# Variable Speed Pumping

*Variable speed pumping can save you money if you select and use systems wisely.*

BY STEPHEN MURPHY

Most users operate their centrifugal pumps at a fixed speed and accomplish any required changes of flow by using a throttling valve. This practice is much like driving an automobile with the accelerator fully depressed and changing speed by stepping on the brake!

There is a better way to drive an automobile and there is a better way to accomplish variable flow for a centrifugal pump. Variable speed motors and associated electronic drives can be used to adjust pump speed to produce exactly the desired flow and head. By varying the speed of the pump, users can enhance performance, save energy, eliminate the need for throttling valves and reduce inputs of heat to the pumped liquid.

But to achieve these advantages, you must properly select the components of a variable speed system. And proper selection requires a thorough understanding of pump, motor and driver designs for variable speed operation.

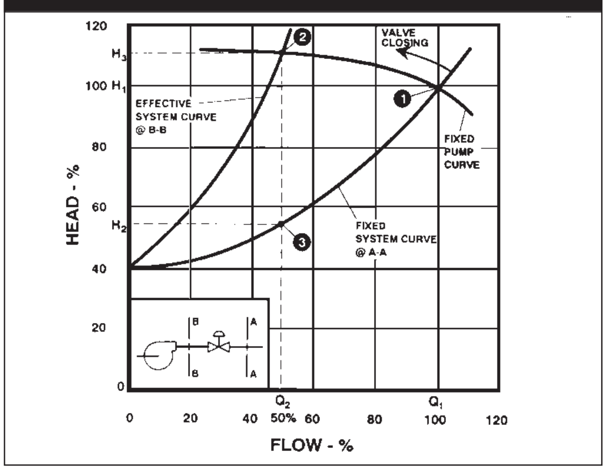
## BEHAVIOR OF VARIABLE SPEED PUMPS

A good place to begin a discussion of variable speed pumping is the interaction between variable speed pumps and the fluid handling system. These interactions are different from those of a fixed speed pump.

For a fixed speed pump with flow controlled by a throttling valve, process demand depends on system back pressure and piping resistance, as shown by a fixed system curve (Figure 1). Pump performance is also represented by a fixed curve. With the discharge throttling valve fully opened, the pump seeks equilibrium with the system (point 1 in Figure 1: flow = $Q_1$ and head = $H_1$).

To change the flow to $Q_2$, the throttling valve is partially closed, changing the steepness of the system curve as seen at a point between the pump and the valve (at B-B in Figure 1). Closing the valve causes the pump to "run back" on its curve to point 2, producing flow $Q_2$ as desired. The pump, which can only operate on its fixed curve, produces head $H_3$ at point B-B. The pump thus produces $H_3$ at $Q_2$ but only $H_2$ at $Q_2$ is delivered to the system. The additional head ($H_3$ - $H_2$) is wasted across the valve in the form of heat and noise.

FIGURE 1



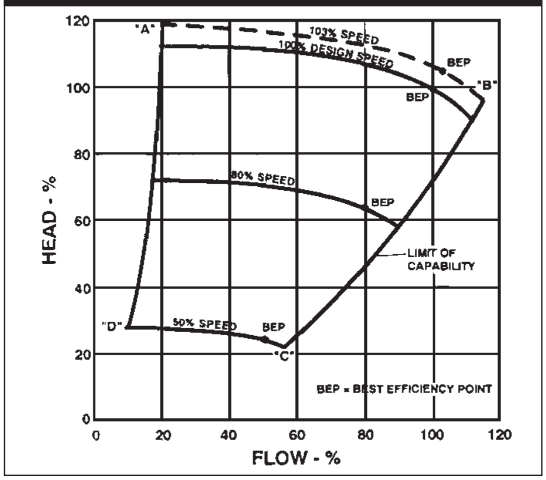

**Fixed speed centrifugal pump operation**

For a variable speed pump, flow is changed by varying speed. The variable speed pump retains its characteristic performance curve shape, changing flow and head in accordance with the well-known affinity laws (Figure 2). With varying speeds, pumps have wide rangeability and thus any head-flow combination within the envelope can be achieved. And with appropriate precautions, pumps can be operated at even higher or lower speeds than those shown on the curve.

The shape of the system curve influences the amount that flow will change with a change in speed. Flow is proportional to speed if no static lift exists but not proportional to speed if static lift exists (Figure 3). In systems with static lift, a minimum speed exists below which the pump will produce no flow.

Such behavior does not violate the affinity laws. It simply reflects the interaction of the shape of the system curve with those laws. In fact, it's this interaction that makes variable speed pumping advantageous (which also illustrates that users must understand these interactions).

**FIGURE 2**




**Variable speed centrifugal pump operation**

## BENEFITS OF VARIABLE SPEED PUMPING

Because variable speed pumps can produce a desired head and flow over a broad range of hydraulic conditions, users do not have to be as certain of required flow when they select a pump. Instead of finding the exact fixed speed pump for the job, they can install a variable speed pump and adjust the speed to produce the exact conditions they require.

For example, one user required Pump A to produce 125 gpm flow at 2500 ft head in an upset condition and 100 gpm at 1500 ft under normal con-ditions and Pump B for a 125 gpm flow at 1500 ft head under normal conditions. The user needed an installed spare for each pump, for a total of four pumps. But by specifying variable speed pumps, the user required only three pumps: one for each duty level and a single spare which was valved to allow operation under either condition. Further savings were achieved for the main pumps since identical pumps were used (desired conditions were met by varying the speed). Parts were interchangeable and significantly less energy was required when running Pump A at the normal (i.e., low-head) condition.

In addition to covering a wide range of conditions, variable speed pumping can also eliminate the need for multiple stages. With increased speed, centrifugal pumps produce increased head and flow.

As mentioned above, variable speed pumping can also eliminate the need for a throttling valve. Also, bypass valves may no longer be necessary since minimal flow requirements for stable operation decrease with speed. Elimination of valves can reduce capital expense, maintenance costs, risk of leakage and pressure losses (pressure drop across the valve often accounts for 10 percent of total pressure rise required).

One user saved $20,000 by converting to variable speed pumping in an application involving injection of water into the combustion chamber of gas turbine engines. Since the system curve had relatively little static lift, the pump could be slowed to produce only the desired flow and head and still maintain good efficiency. A change from a fixed speed pump with throttling valve and bypass valve to variable speed eliminated the two valves, reduced the power requirement of the system from 100 hp to 75 hp and made the assembled skid of equipment smaller.

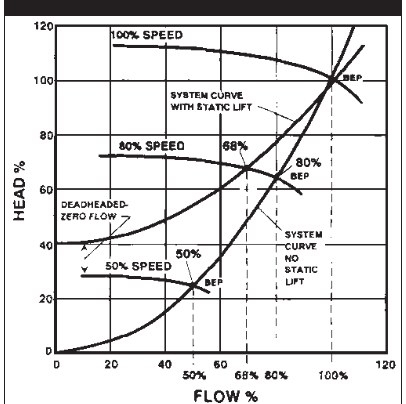
Dramatic power savings are available because of reduced head and flow points due to changing speed rather than by dis-charge throttling (Figure 4). For instance, by achieving 60 percent of design flow and head through variable speed, users can save 50 to 80 percent on energy costs compared to fixed speed pumping with a throttling valve.

Another advantage variable speed pumping offers is reduced heat to the pumped fluid. At constant speed, efficiency falls with reduced flow rate. The result of hydraulic inefficiencies is heat rise in the fluid. But variable speed pumps remain efficient at low flows (i.e., low speeds). Furthermore, horsepower levels are lower at low speeds, which means that heat input to the fluid is kept minimal. Variable speed pumping can thus be advantageous for light hydrocarbon and other volatile fluid applications.

## SELECTING THE RIGHT SIZE PUMP

Like any pumping application, variable speed pumping requires proper sizing of pumps. But unlike constant speed pumps, variable speed pumps are not selected for a single design point. To select the correct size pump, you should construct the desired head versus flow range for all anticipated specific gravities. Then be sure to specify a pump that can cover that range (Figure 5 shows a pump that cannot reach point B).

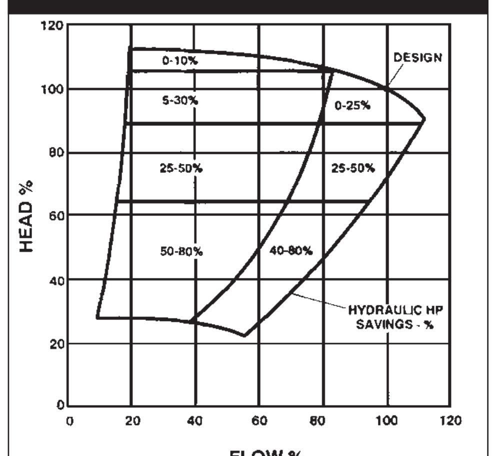
**FIGURE 3**




FLOW PROPORTIONAL TO SPEED - NO STATIC LIFT

**Effects of changing speed of a centrifugal pump**

**FIGURE 4**




**Hydraulic HP savings for a centrifugal pump**

You may need to specify a “fictitious” 100% speed point to ensure the pump has adequate range (Figure 6).

You must also ensure that NPSHA and motor horsepower are adequate for all combinations of flow and speed. NPSHR and efficiency vary approximately as the square of the speed (Figure 7). Since NPSHR increases with speed, in-ducers may be required to reduce NPSHR to available levels. Bearing loads and other pump characteristics must also be carefully examined.

## MOTOR-VARIABLE FREQUENCY DRIVE BEHAVIOR

One of the most common methods of changing motor speed is the AC Variable Frequency Drive (VFD). VFDs are designed to take advantage of the fact that speed, torque and horsepower of an AC motor are all related to the frequency and voltage of the electric power supply:

$$\text{Nominal speed} \quad \frac{2 \times hz \times 60}{\# \text{ of Poles}}$$

Torque Capability = F(volts/hz)

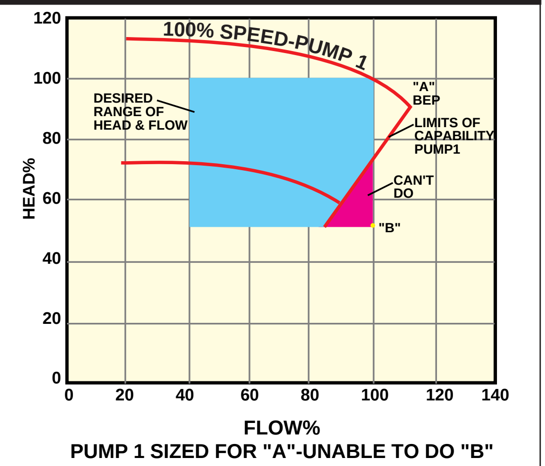
HP Capability = f(Torque x Speed)

VFDs convert incoming AC electrical power to DC then invert the DC power into variable frequency and voltage AC power. A number of technologies are available to switch the DC power through semiconductors to achieve the desired voltage or current pulses. The technologies differ in their ability to create optimal waveforms. Because the motor’s torque and torque ripple are determined by the current, the VFD affect motor and pump operation. Thus, by knowing the characteristics of the VFD output, you can select a VFD suitable for your pump.

Most VFDs produce a constant volt/hz ratio, thus constant motor torque capability up to name-plate frequency (typically 60 hz or 3550 rpm for a two-pole motor — see Figure 8). Horsepower capability therefore rises from zero at zero speed to full horsepower at nameplate speed. Above nameplate speed, the VFD cannot provide increasing voltage, so torque falls due to the falling volts/hz ratio. Horsepower capability, however, remains constant since speed is increasing. Electrically, induction motors can be run at approximately 90 hz in this configuration. But mechanical constraints may limit the safe running speed to well below 90 hz.

VFDs can be used to provide extra motor horsepower above 60 hz. Recall that motor torque capability is proportional to the volts/hz ratio. If a motor is designed for a given volts/hz ratio, and that ratio can be maintained at a higher speed, torque capability will be constant.

**FIGURE 5**




**Improper sizing to meet required duty points**

This technique can frequently be used with standard motors which are commonly wound for either 230 V or 460 V at 60 hz. By connecting for 230 V at 60 hz and operating to 460 V at 120 hz, both motor and horsepower capability and speed are doubled. Be sure to check with the motor manufacturer before using this technique. The motor may not have the thermal capacity or mechanical integrity to run at speeds considerably above 60 hz. Also, the motor may not be properly matched electrically to the VFD.

## SELECTING THE MOTOR

VFDs are most frequently used with the familiar NEMA B squirrel cage AC induction motors. Some special considerations for selecting motors for use with VFDs include cooling, efficiency and operation in hazardous (e.g., explosive) environments.

Motors operated on VFDs operate at higher temperatures due to the irregular shape of the electrical waveforms produced by the VFD. To ensure that the motor will not overheat, the motors are typically derated at full load from 3 to 10 percent, depending on the type of VFD used.

This additional heat makes motors operated on VFDs less efficient than when operated across the line. Thus, many users specify high efficiency motors for use with VFDs. High efficiency is not a requirement, but the extra copper and other features are advantageous for VFD use.

Increased heat can lead to environmental hazards. Motors proposed for use in hazardous (e.g., explosive) environments must be designed differently or derated. The skin temperature of a standard motor operating on a VFD could exceed an area gas autoignition temperature at nameplate horsepower. Motors nameplated for use in Class I, Division I, Groups C and D environments, for example, are available for VFD use but must generally be purchased with a “matched” VFD from a single supplier.

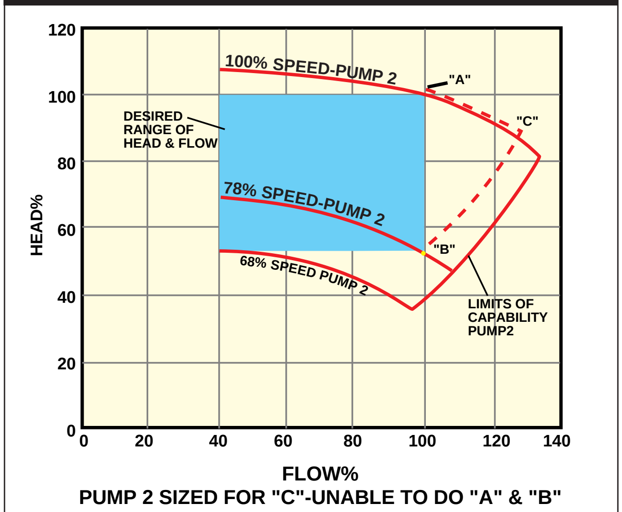
## SELECTING A VFD

Important factors for selecting VFDs include power supply voltage and frequency, amperage requirements, torque requirements and motor and load characteristics.

VFDs must be selected to match the power supply and frequency. Many VFDs are switch selectable for a number of voltage/frequency combinations.

You can determine the amperage requirement of a motor using the equation:

FIGURE 6




**Proper sizing to meet required duty points**

$$\text{AMPS} = \frac{\text{HP} \times 746}{\text{Volts} \times 1.732 \times \text{Motor Efficiency} \times \text{Motor Power Factor}}$$

Nominal horsepower ratings are usually given by the VFD vendors but in some instances a VFD will only produce the stated nominal horsepower if a high efficiency motor is used. Unlike motors, VFDs generally have no continuous service factor. Momentary overloads, however, are permitted. VFDs generally exceed 97 percent efficiency at full load.

VFDs are designated constant torque or variable torque, depending on their current overload capacity. Variable torque VFDs can produce 110 percent of rated current for one minute. Constant torque VFDs can produce 150 percent of full load current for one minute and even more for shorter periods. Variable torque VFDs are generally used for centrifugal pumps.

VFDs must be matched to the load and motor characteristics. Certain VFDs, known as Current Source Inverters or CSIs, may require addition or deletion of capacitor banks to match the load and motor characteristics. The more commonly used Pulse Width Modulation and Six Step VFDs do not require this matching. They are suitable for a wide variety of motors. Most VFDs operate on 480 V input and produce a maximum of 480 V output. If a higher voltage motor is desired, you can install a step-up transformer between the VFD and the motor or use a higher voltage VFD.

## APPLICATION CONSIDERATIONS

Be sure the motor will be capable of delivering enough torque to the pump. Motor torque capability (including breakaway or start-up torque) must exceed pump torque required at every speed. Generally, if the motor and VFD are properly sized for 100 percent speed, they will be adequate at lower speeds. However, in certain instances, such as applications with high suction pressure, motor and VFD sizing may be governed by start-up conditions. VFDs on positive displacement pumps must routinely be oversized to provide sufficient start-up torque.

Avoid lateral critical speeds. As an example, API Specification 610 states that depending on the unbalanced response amplification factor, a pump may not be operated between 85 percent and 105 percent of its critical speed. Adherence to these rules can block out a large portion of the allowable performance envelope of the variable speed pump (Figure 9). Fortunately, many pumps are of a stiff staff design and will operate below their first lateral critical speed. A vendor may be able to change the mechanical design to raise or lower the critical speed to provide full range speed adjustment.

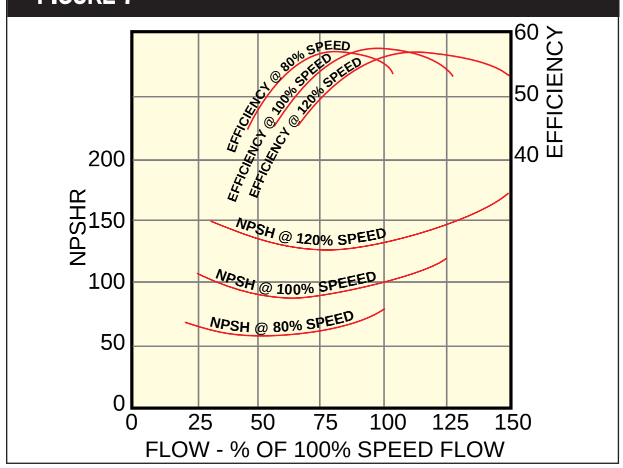
Be aware of torsional critical speed. Torsional critical speeds are resonant frequencies at which motor and driven equipment shafts can begin to oscillate with angular displacement as a result of torsional excitation. VFDs can cause torsional excitation problems known as torque ripple. For example, rather than delivering a continuous 295 ft-lb of torque, a VFD-driven, 200 HP motor may deliver torque cycling between 250 and 340 ft-lb at some 21,000 cycles per minute. This oscillation could be damaging. Clearly, careful analysis and selection of the VFD, motor, coupling and pump train are needed to avoid torsional problems.

## ENVIRONMENTAL CONSIDERATIONS

To avoid potential problems in your application of VFDs, you must take a few precautions regarding their environment.

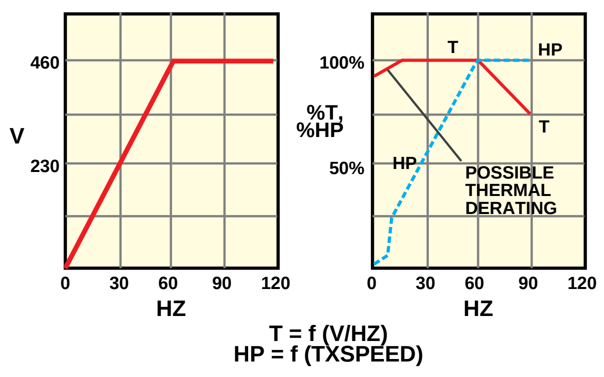
Locate VFDs indoors. Units can be placed outdoors with the proper enclosure, but the cost of the enclosure can run into thousands of dollars. Fortunately, the VFD can be up to several hundred feet

FIGURE 7




**Centrifugal pump NPSHR and efficiency vs. speed**

FIGURE 8




**Performance of conventional variable speed motor**

from the motor. So it can be indoors even if the motor is outdoors.

Derate for high temperatures and high elevations. If operated above 104º F, VFDs must be derated. They must also be derated if used at elevations above 3300 ft.

Be cautious of power supply. VFDs are sensitive to stiffness and irregularities in the electrical supply. You may need to install a line reactor or isolation transformer between the VFD and supply main if the feed transformer is very stiff (high KVA). Input line reactors or isolation transformers may also be necessary to prevent the VFD from feeding electrical noise back into the supply main. Such noise can distort instrument signals if they are fed from the same supply transformer as the VFD.

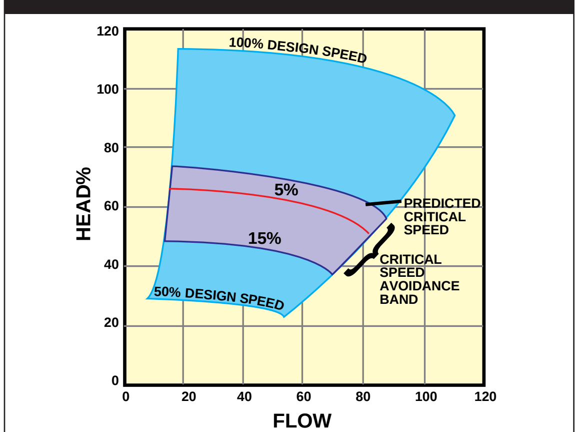
## IS IT WORTH IT?

Despite the list of precautions, variable speed pumping can save you money. As shown, you can eliminate the need for throttling valves. You may be able to use one variable speed pump in place of two fixed speed pumps.

VFDs also eliminate the need for a motor starter. Variable speed pumping often reduces power requirements. And some electrical utilities provide rebates for companies that use energy saving devices such as VFDs. Rebates can be up to one-third the purchase price of the device. Other cost savings come through better process control due to lower heat inputs and fluid shear.

These savings frequently pay back the costs of utilizing variable speed pumping (such as the cost of the VFD, possibly extra costs for high-efficiency motors and possibly oversized pumps). Payback periods of as little as one year are typical when using variable speed pumping.

FIGURE 9




**Avoiding lateral critical speeds**

## THE FUTURE

Variable speed pumping will become more popular as the technology establishes its track record. And as more system and plant engineers design for variable speed operation early in the development cycle, benefits beyond energy conservation will become apparent.

Advances in VFD technology will also increase user acceptance. New features such as greater adjustment in operating parameters will make VFDs easier to use and integrate into a system.

Improved reliability and fault tolerance will make VFDs easier to apply. You can expect manufacturers to add adjustment capabilities of output voltage and current waveforms to optimize motor efficiency and smoothness. Improvements in power semiconductors will provide higher efficiency and smoother output.

Sizes of VFDs will diminish as components on circuit boards are integrated into chips. Reduced size and improved efficiency will allow packaging to be more compact and environmentally rugged, which will allow placement even in hazardous environments.

Prices will come down, possibly by up to 25 percent over the next five years.

Even today, you can achieve greater flexibility, energy savings, equipment savings and extra head and flow through variable speed pumping, provided you take extra care in assembling an appropriate combination of pump, motor and VFD. With improvements in technology, more and more users will begin to take advantage of variable speed pumping. ■

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