APPLICATION OF VARIABLE SPEED ELECTRIC MOTORS FOR PUMPS

by

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ABSTRACT

Pumps operated with variable and higher speed electric motors provide numerous benefits such as greater range of flow and head, higher head from a single stage, valve elimination, and energy savings. To achieve these benefits, however, extra care must be taken in selecting the appropriate system of pump, motor, and electronic motor driver or VFD for optimum interaction with the process system.

Successful pump selection requires knowledge of the full anticipated range of heads, flows, and specific gravities. Motor selection requires appropriate thermal derating and, at times, a matching of the motor's electrical characteristic to the VFD. VFD selection requires an understanding of the electronic technology employed to determine what effect the VFD may have on the mechanical aspects of the driven equipment train. Despite these extra design considerations, variable speed pumping is becoming well accepted and widespread.

In a simple manner, a discussion is presented on how to identify the benefits that variable speed offers and how to select components for trouble free, reliable operation.

INTRODUCTION

Historically, pump applications have benefited from the use of different forms of variable speed. Over the last decade, electronic drives used with variable and higher speed motors have improved their cost to performance ratio and are now considered the variable speed technology of choice for many pump applications. Despite the obvious advantages of both variable and higher motor speed, the use of these specialty drive systems in the process plant environments has been rather limited. A thorough overview is provided of the available benefits and the design considerations necessary to identify attractive variable speed opportunities and select components to provide greatest flexibility and reliability for proper interaction with the process system.

Benefits include pump performance flexibility—the ability of a single pump to cover a broader range of flows and heads, higher allowable head per stage, energy savings, and possible throttling or bypass valve elimination. Design considerations apply to pump, variable speed motor, and electronic drive selection. The pump must be selected to provide the proper range of head and flow, NPSH, and mechanical integrity. The motor must be selected considering special electrical and heating phenomenon, and the electronic drive must be selected considering such factors as the base electronic technology employed to change speed, which has a mechanical impact on the motor and driven equipment.

As described, full identification and consideration of the issues involved in variable speed pumping can be relatively complex. The pump vendor must work with the user to provide an effective, reliable solution.

HISTORY OF VARIABLE SPEED DEVELOPMENT

Early means of varying pump speed were primarily mechanical such as drive belts with selectable sheave sizes. These units provided a fairly wide range of speed and were efficient, but had the disadvantages of being maintenance intensive and requiring the equipment to be stopped for adjustment. Advancements in mechanical and electromechanical devices improved upon early systems, providing a wider range of adjustment capability. Electronics, however, held promise for the optimum in speed adjustability.

Beginning in the 1960s, electronic drives were developed for varying the speed of AC induction motors, the most commonly used industrial motors. These devices, commonly called variable frequency drives or VFDs, use solid state semiconductors to transform fixed frequency AC power available from the electric utility into varying frequency power. This transformation allows variable speed motor operation and operation of motors at higher than standard speed.

The key to the advancement of VFDs has been the development of solid state semiconductors of higher amperage and voltage levels. VFDs in the 1960s typically used semiconductors called silicon controlled rectifiers or SCRs. These SCRs were large, expensive, and difficult to turn on and off quickly, requiring banks of large, heavy capacitors and complex control circuitry.

As semiconductor technology advanced during the late 1970s, new devices such as gate turn-off thyristors or GTOs appeared, providing the ability to easily turn off the power without capacitor banks or complex control circuitry. This advancement gave birth to the modern VFD characterized by low cost, relative simplicity and flexible, reliable operation.

Beyond the GTOs have come insulated gate bipolar transistors or IGBTs that provide rapid switching of higher power levels in smaller packages. This technology is providing continued advancement in the most popular VFD style today, the pulse width modulated, or PWM, drive, described later.

The continued advancements of VFD technology have provided wide application possibilities. VFD usage today is widespread in a number of applications as depicted in Figure 1. Despite the large numbers of VFDs in use today, total usage is less than predicted by many industry prognosticators, based on the numerous benefits of VFDs. One possible reason for the modest growth to date is fear of the unknown and a lack of knowledge of VFD benefits. The steps necessary to successfully apply VFDs to pumps to counter these two problems are detailed.
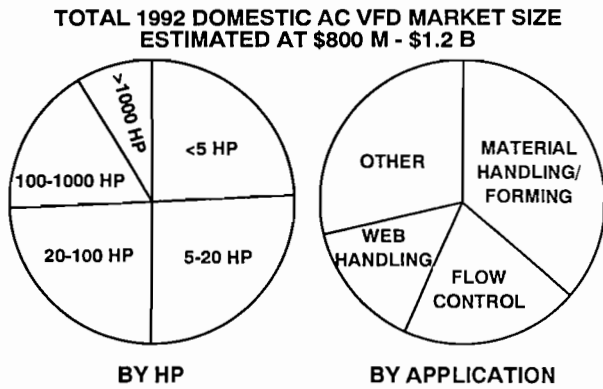
TOTAL 1992 DOMESTIC AC VFD MARKET SIZE ESTIMATED AT $800 M - $1.2 B

Figure 1. Variable Frequency Drive Usage.

VARIABLE SPEED PUMP BEHAVIOR

To understand how a variable speed pump interacts with a customer's system, the following discussion will first examine how a fixed speed pump interacts with the system, secondly, discuss basic variable speed pump behavior, and finally examine the interaction of a variable speed pump with the customer's system. Centrifugal and positive displacement pumps are discussed, with primary emphasis on centrifugals, which have more operational aspects to be considered when changing speed.

Fixed Speed Pump—System Interaction

The most common forms of flow control—discharge valve throttling for centrifugal pumps and bypass flow for positive displacement pumps are demonstrated in Figures 2 and 3.

Centrifugal Pumps

In a centrifugal system, the process demand as measured at point A-A in Figure 2 is represented by a fixed system curve. Fixed speed pump performance is also represented by a fixed curve. With the discharge throttling valve fully open, the pump seeks equilibrium with the system and operates at point 1, the intersection of the pump curve and the system curve. At point 1, the pump will produce Q_1 and H_1.

To change flow to Q_2 in the fixed speed pump system, the throttling valve is gradually closed, increasing the steepness of the system curve as seen by the pump at point B-B. (The system curve at A-A, remains unchanged.) Closing the valve causes the pump to run back on its curve to point 2. When at point 2, the flow is Q_2, as desired. The pump, which can only run on its fixed curve, produces H_3 at point B-B in the system, but the head at point A-A in the system is H_2, which is the head which corresponds to Q_2 at A-A according to the fixed system curve. The centrifugal 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!

Positive Displacement Pumps

In a positive displacement system, the same process demand and resultant system curve applies, as shown in Figure 3. Likewise,
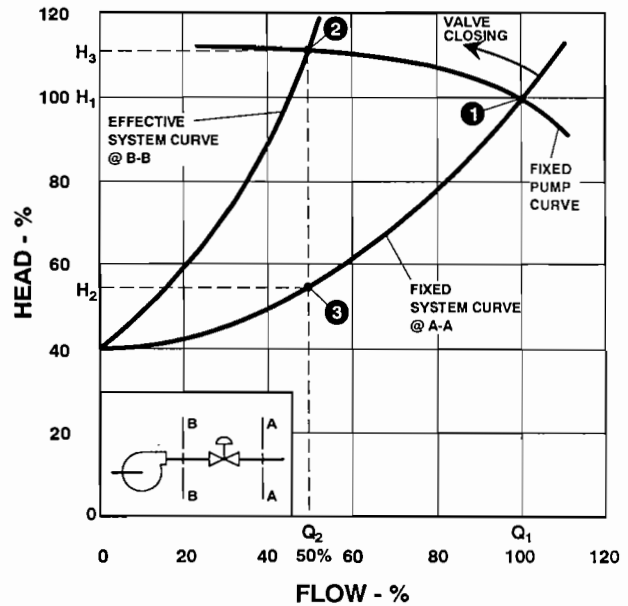

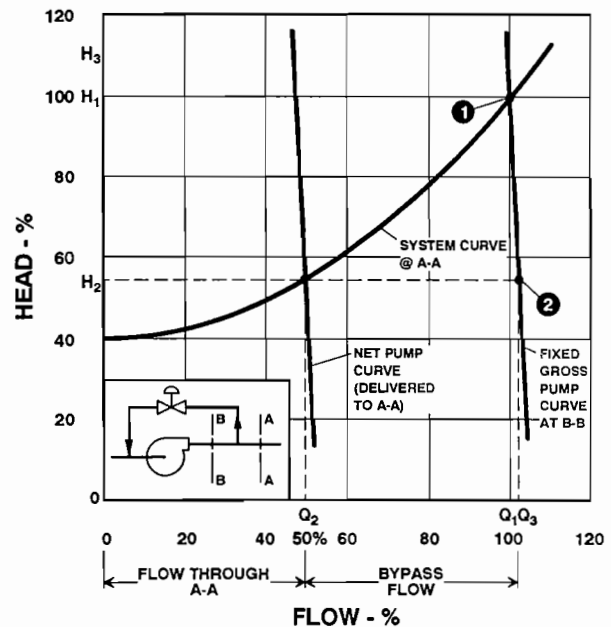*Figure 2. Fixed Speed Centrifugal Pump Operation.*

Figure 3. Fixed Speed Positive Displacement Pump Operation.

fixed speed pump performance is represented by a fixed curve and the pump seeks equilibrium at point 1 - Q_1, H_1. To get Q_2, the pump bypass valve is opened, allowing flow to bypass back to pump suction until the flow to the system through point A-A is the desired Q_2 at H_2. A new pump curve representing the flow to the system (net of the bypass flow) is also shown, shifted to the left of the fixed pump curve. The pump, however, can only operate on its fixed curve, in this case at point 2, producing Q_3 at H_2. The positive displacement pump thus produces Q_3 at H_2, but only Q_2 at H_2 is delivered to the system. The additional flow $(Q_3 - Q_2)$ is wastefully circulated endlessly in the bypass loop!

Basic Variable Speed Pump Behavior

The basic variable speed performance of centrifugal and positive displacement pumps is demonstrated in Figures 4 and 5.
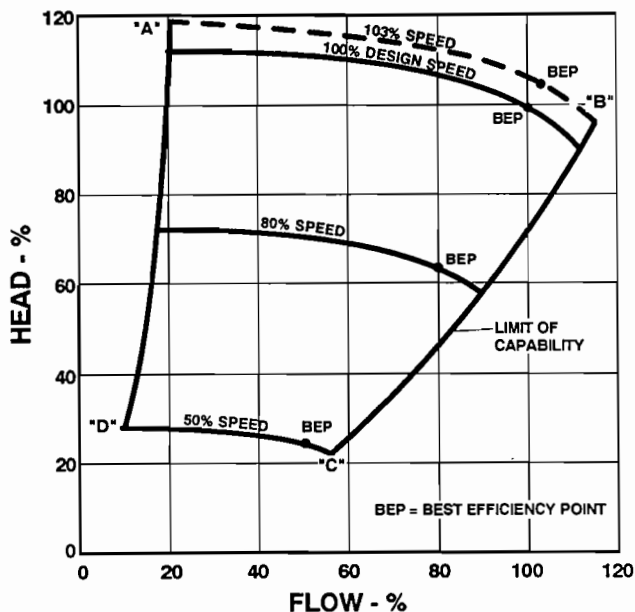
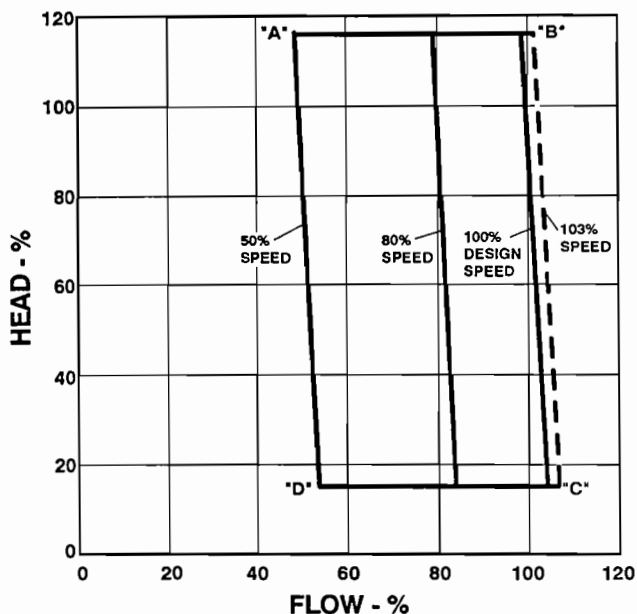*Figure 4. Variable Speed Centrifugal Pump Operation.*

Figure 5. Variable Speed Positive Displacement Pump Operation.

Centrifugal pumps running above or below design speed retain their characteristic curve shape, providing greatly varying head with speed changes. Positive displacement pumps also retain their characteristic curve shapes, providing greatly varying flow with speed changes. Centrifugal pump performance changes with speed in accordance with the affinity laws, as shown in Figure 6. Positive displacement pump performance changes with speed by shifting the pump performance curve in direct proportion to motor speed.

Speed variability thus gives the advantage of tremendous range-ability allowing direct provision of any headflow combination in the envelopes A-B-C-D in Figures 4 and 5. (The upper and lower speed limits of 103 percent and 50 percent shown on Figures 4 and 5 are arbitrary. With the appropriate precautions, pumps can be run at much higher and lower speeds.)
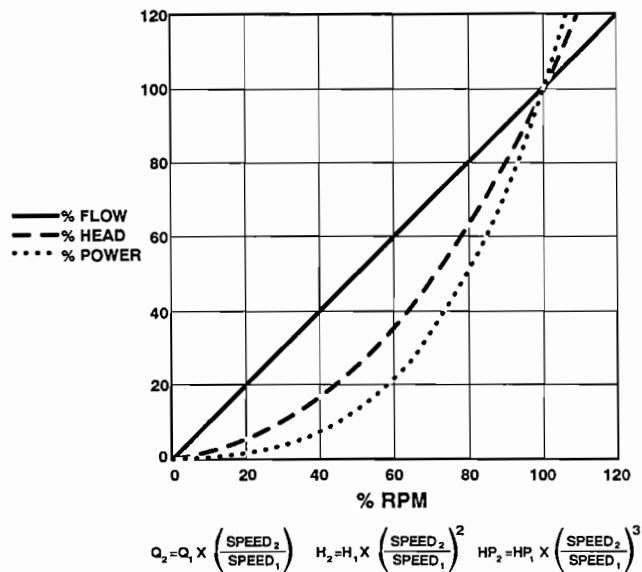

$$Q_2 = Q_1 \times \left(\frac{SPEED_2}{SPEED_1}\right) \qquad H_2 = H_1 \times \left(\frac{SPEED_2}{SPEED_1}\right)^2 \qquad HP_2 = HP_1 \times \left(\frac{SPEED_2}{SPEED_1}\right)^3$$

Figure 6. Centrifugal Pump Affinity Laws.

Variable Speed Pump-System Interaction

With the knowledge of basic variable speed pump operation, examine variable speed pump-system interaction and compare it to fixed speed pump-system interaction. Rather than wastefully develop head and throttle it across a valve, or endlessly recirculate fluid through a bypass loop, variable speed can be used to produce the exact flow and head desired. In most instances, no throttling or bypass valve adjustment is needed.

The amount that flow changes with a given speed change is strongly influenced by the system curve shape. Flow is essentially proportional to speed *if there is no static lift*, as shown in Figures 7 and 8. When a significant static lift exists, flow is not proportional to speed for centrifugal pumps, while it is very closely
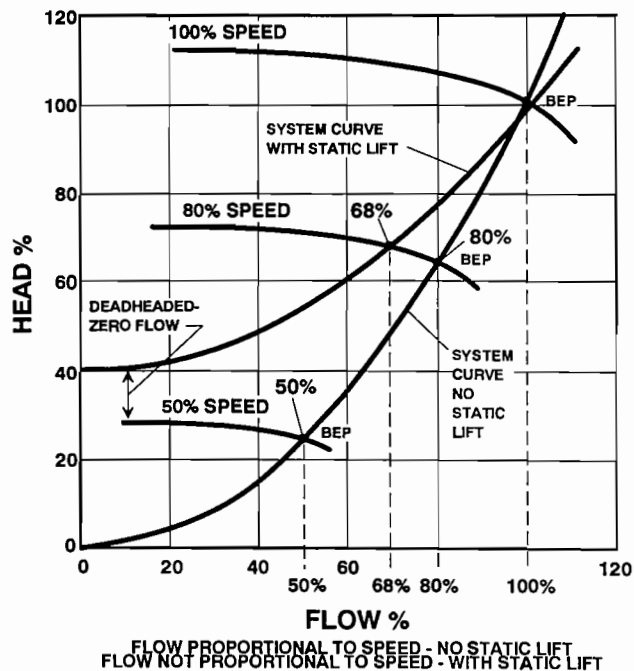

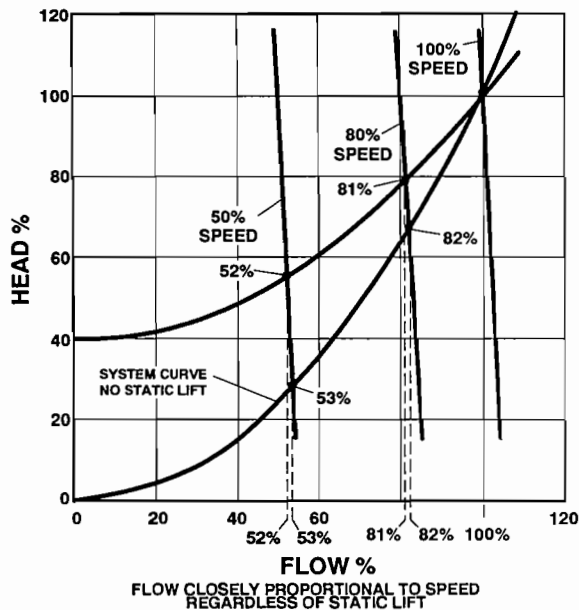*Figure 7. Speed Change Effects-Centrifugal Pump.*

Figure 8. Speed Change Effects-Positive Displacement Pump.

proportional for positive displacement pumps (Figures 7 and 8)! This behavior is not a violation of the centrifugal affinity laws, but only a reflection of the interaction of the system curve shape with the inviolate pump affinity laws. This basic pump curve-system interaction is fundamental to the proper application of variable speed pumps.

BENEFITS OF VARIABLE SPEED PUMPING

The fundamental variable speed pump-system interaction provides a number of significant benefits.

Performance Flexibility

As shown in Figures 4 and 5, centrifugal and positive displacement pumps can cover a broad range of hydraulic conditions, producing exactly the desired flow and head. If a user is unsure of his required flow and head at pump selection time, variable speed can be used in the field to produce exactly the required conditions. If a user has a need for a number of pumps with similar but not identical duty points, he can buy identical pumps (for parts interchangeability) and fine tune their performance with speed. This flexibility also allows for changes in specific gravity and viscosity. From a pump manufacturer's point of view, use of this rangeability can allow a reduction in the number of models stocked to cover a given hydraulic envelope.

Higher Head Per Stage Available

Pumps operated at higher speed produce higher flow. Centrifugal pumps operated at higher speed also produce higher head. Utilization of higher speed can thus eliminate the need for multiple stages.

When pumps are operated at higher speeds, however, radial bearing and other loads can increase dramatically, often with the square of the speed. Centrifugal pump $NPSH_R$ also increases with the square of the speed. Cavitation damage, if allowed to occur, can be more severe.

Throttling or Bypass Valve Elimination

When speed can be used to adjust flow, there is often no need for a throttling or bypass valve. Elimination of the valve saves capital

cost, maintenance, the pressure drop across the valve (often 10 percent of total required pressure rise) and valve stem leakage. The user should, however, use caution when eliminating a throttling valve, since the interaction of the pump with the system could be influenced by the valve in such areas as minimum flow stabilization. Some centrifugal pumps, for instance, can be operated to a noticeably lower flow if a valve or other form of restriction is placed within five feet of the pump's discharge flange. However, minimum allowable stable flow is reduced linearly with speed and thus, depending on system interaction, lower flow may be available from a VFD operated pump with no valve than from a fixed speed pump with valve. The pump vendor is usually best positioned to advise on the need for a valve to provide stable variable speed performance.

Energy Savings

Compared to discharge valve throttling and flow bypass, variable speed pumping can save considerable energy at lower than design flows and heads. Energy savings are greatest for centrifugal pumps when system head is changing considerably. The energy savings are greatest for positive displacement pumps when flow is changing considerably.

As is shown in Figure 2 for centrifugal pumps, a fixed speed pump using discharge throttling would produce H_3 at Q_2 to deliver the desired H_2 at Q_2 to the system. Alternatively, by using variable speed, only Q_2 at H_2 need be produced if the proper speed is selected. Hydraulic horsepower savings from using variable speed in this manner is displayed in Figure 9 for centrifugal pumps operating at off design conditions. Similar horsepower savings are displayed in Figure 10 for variable speed positive displacement pumps which eliminate bypass flow. Note that maximum savings for centrifugal pumps is in cases with large head changes and for positive displacement pumps in cases with large flow changes.
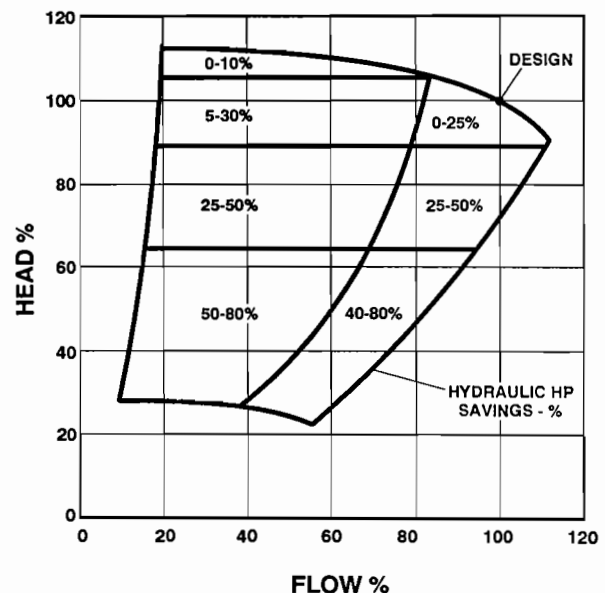

Figure 9. Hydraulic HP Savings-Centrifugal.

To use these charts, locate the desired off design point and read from the chart the percentage amount of energy saved when reaching an off-design point by variable speed, rather than by discharge throttling or flow bypass. These charts refer to the hydraulic horsepower savings of the pump. Any gearbox or other ancillary loads may vary with speed in a different fashion. Offset-
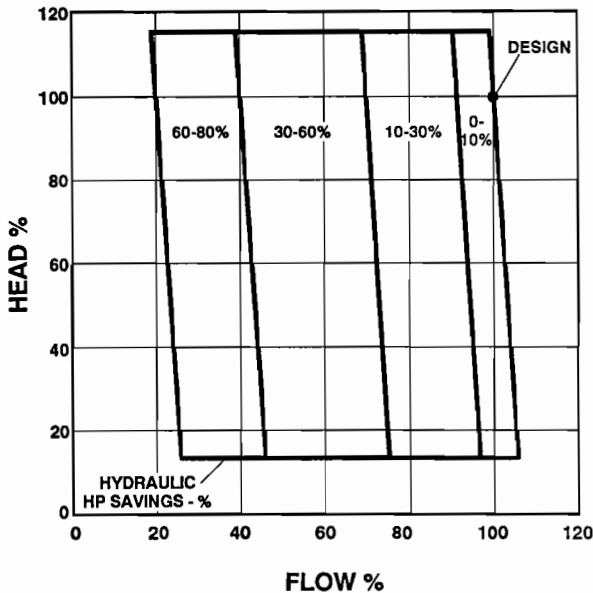
Figure 10. Hydraulic HP Savings-Positive Displacement.

ting these savings are the increased losses in the VFD and motor at lower speeds and loads as described later.

Reduced Heat to Pumped Fluid

Centrifugal pump efficiency is typically maximum at its design point. At constant speed, as flow is reduced, efficiency falls. However, at this lower efficiency and flow, the total heat input into the pumped fluid in the pump case due to hydraulic inefficiency remains approximately unchanged. Since flow is lower, the temperature rise of the fluid through the pump case is increased considerably at low flow in this constant speed mode. However, if lower flow is achieved by lowering speed, as shown in Figure 7, pump efficiency can remain high at low speed. This will considerably reduce total heat input into the pumped fluid. Thus, with variable speed, even given the lower flow, total heat rise of the fluid will generally be reduced, rather than increased as in the fixed speed method. This can be of considerable benefit when pumping light hydrocarbons and other volatile fluids.

Product Development/Troubleshooting

Whether in the development lab or the process plant, a variable speed motor can be extremely useful for troubleshooting by running pumps at various speeds to determine pump or system critical speeds, resonances, or other mechanical phenomenon.

Utility Rebates

Some electric utilities offer substantial rebates, at times as much as one-third or more of the cost of a VFD as an energy savings incentive.

PROPER PUMP SELECTION

Selection of the proper pump for variable speed usage is enhanced by knowledge of the customer's system curve shape and any special effect of variable speed motors. The following steps should be taken in sizing a variable speed pump.

Determine Desired Range of Flows and Heads

This information, critical in proper sizing, is usually available, but not frequently transmitted to the pump vendor. The pump vendor should be given the flow and head limits for all anticipated

specific gravities as shown in Figure 11, and a pump should be selected to accommodate the entire range, if possible.
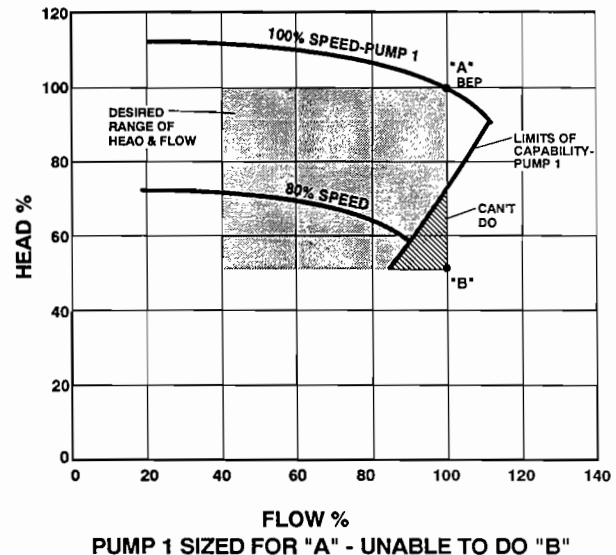

FLOW %
PUMP 1 SIZED FOR "A" - UNABLE TO DO "B"

Figure 11. Improper Sizing to Meet Required Duty Points.

Size Pump for Desired Duty Points

If possible, a single pump should be selected to cover all duty points. As shown in Figure 12, for a centrifugal pump, this may require selecting a pump with an extra flow capacity at full speed to ensure that it provides sufficient flow at reduced speed. That is, if the customer's duty points are A and B, rather than selecting a pump for duty point A, a pump should be selected for a fictitious duty point C, which will still produce sufficient flow for point B when the pump is slowed down.

FLOW %
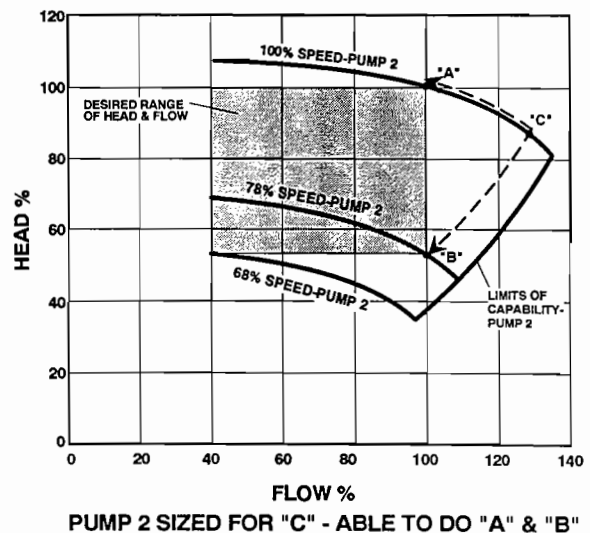**PUMP 2 SIZED FOR "C" - ABLE TO DO "A" & "B"**

Figure 12. Proper Sizing to Meet Required Duty Points.

Determine $NPSH_R$ and Efficiency Vs Speed

Centrifugal pump $NPSH_R$ varies with the square of the speed as shown in Figure 13. The efficiency curve of the pump also changes as shown in Figure 13. Minimum and maximum efficiencies
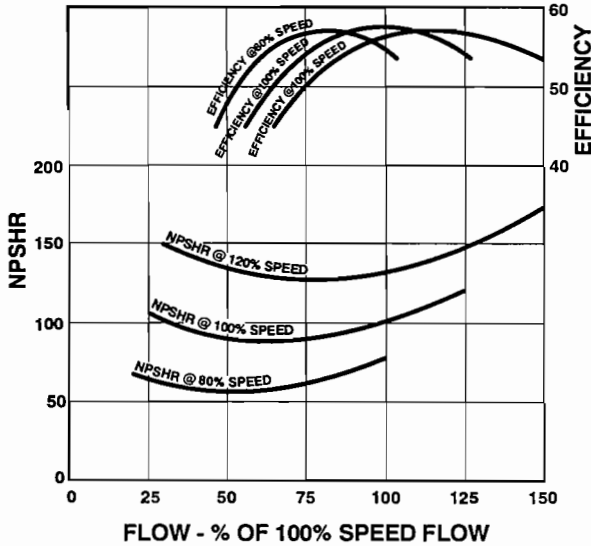
Figure 13. Centrifugal Pump NPSH$_R$ and Efficiency Vs Speed.

remain unchanged, but the flows at which they occur are shifted by the amount of the speed change. Care must be taken in pump selection to ensure that NPSH$_A$ and motor horsepower are adequate for all combinations of flow and speed. Since NPSH$_R$ is increased at higher speed, inducers may be required to reduce NPSH$_R$ to available levels.

Match Required Pump Torque to Available Motor Torque

Available motor torque must exceed required pump torque at startup and at every speed. For centrifugal pumps this is not generally a concern. As will be shown later, motor torque capability remains constant as speed is lowered, while the centrifugal pump torque required always falls rapidly, its exact value being dependent upon the shape of the system curve. This relationship for the case of zero static lift is shown in Figure 14. Starting torque for a centrifugal pump is generally small and easily provided for
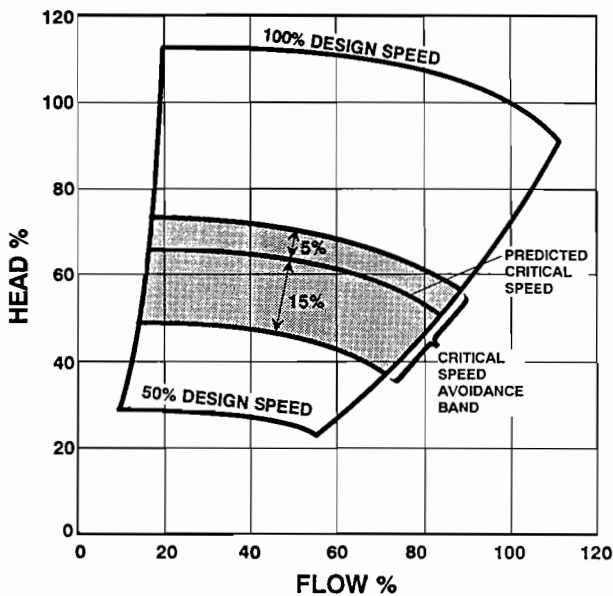
by a variable speed motor. On occasion though, some forms of centrifugal pumps with high suction pressures may have a high instantaneous break away torque required.

Positive displacement pumps require more careful matching of pump torque to motor torque at start-up and during operation. At startup, a positive displacement pump must develop full system head to allow fluid to flow. If the pump is being started into a high head system, significant motor torque at low speed will be required to provide sufficient force to push the fluid through the pump into the system. An oversized VFD may be required to produce sufficient amperage to start the motor in this condition. A centrifugal pump, on the other hand, even if starting against a high head system, can operate dead headed at low speed with very little torque, thus starting easily. Steady state operation of a positive displacement pump could require high torque at low operating speeds as well. Since the positive displacement pump can produce full head at any speed (if the system demands it), and is essentially a constant efficiency device, horsepower may only fall linearly with speed (in a constant head demand system) and, therefore, torque may remain constant throughout the speed range. Further, the stroking action of some forms of positive displacement pumps, such as reciprocating pumps, cause instantaneous torque peaks above average peak values. The possibility of high torque required across a broad speed range, coupled with high instantaneous torque, requires use of a constant torque VFD as described later.

Avoid Lateral Critical Speeds

Lateral critical speeds must be avoided. API 610 states that, depending on the unbalanced response amplification factor, a pump may not be operated between 85 percent and 105 percent of its predicted critical speed. Adherence to these rules can block out a large portion of the allowable performance envelope, as shown in Figure 15. This potential problem indicates the need for careful application of variable speed technology with additional knowledge of the customer's system and desired duty points to ensure a careful matching of pump performance to the desired range of flow and head. Fortunately, most pumps are of a stiff staff design and will operate below their first lateral critical speed. However, if faced with this block out, a pump vendor may be able to change the mechanical design to raise or lower the critical to provide full range speed adjustment.
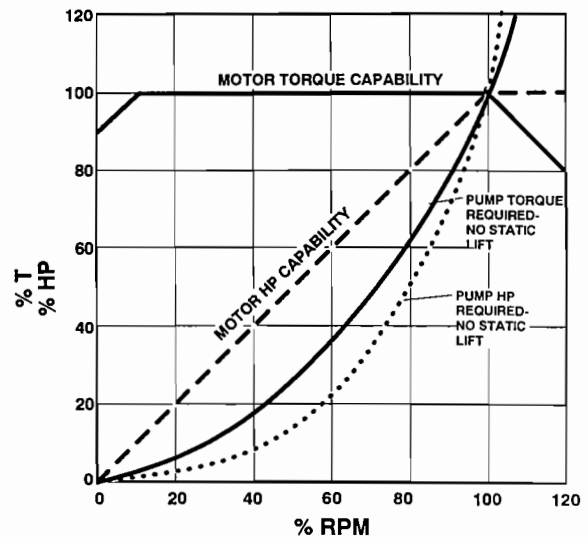

Figure 14. Motor Capability Vs Centrifugal Pump Requirements.

Figure 15. Lateral Critical Speed Avoidance.

Account for Torsional Critical Speeds

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 known as torque ripple. Typically, torque ripple is not a concern for units below 200 hp.

In fixed speed systems, torsional excitation may occur at some multiple of fixed motor speed such as 2 × running speed due to coupling misalignment. If this excitation is at a torsional critical frequency, the equipment can suffer serious damage depending on the amplitude of the excitation and the resulting stress on the system. Frequently, however, the pump design or coupling angular stiffness can be changed to avoid this fixed speed induced torsional problem.

With variable speed, however, the situation is complicated considerably since the base speed changes and the VFD causes torque ripples due to electrical harmonics at multiples of base frequency or speed. Electrical harmonics are often produced at 6n ±1 × the base frequency where n = 1, 2, 3, etc. Thus, electrical harmonics exist at 5 and 7 × base frequency, 11 and 13 ×, etc. These electrical harmonics combine to form mechanical torque ripples at 6n × base frequency, that is 6 ×, 12 ×, etc. The 6 × ripple has the largest amplitude and is generally the only one of concern. Occasionally, the 12 × will be of importance, rarely the 18th or higher due to their very low amplitude.

The following table lists the magnitude of torque ripple for several types of VFD switching technologies which are described later.

VFD SWITCHING TECHNOLOGY	TYPICAL WORST CASE AMPLITUDE OF VFD - INDUCED TORQUE RIPPLE*
PWM	5 - 10%
SIX STEP	10 - 20%
CURRENT SOURCE	20 - 30%

*Torque ripple delivered to the motor rotor as a % of base torque.

For a 200 hp 3,550 rpm motor, full load torque is 295 ft/lb. A typical six step drive produces torque ripple of 15 percent of 295 or 44 ft/lb. Thus, torque oscillates from 251 to 339 ft/lb at a frequency of 6 × the base frequency or speed, that is 6 × 3,550 = 21,300 cycles per minute. Actual torque ripple can be controlled by special techniques in some VFDs, and can be as low as only a percent or two. The amplitude of the ripple is a percentage of full load torque, and remains at that percentage (for a given speed), regardless of the actual base torque delivered.

If torsional excitation from VFD-induced torque ripple occurs at the torsional critical response frequency, analysis must be performed to determine if the resultant stresses are harmful. If the predicted stresses are high, they can sometimes be lessened by using a torsionally soft coupling, increasing shaft diameters, etc. Torsional excitation can especially be a problem at startup. Clearly, successful avoidance of possible torsional problems relies upon careful analysis of the VFD, motor, coupling, and pump train considering the characteristics of the actual VFD to be employed. This analysis is usually best left to the pump vendor in conjunction with the VFD supplier.

PROPER VARIABLE SPEED MOTOR SELECTION

Basic Motor Behavior

AC induction motor speed is governed by the frequency of the electric power supplied to it. Torque capability is proportional to voltage divided by frequency. Horsepower capability is proportional to torque × speed.

$$\text{Speed} = f \text{ (hz)} \tag{1}$$

$$\text{Torque Capability} = f(V/hz) \tag{2}$$

$$\text{HP Capability} = f \text{ (Torque x Speed)} \tag{3}$$

As most commonly configured, a VFD produces constant volts/hz, and as such, constant motor torque capability up to nameplate frequency (typically 60 hz, or 3550 rpm for a two pole motor) as shown in Figure 16. For purposes of this paper, 460 Volt, 60 hz, 3 phase power will be described as the standard. VFDs are also available in other voltage/frequency combinations. Horsepower capability, therefore, rises from zero at zero speed to full horsepower at nameplate speed. Above nameplate speed, the VFD is unable to provide increasing volts, and thus torque falls due to falling volts/hz ratio. Horsepower capability, however, remains constant since speed is increasing. Actual torque and horsepower will match the load requirements and be provided by varying the current. Electrically, induction motors can be run to approximately 90 hz in this configuration. Mechanically, however, the safe running speed may be well below 90 hz.
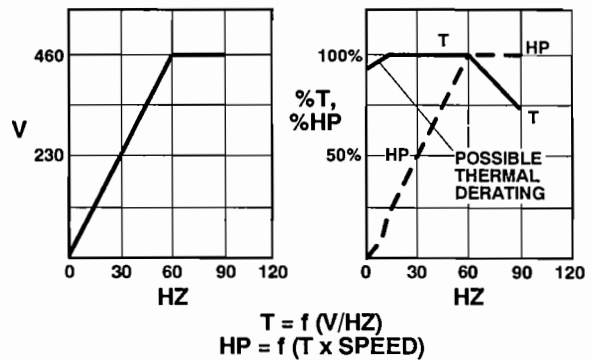

Figure 16. Conventional Variable Speed Motor Performance.

Enhanced High Speed Motor Behavior

VFDs can be used to provide extra motor horsepower above 60 hz. Motor torque capability, per Equation (2), is proportional to volts/hz. If a motor is designed for a given volts/hz, and the volts/hz can be maintained to a higher speed, torque capability will be constant. Horsepower capability, therefore, can be increased at that higher speed, obtaining more than nameplate horsepower from a motor.

Many conventional AC induction motors up to 100 hp can typically be connected for 230V, 60 hz or 460 V, 60 hz. If the motor is connected for 230V, 60 hz and is supplied with 230V, 60 hz from the VFD (which most VFDs can do), it will produce nameplate horsepower (note however that the motor will draw twice the amps it would at 460 V). If the VFD frequency is increased above 60 hz, while maintaining constant volts/hz to maintain constant torque (again as most VFDs can do), the horsepower will increase linearly with speed up to 120 hz, providing theoretically two times the 60 hz horsepower capability, as shown in Figure 17. At this point, the voltage will be 460 V. This combination of volts and hz provides superior motor performance over the conventional method of reaching 460 V at 60 hz and holding at 460 V to 90 hz. Taking this technique further, the motor can be wound for 153 V at 60 hz, 460 V at 180 hz, providing triple hp capability at triple speed, etc.
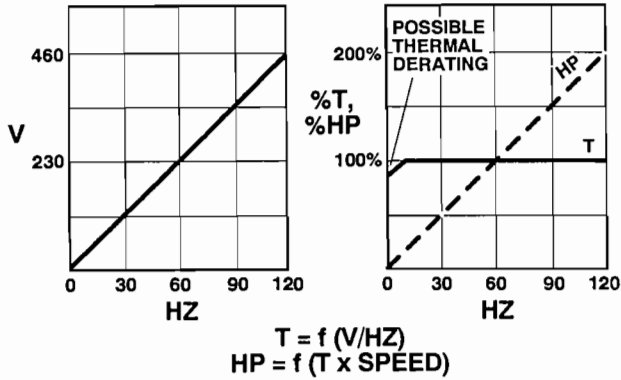
$$T = f \ (V/HZ)$$
$$HP = f \ (T \times SPEED)$$

Figure 17. Enhanced Variable Speed Motor Performance.

The motor manufacturer must be consulted before using this technique, because the motor may not have the mechanical integrity to run at speeds considerably above 60 hz. Also, this type of motor may not be properly matched electrically to the VFD. As an example, refer to Figure 18 in which is shown the extremely rough current waveform of a motor connected for 230V, 60 hz and 460 V, 120 hz with and without an impedance matching line reactor between the VFD and motor. Without the reactor, the motor could not exceed 20 hz. With the reactor, the motor ran successfully at the design level of 120 hz. The sizing of such line reactors requires careful consideration of the electrical characteristics of the VFD and motor.
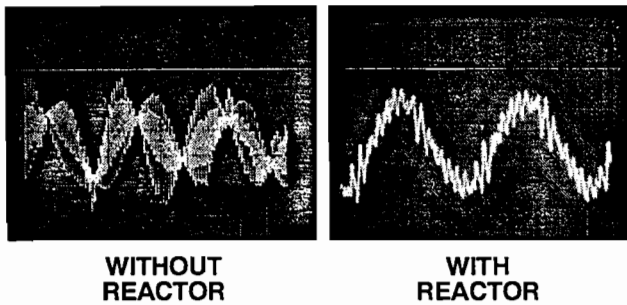

WITHOUT   WITH
REACTOR   REACTOR

Figure 18. Current Waveform from High Speed Motor.

Selecting a Motor

VFDs are most frequently used with NEMA B motors. In general, the following factors should be taken into account when selecting a motor for VFD usage.

Speed

Nominal speed of the induction motor is given by the equation:

$$\text{speed (rpm)} = \frac{2 \times HZ \times 60}{\# \text{ poles}} \qquad (4)$$

Actual speed is slightly less due to motor slip.

Derating for Cooling

Motors operated on VFDs operate hotter than across the line due to the irregular shape of the electrical waveform produced by the VFD. Thus, they must be derated at full load by three to ten percent depending on the type of VFD used.

Efficiency Considerations

Motors operated on VFDs are less efficient, the extra energy required appearing as the additional heat mentioned above. The shape of the efficiency vs load curve, however, is constant regardless of speed. The full load efficiency at half speed is roughly equal to the full load efficiency at full speed. The difference, however, is that full load at half speed is equal to half the horsepower of the full load at full speed as shown in Figure 19. A number of users always specify high efficiency motors for VFD usage. While not a requirement, high efficiency motors do have some extra copper and other features desirable for VFD use.
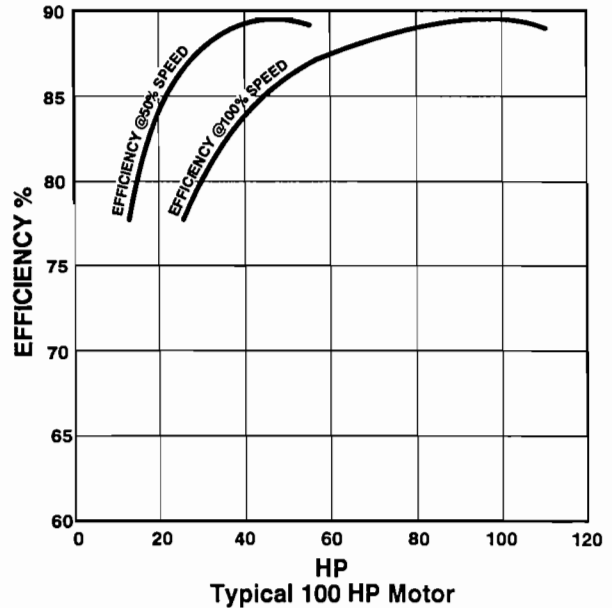

HP
Typical 100 HP Motor

Figure 19. Variable Speed Motor Efficiency.

Hazardous Environment

A standard motor operates hotter on a VFD and thus its skin temperature can exceed an area gas autoignition temperature at nameplate horsepower. For use in hazardous (explosive) environments a motor must be designed differently or derated. Motors nameplated for use in Class I, Division I, Groups C and D environments, for instance, are available for VFD usage but must generally be purchased with a "matched" VFD from a single supplier.

PROPER VFD SELECTION

Basic VFD Behavior

Variable Frequency Drives (VFDs) are electronic devices which convert incoming Alternating Current (AC) electrical power to Direct Current (DC) and then invert the DC into variable frequency and voltage output AC power. The power is produced by switching the DC power through power semiconductors controlled to produce output voltage or current pulses. The choice of switching technologies has significant impact on the current waveform which in turn affects the motor's torque and torque ripple, since torque is a function of current. Selection of a VFD should be made with knowledge of the switching technique employed, and what effect the switching technique will have on the motor and, consequently, on the pump.

Switching Techniques

The two most common forms of voltage controlled VFDs are pulse width modulation (PWM) and six step. The most common form of current controlled VFD is a current source inverter (CSI). An across the line current waveform is compared in Figure 20 with waveforms from PWM, six step, and CSI VFDs.
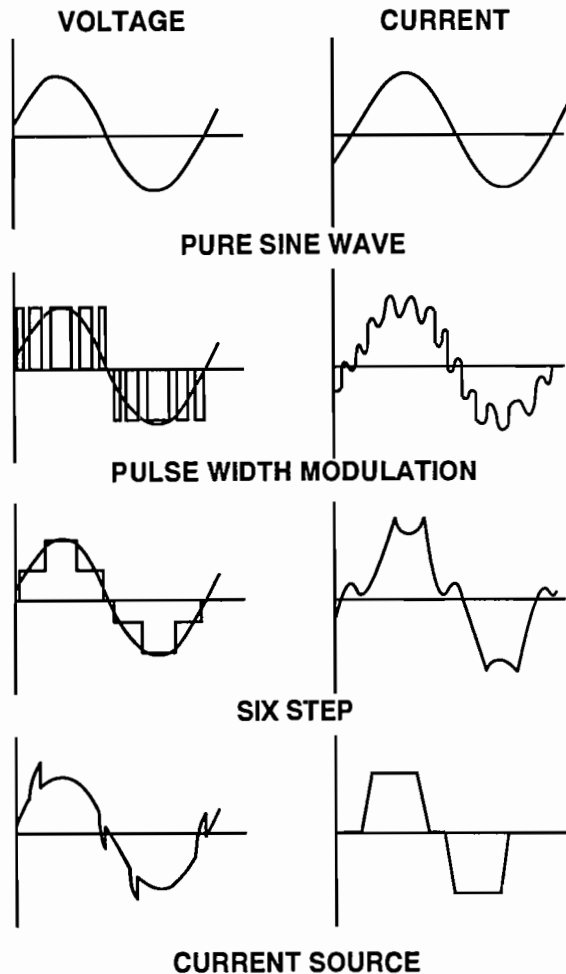

VOLTAGE   CURRENT

PURE SINE WAVE

PULSE WIDTH MODULATION

SIX STEP

CURRENT SOURCE

Figure 20. VFD Current Waveforms.

PWM Technology outputs a series of voltage pulses with constant amplitude and varying or modulating width. These pulses simulate the voltage sine wave of an across the line system. The resultant current waveform which is produced is a function of the motor characteristics, but in general the current waveform is as shown in Figure 20. The PWM current waveform is quite smooth, minimizing torque ripple and other disturbances.

Six Step Technology outputs a series of voltage pulses with varying amplitude and constant width, using six steps or pulses to simulate one full sine wave. The resultant current waveform is more irregular than the PWM, producing additional torque ripple.

Current Source Inverter Technology outputs current pulses, rather than voltage pulses, causing a significantly more irregular current waveform (Figure 20). This irregular current waveform leads to increased torque ripples.

Below several hundred horsepower, PWM VFDs have become the technology of choice. Above 500 to 700 hp, CSI is often the technology of choice. Between these levels PWM, six step and CSI

are all used. PWM is expanding with some vendors, however, to as much as 2000 hp or more.

Types of Control

VFDs are made in digital and analog forms. A digital control utilizes a dedicated microprocessor to control the unit. User interface is accomplished through a digital keypad with numerous operating parameters displayed on a digital alphanumeric display. Analog drives are controlled by potentiometers, have analog gages for a few key operating parameters, and are less flexible than their digital counterparts. While analog units are perfectly satisfactory for most pump applications, the digital units are rapidly dropping in price to near the analog level and soon it appears most VFDs will be digital. Speed and start/stop functions can be accomplished remotely or at the VFD.

VFD Efficiency

VFDs typically consume two to three percent of input power at full load and full speed. At 25 percent load and 25 percent speed, VFDs consume around five percent of input power. Motor inefficiency increases at lower load too, but VFD and motor inefficiencies are small in comparison to the pump horsepower savings available through speed reduction.

Selecting a VFD

There are a number of key elements which must be considered when selecting a VFD.

Amperage Required

VFDs should be sized by amps. A motor's amperage for a three phase system is defined by:

$$\text{Amps} = \frac{\text{HP X 746}}{\text{Volts X 1.732 x motor efficiency x motor power factor}} \quad (5)$$

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 have no continuous service factor. Momentary overloads, however, are permitted.

Constant Torque vs Variable Torque

VFDs are designated constant torque or variable torque depending on their current overload capability. Variable torque VFDs typically can produce 110 percent of rated current for one minute. Constant torque VFDs typically can produce 150 percent of full load current for one minute and even more for shorter periods. Centrifugal pumps generally use variable torque VFDs. Positive displacement pumps, due to their starting and operating characteristics, generally require constant torque VFDs to provide sufficient current, and hence, torque for proper pump startup and continuous operation.

Acceleration/Deceleration Rates

Acceleration rates are limited by the VFDs current capacity. Rapid across the line, starting without a VFD requires five to seven times full load current. Since VFDs are limited at peak to two or less times full load current, they accelerate the motors less quickly, but can typically start a fully loaded motor in five seconds or less. Deceleration rates are likewise limited. Most VFDs can provide about 10 percent of their rated power in the form of braking to hasten deceleration. Very fast deceleration rates can be achieved with the use of dynamic or regenerative breaking options on the VFD.

Torque Required

Starting torque should be carefully considered, particularly with positive displacement pumps.

Low Speed Operation

Due to the irregular voltage and current waveforms, motors operated on VFDs below 10 percent of their design speed can exhibit cogging or rough, jerky motion. PWM waveforms generally produce smoother motion than other types.

Matching VFD to Motor

Large current source VFDs may require addition or deletion of capacitor banks to properly match motor and load characteristics. PWM and six step VFDs do not require this matching and are suitable for use on 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, a step up transformer between the VFD and the motor can be used, or a higher voltage VFD can be used.

VFD Economics

Selling prices of VFDs vary primarily due to:

- vendor to vendor differences.
- analog vs digital.
- enclosure type.
- customization.

The table below shows 1992 price ranges for 480 V, 60 hz, three phase input VFDs with output frequencies to 120 hz. The lower band represents fairly standard units, while the upper band represents a high degree of specification content and customization.

VFD HP	$/HP
5	$200-$500
10	$200-$400
20	$125-$250
50	$ 90-$200
75	$ 80-$180
100+	$ 80-$160

The economics of VFD usage are relatively straightforward with a few subtleties. The following capital and operating aspects must be considered.

- *VFD Cost*-The installed cost of the VFD is offset by the cost of a motor starter which is not required with a VFD.

- *Valve Cost*-Often a throttling or bypass valve can be eliminated.

- *Motor Cost*-Extra cost may be incurred for a high efficiency or high speed motor.

- *Pump Cost*-Pump cost evaluation can be tricky. For instance, a pump may need to be oversized in flow as shown in Figure 14. Two variable speed pumps and one common spare may be substituted for two sets of fixed speed pump plus spare. One variable speed pump may be substituted for one large and one small fixed speed pump. A single, higher speed, single stage pump may be substituted for a multiple stage.

- *System Cost*-Other parts of the system may be designed differently due to the variable speed operation mode.

- *Energy Costs*-Energy savings is often substantial.

- *Process Control*-Processes can sometimes be better controlled with less heat input, fluid shear, etc., by using variable speed.

When all these costs and operational aspects are considered, the economics of variable speed motor and VFD usage can be very favorable, showing at times a capital and operational savings, or more frequently a "payback" of extra capital cost in as quick as one year, if significant energy savings are available.

ENVIRONMENTAL AND OPERATING CONSIDERATIONS

Environmental Considerations

VFDs are reasonably rugged pieces of electronic gear, but do require some special considerations, the most significant of which are listed below.

- *Location*-Typically indoors. Units can be placed outdoors with the proper enclosure but such an enclosure often adds many thousands of dollars. Location can be several hundred feet from the motor.

- *Temperature*-VFDs operated above 104°F ambient must be derated.

- *Elevation*-VFDs operated above 3300 ft above sea level must be derated.

- *Electrical supply stiffness and irregularities*-Very stiff [high kilovolt-ampere (KVA)] feed transformers may require the use of a line reactor or isolation transformer between the VFD and the supply mains. Either of these devices, with their copper windings around an iron core, will smooth out irregularities in a stiff electrical supply, minimizing the chance of power irregularities causing a VFD to shut down in a protective mode. They should be sized to add three to five percent impedance to ensure trouble free operation of the VFD. Typically, if the feed transformer has more than 10 times the KVA rating of the drive, a line reactor or isolation transformer should be considered. Despite the benefits of line reactors and isolation transformers, numerous VFDs are installed without them.

Electrical Noise

VFDs feed electrical noise back into the supply mains. This noise can distort instrument signals if they are fed from the same supply transformer as the VFD. Use of an input line reactor or isolation transformer upstream of the VFD can minimize the disturbance. Generally, an input line reactor is adequate; an isolation transformer adds the additional benefits of protection from grounds and provides voltage changing if necessary. Some VFDs come with input line reactors built in.

Operations/Maintenance Personnel

Today's VFDs are reliable solid state devices. Troubleshooting of all but the largest units can be accomplished with basic electronic technician tools such as multimeters and clamp on ammeters. Most VFDs have some form of built in diagnostics and fault annunciation to aid troubleshooting. Precise measurement of amperage, voltage and kilowatt levels, however, requires more sophisticated instrumentation like a digital power meter capable of accurate measurements of the complex waveforms. For approximate measurements, standard analog measurement devices generally work better than standard digital devices.

If operating problems do occur, they can typically be narrowed to a single printed circuit board which can be replaced in a modular fashion. It is, of course, important to maintain proper spare parts or other back-up provisions for the inevitable down time occurrence.

THE FUTURE

Unlike mechanical hardware, which has been pretty well optimized over the years, the VFD industry is only in its adolescence.

Continued improvements are continually forthcoming in the following areas.

Features

Features of basic VFD control and troubleshooting are already rather advanced. Additional features will focus on making the VFD easier to use and integrate into a process system. Among these will be easy to use multilanguage display prompts and greater operating parameter adjustment capability.

Performance

Continued improvements in reliability and fault tolerance will lead the performance improvements. VFDs will be easier to apply. Output voltage and current waveforms will be monitored and adjusted to optimize motor efficiency and smoothness.

Size will be reduced by integrating discrete components on the circuit boards into integrated chips. Reduced size and improved efficiency will allow packaging to be more compact and environmentally rugged.

Pricing

Pricing will continue to fall in real terms while features and performance rise. Price reductions in the order of perhaps 25 percent may be expected in the next five years. Prices are not expected to plummet the way they have in consumer electronics, for instance, due to the relatively lower volumes involved and the fact that a large proportion of the cost is in components such as large mechanical switches, capacitors, enclosures, etc., which are not expected to fall in price.

CONCLUSION

Variable and higher speed pump operation utilizing variable frequency drives (VFDs) and electric motors provides many benefits to the centrifugal and positive displacement pump user:

• *Pump Flexibility*-Variable speed pumps can efficiently handle a wider range of flows and heads.

• *Higher Pump Speeds*-Standard or modified motors can be operated at higher than normal speeds producing extra head and flow from a fixed pump design.

• *Throttling or Bypass Valve Elimination*-Flow can be varied by changing speed rather than by use of discharge throttling or bypass valves. In many instances, the valves can be eliminated, reducing capital and maintenance costs, and the number of potential leak sources.

• *Energy Savings*-In situations where centrifugal pump head or positive displacement flow is changing considerably, significant energy savings is available, often providing economic payback of one year.

• *Reduced Heat to Pumped Fluid*-Achieving low centrifugal pump flow by lowering speed rather than by discharge throttling reduces heat added to the pumped fluid.

To achieve these benefits, extra care must be taken in selecting an appropriate system of pump, motor, and VFD. The user, with the pump vendor, must consider the following:

• *Process System*-The full range of system requirements in terms of head, flow, and specific gravity must be identified.

• *Pump*-A pump should be selected to cover the full desired range of flow and head if possible. This may require sizing the pump for other than a given duty point to provide full coverage at varying speeds. Special consideration must be given to lateral and torsional critical speeds and high speed requirements.

• *Motor*-Most standard and high efficiency NEMA B induction motors are suitable for VFD usage from 10 percent to, at times, as much as 150 percent of base speed, typically with a slight horsepower derating. Specially designed VFD operated motors can be run to many times base speed, producing extra horsepower at higher speed.

• *VFD*-The wide variety of VFDs available offer the user a broad range of options. The electronic technology employed in the VFD can have mechanical impacts on the driven equipment. VFDs should be selected with full knowledge of the driven load's torque requirement and with full knowledge of any induced irregularities the VFD may cause in motor torque.

When significant benefits can be identified, and the pump, motor and VFD are selected for proper interaction with the user's system, variable speed pumping can be very worthwhile. Variable speed usage is growing, and will continue to do so as electronic technology advances and users become more knowledgeable and comfortable with its application.