7-4. Variable Speed Drives

Control valves change flow by changing the system resistance (restriction area) to flow. Variable speed drives on axial and centrifugal prime movers (blowers, compressors, fans, and pumps) change the discharge head (pressure) of the prime mover. The speed of peristaltic and positive displacement pumps is also manipulated but the speed control is simple. Positive displacement pumps create disruptive pressure pulses, can overpressurize downstream piping and equipment if the discharge flow is blocked, and generally require more maintenance. Consequently, positive displacement pumps are relegated to metering relatively low additive and reagent charges to vessels.

This section focuses on variable speed drives for centrifugal pumps. A liquid flow control application is used to illustrate the potential benefits and problems.

Modern variable speed drives (VSD) for pumps are variable frequency drives (VFD). The motors are AC induction motors. A DC motor has a faster response but the initial cost is much higher, as are maintenance costs due to brushes that need to be periodically replaced. DC motors are used for servomechanism control where smaller size and faster speed of response are needed.

Static Head

In non-positive-displacement pumps, flow rate is proportional to pump speed except at low speeds. The change in flow rate with speed increases at low speeds where the pump head curve is flatter, or as the pump head approaches the static head (see section 7-6 on Linearity). If the pump head becomes less than the static head, reverse flow through the pump can occur. In one disastrous case that soured a customer on the use of variable speed drives, the pump head from a VSD pump feeding a reactor dropped below the reactor pressure. Catalyst and reactants blew back through the pump into the feed tank, damaging the pump and creating a potentially hazardous situation from exothermic chemical reactions in the storage tank. This case illustrates that the pump head should not be able to drop below the highest reactor pressure excursion. On-off valves should shut to provide positive isolation and perhaps check valves should be used to prevent reverse flow.
Static head is the downstream pressure that doesn’t vary with flow (e.g., liquid head and vessel pressure). The term can be misleading in that static head is not constant. Pressure excursions in vessels from batch operation or process disturbances can be fast and frequent. For example, if a pump was providing a flow that entered the top of a pressurized vessel, the static head would be the result of gas pressure in the top of the vessel plus the liquid head associated with the elevation change between the pump and vessel entry point (Figure 7-31a). The worst-case vessel pressure must be considered. The discharge head of the prime mover is proportional to the speed squared. The pump head must equal the sum of the static head and the system pressure drop. Since there is no control valve, the pump flow is at the intersection of the pump and system curves. Figure 7-31b shows how the addition of a static head shifts the intersection (operating point) to the left reducing the flow delivered.

The pump curve shifts down with speed. When the speed causes the intersection to approach the static head, the flow is no longer controllable. Hence, the magnitude of the static head determines how low in speed a VSD can go (see the subsection on turndown and the end of Section 7-7 on Rangeability).

\[
P_s = k \cdot \gamma \cdot H + P_v
\]

Where:
- \(k\) = units conversion factor
- \(H\) = elevation (height of nozzle)
- \(P_s\) = static pressure
- \(P_v\) = vessel (destination) pressure
- \(\gamma\) = liquid density

**Figure 7-31a. Static Head from Elevation Change and Destination Pressure**
VFD Pulse Width Modulation

Pulse width modulation (PWM) is predominantly used today to vary the frequency of the voltage or vary the current to the pump motor. PWM introduces lower noise, has a higher input power factor, and has better low speed performance than older drive technologies. PWM also offers better rangeability from less cogging (torque pulsation) at low speeds [26]. Figure 7-32a shows the functions in a VFD inverter to convert an AC line voltage to a variable frequency voltage for speed control of an AC induction motor. Industrial motors use three phases, staggered to provide a smoother output. The AC line voltage is rectified and filtered to create a DC voltage. The DC voltage is then inverted to a variable frequency voltage whose frequency is proportional to the drive input signal by PWM. The square wave output is then filtered to create a sine wave. The rounding from the peak is more accurate for finer pulse widths. Insulated gate bipolar transistors (IGBT) are used to create a series of pulses of varying width. The dominant carrier frequency from PWM is proportional to the

Figure 7-31b. Static Head Effect on Intersection of Pump Curve and System Curve
drive input signal. The resulting waveform from PWM is closer to a sine wave [26]. These drives come in a wide spectrum of sizes as shown in Figure 7-32b.

PWM inverters do not have the performance problems, the harmonics, and sharp spikes seen in older drives that can damage bearings and create electrical noise in instrument signals. For example, the older six-step volt-
age drive technology, while inexpensive, had a number of undesirable characteristics. The motor can be pushed to its breakdown point. Shorts can cause an infinite current spike. The inverter puts out the same voltage and current at half load as at full load, which reduces efficiency. The waveform has wide and fast current variations that can damage the inverter. The inverter has numerous harmonics that increase motor losses, heat generation, and electromagnetic interference.

These invertors used an output choke to prevent damage to motor insulation; however, the input choke was optional and was often missing or insufficient. Eventually, the noise in instrument signals became bad enough that chokes were offered to meet the International Electrotechnical Commission (IEC) standards. Alternatively, isolation transformers were located close to the inverters with the power wiring between the inverter and transformer in hard pipe conduit to minimize the noise from this section of wiring [27]. While the PWM drive has lower harmonics and spikes, the rapid rise time of the pulses for precise speed control is still a source of noise and potential damage to bearings and cables.

**VFD Cable Problems**

Belden Inc. has studied the radiated noise from cables between the VFD and the motor. Unshielded VFD cables can radiate 80V noise to unshielded communication cables and 10V noise to shielded instrument cables. The radiated noise from foil tape shielded VFD cables is also excessive. A foil braided shield and armored cable performs much better [28]. Still a spacing of at least one foot is recommended between shielded VFD and shielded instrumentation cables. The cables should never cross. As a best practice, separate trays to isolate VFD and instrumentation cables should be used to avoid mistakes during plant expansions and instrumentation system upgrades.

All VFD systems have reflected waves from an impedance mismatch between the VFD and the motor. The amplitude of the waves depends on the voltage magnitude and rise time from the PWM drive, the distance between the VFD and motor, and the impedance mismatch. If a reflected wave gets in-phase with the radiated wave, the voltage can double and the PVC jacketed VFD cables can be damaged. XPLE jacketed VFD cables that are capable of withstanding a high voltage impulse are recommended [28]. For the “Ten Things to Consider before Selecting Your VFD” from Belden Inc., see Appendix B.
**VFD Bearing Problems**

The electric discharge machining (EDM) effect from inverter drives can cause arcing across the lubrication gap of a motor bearing “almost like a series of little lightning strikes” [29]. The arcing damages the bearing surface. The damage is seen as pit marks in variable speed operation and fluting in constant speed operation. The localized high temperatures from the strikes cause reactions in lubricant additives and burning or charring of the lubricant [29]. Pitting, fluting, and poor lubrication cause an increase in noise and vibration. Eventually the bearing fails.

Mechanical solutions insulate the bearing or provide a path to ground. Ceramic coatings and ceramic balls or rollers may be used for insulation. However, the insulation forces the current to go elsewhere and possibly cause damage, such as the erosion of pump impellers in prime movers.

**VFD Slip**

In an AC induction motor, the rotor and hence shaft speed lags behind the speed of the rotating electrical field of the stator because a difference in speed is needed to provide the rotor current and consequently the torque to balance any motor losses and the load torque from prime mover operation. This difference in speed between the stator field and the rotor of the motor is called slip. In pumps, there is dynamic slip for large changes in the pump load (e.g., static head) or desired flow rate (speed signal). There is also steady-state slip for operation at a particular load and speed. The relationship of slip to load and motor torque can be seen in the motor torque curve. National Electric Manufacturers Association (NEMA) design B motors are commonly used for pumps. The torque curve for design B as shown in Figure 7-33 has a dip on the left side of the peak but a nearly linear decrease in torque with speed on the right side of the peak. NEMA design A has a higher peak and a much sharper fall-off in torque with speed. Since variable speed motors are designed to operate on the right side of the peak, the more gradual slope of design B translates to smaller process variable errors and oscillations from disturbances and speed regulation limitations. The torque curve is shifted to the left by the inverter controls to keep the operating point on the right side of the peak as shown in Figure 7-33.

It is important to note that speed slip is not the same as valve stroke slip. In speed slip, the speed still responds smoothly to a change in drive signal, but the proportional change in speed is less. In stroke stick-slip, there is no
response in the valve stroke until the change in signal is greater than the stick, at which time the valve stroke jumps to a new position corresponding to the stroke slip. Speed slip causes a change in process gain. Stroke slip introduces time delay and discontinuous action that results in a limit cycle (see section 7-5 on Dynamics).

In a synchronous motor, the rotor is designed to inherently eliminate slip so the rotor speed is at the synchronous speed of the stator. Synchronous motors are significantly more expensive and complex and are used only where inherently fast and precise speed regulation is needed. Synchronous motors have been used for ratio control of reactants or additives where small transients or offsets in the speed could cause a significant variation in the product.

**VFD Turndown**

Since the inverter waveform is not purely sinusoidal, it is important to select motors that are designed for inverter use. These “inverter duty”
motors have windings with a higher temperature rating (Class F) [30]. Another option that facilitates operation at lower speeds to achieve the maximum rangeability offered by a PWM drive is a higher service factor (e.g., 1.15).

To help prevent motor overheating at low speeds, larger frame sizes and line powered ventilation fans are used. In the process industry, totally enclosed fan cooled (TEFC) motors are used to provide protection from chemicals and receive ventilation from a fan that runs off the same power line as the motor. The fan speed decreases as the motor speed decreases. To reduce the problem of motor overheating at low speeds, an AC line power constant speed ventilation fan and a larger frame size to provide more ventilation space can be specified. Alternately, a separate booster fan can be supplied. For very large motors (e.g., 1000 HP), totally enclosed water cooled (TEWC) designs are used to deal with the extra heat generation. For low static head pump applications, overheating at low speeds is not a problem because the torque load decreases with flow.

**VFD Controls**

The turndown (rangeability) of a VSD can be increased by ensuring that the pump head is large compared to the static head (see the end of Section 7-6 on Linearity and Section 7-7 on Rangeability), by using PWM inverters, and by dealing with the heating problems at low speeds. Turndown also depends upon the control strategy in the variable frequency drive. All the control strategies discussed in this section use PWM to manipulate the frequency and amplitude of voltage and current to each phase.

Open loop voltage (volts/Hertz) control has the simplest algorithm but is susceptible to varying degrees of slip. Most of the drives provided for pump control use this strategy, in which the rate of change of flux and hence speed is taken as proportional to voltage. At low speeds the motor losses are larger, making the difference between the computed and actual speed (slip) much larger. As shown in Figure 7-34, some drives make a correction to the voltage to account for estimated motor losses. Ultimately these drives depend on the DCS to correct for dynamic slip through proportional action and to correct for steady state slip through integral action in process controller(s). The turndown is normally 40:1 with 0.5% speed regulation [30].

Closed loop slip control has a speed loop cascaded to a torque loop. The torque feedback may be calculated from a current sensor. A DCS process
controller output is the speed set point for the speed controller, whose output is the set point to a torque controller. PI rather than P-only controllers can be used since stiction and resolution limits are negligible, eliminating any concern about limit cycles from integral action.

The speed controller plays a role similar to that of the valve position controller and the torque controller serves a similar purpose as the relay controller. However, in a digital positioner the relay response is inherently much faster than the valve position response. In the VSD, the torque controller can have a relatively sluggish response. To prevent a violation of the cascade rule that requires the secondary loop (torque) to be 5x faster than the primary loop (speed), the speed loop is slowed by decreasing the speed controller gain and integral time. Since the speed set point comes from a process controller in the DCS, there is at least a triple cascade. In many cases there is a quadruple cascade control system when the DCS has a cascade control system as shown in Figure 7-24. As a result of the quadruple cascade, the detuning of the speed controller causes detuning of the flow controller, which in turn may cause detuning of the temperature controller. As a result, the ability to reject fast process disturbances may be compromised. The turndown of speed using closed loop slip control is normally 80:1 with 0.1% speed regulation [30].

Flux vector strategies offer sophisticated methods for incredibly fast multivariable motor control. Motor models can be used to provide inferential speed and torque measurements, eliminating the maintenance and response limitations of sensors. The effect of rotor temperature on rotor resistance is computed and used in the motor model. The specific strategy details are proprietary to each manufacturer. Optimum operation depends
on the correct setting of numerous parameters for the application. Some of these parameters are available from the motor nameplate. Other parameters may depend on the mechanical design and process load. These strategies are used particularly for servo mechanism control systems that require a much faster and better definition of system response than process applications such as pump control systems [30]. High-performance drives that use this strategy have a rangeability of 120:1 with 0.001% speed regulation [30].

With these drives, the current or voltage state vector is controlled in an optimized orientation to maximize torque with minimal motor losses [31]. Current measurements from two of the three phases are transformed and used as feedback for closed loop control of the current state vector (Figure 7-35). Position feedback is differentiated and used as feedback for a PI torque controller whose output is the desired y-axis current (i*y). The output of the y-axis current controller sets a y-axis voltage (v*y) to affect torque. The x-axis current (i*x) controller, whose set point is zero, sets an x-axis voltage (v*x) to affect flux. A space vector modulator computes a modulation depth and angle that define the output voltage from the inverter and the angle of the conceptual voltage vector, respectively to achieve the desired flux vector as exemplified in Figure 3-35 [32].

For liquid flow and liquid pressure control, the process response from an open loop volts/Hertz drive is so fast that slip can be corrected by the flow or pressure controller in the DCS. Inferential speed or tachometer feedback control in the DCS may require the DCS loop to be detuned because of the cascade rule and thus do more harm than good. The volts/Hertz
strategy provides enough turndown for most applications. For gas pressure and flow, there may be some benefit from closed loop speed control in the drive, particularly for large volumes. For concentration, vessel pH, level, and temperature control where there is no secondary flow loop, the benefit of closed loop speed control is much more obvious because these primary loops are so slow. Flux vector control is probably not required for any of these loops but may be useful for conveyor control.

**VFD Justification**

As documented in the literature, the primary justification for going to variable speed pump drives is the desire to save energy. Eliminating a control valve and its pressure drop decreases the amount of head the pump must provide. Also, the pump speed can be reduced at lower flow requirements. The big incentive is seen in the relationship where the power required varies with the cube of speed [33]. Also, the cost of a motor starter can be eliminated [34]. However, the estimated energy savings often do not account for the decrease in motor efficiency with speed, the minimization of valve pressure drop by proper valve selection and sizing, the amount of time the motor is actually needed to operate at lower speeds, or the limitation imposed by static head.

For example, the motor efficiency can decrease by 40% or more at low speeds. Most continuous processes run at a relatively fixed flow rate except during grade transitions or startup. Batch processes have a fixed feed rate to reach preset total charges unless the feeds are manipulated for closed loop concentration control. Equal Percent valve characteristics allow the valve pressure drop to be decreased to 10 to 20% of system pressure drop (see section 7-6 on Linearity). Finally, a high static head will prevent the turndown of motor speed.

In the future, new microprocessor based motor controls that maintain high motor efficiency throughout the speed range may increase the potential energy savings at low speeds but decrease the energy savings at normal speeds [36].

Even in the absence of energy savings, variable speed pump drives may be the best solution for certain process applications by eliminating problems with control valves. For slurries, a VSD pump eliminates a control valve with coating, erosion, corrosion, and plugging problems. For molten metals, a VSD pump eliminates a control valve with high temperature seizing and stiction from high temperature stem packing. For highly viscous
flows, a VSD eliminates a control valve with an erratic flow response from a transition between turbulent and laminar flow. For corrosive fluids that require special materials of construction, given that a pump and an isolation valve are required, the VSD eliminates an expensive control valve.

Variable speed drives are more complicated to set up and maintain than control valves. Proper implementation requires a cross-disciplinary effort drawing upon electrical, mechanical, instrumentation, and process control skills [33]. The expertise needed to set up and maintain the VSD may necessitate onsite support from a contractor or vendor.

In summary, the four main practical reasons that VSDs are not used as extensively as one might think for pump control are as follows [35].

1. **Drives are generally not built just for pumps.** They handle conveyors, extruders, etc. There are a lot of VSD menu choices and options not pertinent to pumping applications.

2. **Users don’t like the complexity of the VSD.** The user must address setup, maintenance, and design issues. Special practices are needed to prevent EMI (electromagnetic interference) in instrument signals and to keep from getting harmonics back into the power supply.

3. **Someone needs to do the right calculations on dollars saved.** As mentioned, calculations typically don’t take into account the drop in drive efficiency at low speeds. The duty cycle (the amount of time that speed is actually turned down) is not known (or perhaps not considered) in advance. If there is a high static head, the energy savings of a VSD disappear.

4. **It is rare to compare a VSD and a valve.** There are generally no decision points in the project for this comparison.

**Which Is Faster: a Valve or a VSD?**

Exceptionally fast loops (e.g., furnace pressure, liquid pressure, and compressor surge control) can ramp off-scale in milliseconds. These loops have essentially a zero process deadtime and may have a high process gain due to a narrow control range (e.g., fractional inches of water column for furnace pressure). These loops require DCS scan times of 0.05 to 0.1 seconds. Special fast scan rate digital controllers or analog controllers are needed. DCS scan time requirements of 0.2 seconds or less signify a VSD opportu-
nity. A properly designed VSD has no measurable deadtime, while control valves and dampers take anywhere from 0.2 to 2.0 seconds to start to move. For example, an incinerator pressure and polymer pressure loop that could get into trouble in less than 0.1 second required a VSD and analog controller to stay within the desired control band [20][23][35].

A VSD has a negligible response time delay unless a deadband or dead zone is introduced into the drive electronics to slow response to process measurement noise, or if a low resolution input card is used. A control valve or damper has a deadtime that is proportional to the resolution limit (e.g., from stiction and windup) and deadband (from backlash and windup) divided by the rate of change of the process controller output. For large or fast changes in signal this deadtime disappears.

A pneumatic actuator has a pre-stroke deadtime that is the time it takes for the actuator pressure to change enough to move the actuator shaft. For large actuators, the pre-stroke deadtime can be several seconds unless a booster is added.

The inertial time constant of liquid flow response is inversely proportional to flow rate. Consequently, the process lag at low flow rates and at the start of flow can be quite long (e.g., 5 seconds) compared to the process lag at normal flow rates (e.g., 0.5 seconds). The comparison between VSD and control valve response should be at normal flow rates.

In a published comparison of the dynamic response of a control valve and a VSD-controlled pump for flow control for a system with negligible static head, the integral times were about the same for the VSD and valve loops. However, the controller gain could be increased by over a factor of six for the VSD loop. As a result, the set point response was faster [38]. In this test the valve deadband was about 8%.

In an unpublished lab test comparison between a control valve with low stiction, low backlash, and a digital positioner and a VSD with a volts/Hertz PWM drive for liquid flow control, the speed of response of the valve and VSD were similar.

Variable speed drives, control valves, and dampers have a velocity limited exponential response. The velocity limit in a pump drive depends upon the available motor torque and the inertia of the motor rotor, the pump shaft, and the pump impeller. The exponential term is generally much smaller for a VSD than for a control valve or damper. On the other hand,
the velocity limit is lower for a VSD unless the actuator size is large and boosters are not used. Consequently, for small changes in signal, a well designed VSD is faster. Conversely, for large changes in signal, a small control valve is faster (see section 7-5 on Dynamics). This leads to the conflicting statements about whether a VSD or control valve is faster. Application for application, which final element is faster often depends upon the size of the change in signal.

To summarize, a VSD is most likely to offer energy savings or better loop performance as a final element for the following types of applications:

- Loops that require 0.2 seconds or faster scan time
- Valves and dampers with a 0.5% or more resolution limit or deadband
- Large utility flows
- Integrating and runaway processes without a secondary flow loop
- Low static head processes requiring frequent turndown

**VSD Best Practices**

With a VSD, a tachometer or inferential speed feedback signal should be sent to the process controller in the DCS that is sending the signal to the drive. The speed feedback should be used in a similar way to the position feedback from a digital positioner to prevent the process controller output from changing faster than the VSD can respond. The use of the dynamic reset limit option for the loops in the DCS can automatically prevent the process controller from outrunning the response of any type of final element (see Section 7-5 on Dynamics).

For best performance, users should consider the following during the specification and implementation of variable speed drive systems:

- High resolution input cards
- Pump head well above static head
- On-off valves for isolation
- Design B TEFC motors with class F insulation and 1.15 service factor