	$862	$966	$1,436
40	$979	$1,180	$1,676	$1,860	$1,438	$1,808	$2,359

Comparison of the cost of basic single-speed pump starters with that of variable-speed drives for pumps of equal size. The information was obtained from four manufacturers' representatives across the country.

utilitarian, entirely sensible for broad use—even for constant-volume systems—because of the huge operating-cost advantages and reduced maintenance.

"I compare it to the difference we see today between cars with carburetors and those with fuel injection," Kiani added. "The automotive industry shifted to new technology for very good reason, including greater fuel efficiency, reliability, and (throttle) response. Variable-speed pumps are designed to track the load closely, an ability that constant-speed systems simply don't have."

Control Schemes

According to Dalhoff, the on-board intelligence of VFDs and ECMs has improved to the point that system engineers and pump manufacturers can optimally meet the needs of either control scheme required: delta-T or delta-P.

Delta-T. John Barba, one of Taco's variable-speed experts, is a proponent of pump or circulator application based on delta-T, the difference between supply and return temperatures.

For variable-speed circulators, delta-T relates directly to the amount of British thermal units being taken out of a system or zone.

The Universal Hydronics Formula states:

$$\text{gpm} = \text{Btuh} \div (\Delta T \times 500)$$

where:

gpm = the flow rate, in gallons per minute, required to deliver a specific amount of heat at a specific time

Btuh = the heating load, or the British-thermal-unit-per-hour requirement at a given point in time

ΔT = the design temperature drop across a piping circuit

500 = the weight of 1 gal. of 100-percent water (8.33 lb) multiplied by the 60 min in an hour multiplied by the specific heat characteristic of the water (1, for 100 percent)

A Taco 60/13 40-hp KV vertical inline pump with Baldor Super E motor with multipurpose valves (MPVs) and suction diffusers connected to a variable-speed drive circulates water to and from a cooling tower. (Taco recommends a spool piece between the discharge nozzle of a pump and a MPV. The MPV to the right of the pump is installed incorrectly; mounting a valve directly to a pump is not recommended.)

"I don't see delta-P in the equation," Barba said. "What I do see is that delta-P seeks out gaps in the system and changes speed to fill the gaps.

"But it doesn't take into account what happens out there in the loops because it doesn't know how many Btus a zone is using when ambient temps are 5°F or 25°F," Barba continued. "It doesn't know what combination of zones is calling or if two zones of equal length—but unequal heating load—are calling. A delta-T circulator will monitor the temperature differential between the supply and return piping and will speed up or slow down to maintain the delta-T that's selected."

In the Universal Hydronics Formula, if delta-T is fixed, then flow rate will adjust based on the heat required.

"What's seen in systems with a delta-T of 1°F is water rushing through the system," Fina said. "The delta-T that's seen is a result of a fixed-speed circulator slamming water through the system at a fixed gpm, while the Btu load has decreased. The math says the variable now isn't the gpm, but the delta-T."

Barba added: "In a case like this, the system is getting the Btus it needs, but the flow rate is way too high, so the delta-T shrinks. Now, how would that affect, say, a system with a modulating-condensing boiler? Would it work more efficiently if the water returning to the boiler was 109 degrees or 90 degrees? If the delta-T pump was set at 20 degrees, the water temperature coming back to the boiler would be lower, and that would help the boiler operate far more efficiently."

Consider the effect of short cycling. A boiler certainly will run longer to raise water temperature 20 degrees than it will to raise water temperature 1 or 2 degrees. Unfortunately, short cycling is a fact of life with modulating-condensing boilers because of low water content. Many experts recommend use of a buffer tank to build volume.

"Ideally, a broad delta-T works well for many hydronic systems," Barba said. "Let's say we have a lightcommercial building with baseboard radiation. Fin-tube baseboard is generally sized and rated at a 20-degree delta-T. There's nothing magic about a 20-degree delta-T; that's just what it's rated at. If you wanted to set it for 10 degrees, you'll have a higher flow rate through the system, and the pump will run faster. Set it for 30, and the flow rates will be lower, and the pump will run slower.

"So, for a fin-tube system, 20°F delta-T makes sense," Barba continued. "Outdoor reset doesn't make much difference to either delta-T or delta-P. It's all about the Btus, so a 20-degree temperature drop at 150 and a 20-degree temperature drop at 110 is still a 20-degree temperature drop."

The key, Barba said, is the circulator offers the flow required to deliver the heat needed simply by noting supply and return temperatures. These tell the circulator how much heat is being removed from the system.

Delta-P. Optimizing pump performance based on delta-P is accomplished by setting and maintaining a prescribed pressure within a piped system.

"To move fluid, the pump or circulator adds energy (head) to the fluid to overcome friction loss—what occurs when the moving fluid comes in contact with the inner walls of the pipe," Thompson explained. "The faster the fluid moves, the higher the friction loss is—like driving your car faster into the wind.

"The graphical representation of this event, of course, is called a system curve—and it goes up in an arc, starting at 0 gpm (no velocity, no friction) to where it intersects with the circulator's performance curve," Thompson added.

Dropping Delta-Ts

As zone valves close, a system curve intersects a pump curve at higher and higher pressure differentials. Higher pressure differentials can lead to higher flow velocities, which, in turn, can lead to velocity noise.

One way to deal with velocity noise is to install a pressure-differential bypass valve, which prevents flow when all heating zones are calling. As zone valves close, increasing pressure differential, the bypass valve opens to allow excess pressure and flow to pass back to the suction side of the pump.

A better solution is to use a mid-flow, low-head, flat-curve circulator. With such a pump, system pressure rises minimally, eliminating the need for a bypass valve.

If more head than a circulator can deliver is required, a variable-speed pump should be considered.

"If all of the zones in a system are calling for heat, we may find that the delta-T drops to 16 degrees, not the 20 typically designed for," Barba said. "Doesn't sound like much, right? But that also equates to about a 20-percent difference. With only two zones calling, the delta-T drops to about 15 degrees—a 25-percent difference. And with only one zone calling, the delta-T drops to 12 degrees ... a whopping 40-percent difference."

Those scenarios, Barba added, are under design conditions. If outdoor temperature were, say, 35°F, the delta-T would be much smaller because heat losses would be reduced dramatically. A fixed-speed pump—or a delta-P pump—would be running at the same speed; the result: reduced delta-T and boiler short cycling.

"System designers can solve the dilemma of dropping delta-Ts by using a variable-speed, fixed-delta-T circulator," Barba said. "You may never have to worry again about oversizing a circ."

Rather than search for the point where a system curve intersects a pump curve, let the pump curve self-adjust, Barba said.

Back to Delta-P, a Viable Variable

So, it is settled; delta-T is better.

"Not so fast," Thompson said. "Delta-P is viable and has many just-right applications."

According to Thompson, constant-speed circulators operate contrary to their intended purpose.

"A circulator is a centrifugal pump with the sole purpose of moving Btus within a hydronic system," Thompson explained. "Application, not size, should determine the 'circulator' descriptor."

A circulator's curve slopes down from left to right, meaning more flow, less head energy (what the circulator contributes to move heat). So, as the flow (or system British-thermal-unit requirement/load) goes down, friction loss is reduced. The circulator's pressure, however, goes up.

A circulator's maximum head is at zero flow when there is no friction loss.

"It's actually the opposite of what it really needs to do," Thompson said.

Discussing the "perfect circulator," Thompson said:

Two 10-hp inline pumps are mounted vertically with multipurpose valves and suction diffusers. The mechanical installer increased the size of the pipe to reduce both friction within the pipe and required pump energy, allowing smaller pumps to be used.

"The system need may call for a small, 1/25-hp model or a much larger 25-hp pump—think application. If it's true that a circ's mission in life is to overcome friction loss, doesn't it make sense that the perfect circulator's pump curve would look exactly like a system curve? After all, any head above the system curve wastes energy."

Optimizing energy consumption requires a good control strategy. Thompson offers an example of a commercial pump set at factory defaults of 23 ft at 50-percent proportional. Twenty-three feet refers to the maximum head the pump will produce (adjustable up to 40 ft) at its maximum speed. Fifty-percent proportional means at 0 gpm (dead head or zero fluid velocity).

Assume that, at maximum speed, the flow at 23 ft is 100 gpm (or 1 million Btu at 20°F delta-T). The pump's head is 50 percent of 23 ft, or 11.5 ft. Thompson draws a straight line between 0 gpm at 11.5 ft and 100 gpm at 23 ft. That is the pump's curve—an *inclining* curve. Does it match the system curve exactly? No, but it is cost-effective, is simple (sensorless), and does not overpressure or overflow zones.

Delta-P is a poor fit for:

- Mono-flow systems requiring relatively high, constant velocity/flow.
- Main-system pumps in single-pipe systems because of limited pressure feedback to the delta-P pump.
- Injection systems.

Additionally, a delta-P pump may not be the best fit if used as the main "flow" circulator on a boiler sensitive to low flow, especially with low-mass, high-friction-loss heat exchangers.

So why bother with delta-P? For many other hydronic systems—applications such as reverse return systems and secondary chilled-water distribution circuits—pressure-differential pumps are well-suited.

This brings us back to an overarching theme: It's all about flow. Hydronic HVAC systems are dynamic in that loads change constantly. Changes in load means changes in pounds of water, based on the law of thermodynamics. Changes in pounds of water means changes in flow. The application dictates delta-T or delta-P control. The bottom line is changing flow and maintaining it smartly, exactly as dictated by demand. Today, pumps and circulators can get the gift of this intelligence as a retrofit improvement. Or, even better, new smart pumps are "born" with the brains to meet system needs precisely.

Reference

1) Hydraulic Institute, Europump, & U.S. Department of Energy Industrial Technologies Program. (2004). *Variable speed pumping — A guide to successful applications, executive summary*. Available at http://www.nrel.gov/docs/fy04osti/36074.pdf

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