From ISA's Ask the Automation Pros Series

Advice on How to Specify the Best Variable Frequency Drive

What is the best variable frequency drive (VFD) design and installation plan for a pump motor, considering noise, linearity, slip, reliability, rangeability, and response time? This discussion is part of the Ask the Automation Pros series from the International Society of Automation.

By Erik Cornelsen, Gregory K. McMillan, Michael Taube, Matthew Howard, Michel Ruel, and Peter Morgan

Greg McMillan’s Question

What is the best variable frequency drive (VFD) design and installation plan considering noise, linearity, slip, reliability, rangeability, and response time?

Erik Cornelsen’s Response

When selecting a VFD for an application, I consider a few key factors to ensure optimal performance. Understanding the relationship between torque and speed is fundamental. Applications generally fall into two categories: constant torque, like conveyors, material handling systems, and hoists, or variable torque, where torque is proportional to the square of the speed, as in fans and pumps. Most VFD manufacturers provide models tailored to these categories, making it easier to choose the right one.

Matching the VFD to the motor is equally important. Selecting a VFD with a power rating slightly above the motor's ensures it can handle the application without strain or performance issues.

During commissioning, I configure parameters such as motor nameplate details, acceleration/deceleration ramp times, and then perform an auto-tune operation. This allows the VFD to account for actual installation factors, like cable distances, and fine-tune its settings for optimal performance.

These are the basic steps to get the motor running, but fine-tuning is often necessary to tailor the system for the specific application. I monitor and adjust parameters such as duty type (heavy or normal, selecting heavy for higher overload tolerance), motor control mode (e.g., vector control or V/f), maximum motor frequency, control method (e.g., Ethernet or hardwired signals), brake release configuration (if the motor has a brake), and IGBT switching frequencies.

Many of these adjustments are guided by field observations, alarms, and warnings displayed by the system. The ultimate goal is to achieve smooth operation during both starting and stopping. Key parameters I monitor include motor current and motor speed to ensure the system is functioning efficiently and reliably.

Greg McMillan's Response

In an AC induction motor, the rotor and hence the pump shaft speed lag 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 pump operation. This difference in speed between the stator field and the rotor of the motor is called slip. There is a dynamic slip for large changes in the pump load (e.g., static head) or desired flow rate (speed signal). There is also a steady-state slip for operation at a particular load and speed.

It is important to note that VFD speed slip is not the same as valve stroke slip. In speed slip, the speed still responds smoothly to a change in the drive signal. At low speed, the loss in pump efficiency and an increase in slip cause a dip in flow. Slip affects the minimum controllable speed and hence the VFD rangeability, particularly for high static heads.

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 complicated and are used only where inherent 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 concentration.

If there were no static head and no slip, and the motor and frame are properly designed to prevent overheating at low flows, the rangeability of a VFD would be impressive. A drive with closed-loop slip control by the cascade of speed to torque control can achieve a rangeability of 80:1, which is comparable to the rangeability of a magnetic flow meter.

When the pump head is operating near the static head, the minimum controllable flow is set by rapid changes in the static head and frictional loss. These rapid changes could be due to noise and sudden or large disturbances. The speed cannot be turned down below the amplitude of these fast fluctuations. The rangeability for a static head that is more than 30% of the system head at 100% speed is only 2:1, regardless of drive technology.

What is interesting is that a control valve's rangeability deteriorates for a valve pressure drop that is less than 30% of the system pressure drop. Thus, if you had a situation where the frictional losses in the piping are low, like in pH control, but the static head was high, a control valve with minimal stiction and lost motion would have much greater rangeability than a VFD.

Here are some best practices for VFD design and installation:

- 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
- Larger motor frame size
- XPLE jacketed foil/braided or armored shielded cables
- Separate trays for instrumentation and VFD cables
- Inverter chokes and isolation transformers
- Ceramic bearing insulation
- Pulse width modulated inverters
- Minimum deadband and rate limiting in the drive configuration
- Drive control strategy to meet rangeability and speed regulation requirements
- If tachometer feedback control is used, speed control should be in drive not DCS
- External reset feedback (dynamic reset limit) using tachometer or inferential speed feedback to prevent PID output from changing faster than drive can respond.

More information: For more information and details, see Chapter 7 – "Effect of Valve and Variable Frequency Drive Dynamics" in my book, *Tuning and Control Loop Performance, Fourth Edition*. It is available as a free download. Another extensive resource is "The Control Techniques Drives and Controls Handbook," edited by Bill Drury and published by The Institution of Electrical Engineers, London.

Michael Taube's Response

Both Greg and Erik have addressed aspects of VFD applications that I never considered (or would have thought of)! Admittedly, my exposure to VFD application has been limited to just some pump applications and, invariably, the controls design (by others) was less than optimal: In most instances two separate controllers were implemented, one using the VFD and another manipulating a control valve to "control" the same variable (e.g., level, flow, etc.), which, of course resulted in the controllers "fighting" each other or as the Operators would say: "It just doesn't work!"

When I've encountered such applications, I recommend that the VFD be used as a valve position controller that adjusts the motor speed to keep the control valve (which maintains the process variable of interest, e.g. level, flow, etc.) in some "optimal" range (nominally 60-70%). The VFD controller would be tuned to react to changes in the control valve position "slowly," perhaps even using an error-squared algorithm, as well as a filtered value of the valve position. There's no need to have the VFD react to every tick, jerk or movement of the control valve.

Thinking further on the topic, I have to question why have both a VFD and a control valve? Some years ago, when meeting with a prospective client about implementing pipeline automation, the client pointed out that it was far more energy efficient (meaning, lower in operational cost) to modulate the speed of the pipeline pump(s) rather than run them at constant power and then dissipate that energy across a control valve. So, if "energy efficiency" is the justification for using a VFD, then don't bother with a control valve! And, as you point out, there is turn-down performance in addition to system hydraulics to consider if pursuing such a design.

Matthew Howard's Response

My experience is in line with Michael's second paragraph. We use VFDs with no valves for optimum energy efficiency. If we have a valve downstream, it is often due to the minimum pumping of the VFD being too large for the process, so the valve is used to backpressure, usually in a split-range control scheme. A "valve" position controller is better, but I would prefer to move the VFD more quickly than the valve. This is because the VFD has more precision and no stiction.

Also, my experience in pulp and paper is that there are "drives guys" and "controls guys." My experience is limited, but drives seem to be a subset of controls that is very specialized and electrical in nature, similar to our quality control system (QCS) scanner systems. It is unlikely in my experience for a DCS manager to spec out and be an expert in VFD selection and installation.

Michel Ruel's Response

I agree with the comments from my colleagues and would like to add my thoughts on loop tuning with VFDs. Proper VFD configuration is crucial, and a common mistake is using inappropriate parameters, particularly the current limit and acceleration/deceleration ramps.

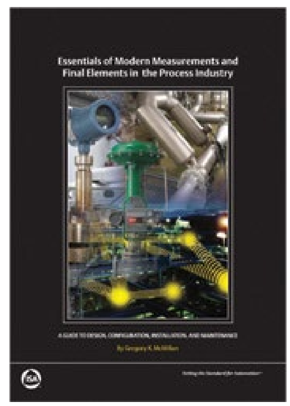
When a PID controller sends a signal to the VFD, if the change is within the configured limits, the control loop behaves as expected. However, if the PID controller requests a large change, the VFD's limits (e.g., current limit or ramp time) will restrict its behavior. This restriction can cause the loop to appear as if it has a large time constant, which may lead to the mistaken conclusion that a higher proportional gain is needed.

If the loop is tuned for large changes (which involve these limits), it will work well for those cases. But when the process variable (PV) is close to the setpoint (SP) and the PID controller makes small adjustments, the dynamics change. The apparent time constant for these small changes becomes much smaller, which can lead to oscillations in the loop.

It is common to see cycling loops with VFDs when the PV is close to the SP. The key is to focus on tuning for small changes, rather than large ones. Properly setting the VFD parameters is also essential to ensure stable loop performance.

Greg McMillan's Follow-up

As I previously noted, there is a serious decline in VFD rangeability when the static pressure is large compared to the system pressure drop. A possible option to extend the rangeability I have not tested, but was mentioned in an email to me 8 years ago by ControlSoft Inc., is the option of installing a throttling valve that is normally wide open. Split-range control is used to start to throttle the valve when the VFD reaches its low-speed limit to move the intersection of the system curve with the VFD curve to a lower flow on the plot of pressure versus flow. The tuning for when the VFD speed is being modulated and when the throttle valve is being positioned is quite different, requiring scheduling of the tuning settings. Directional move suppression offered by external reset feedback might be useful in suppressing unnecessary crossings of the split range point. Also, moving the speed control from the drive into the DCS can result in complications in coordination with speed to torque cascade control and a slower response due to DCS scan time and update rate. In the meantime, more information on variable speed drives can be found in my book, published by ISA, *Essentials of Modern Measurements and Final Elements*.



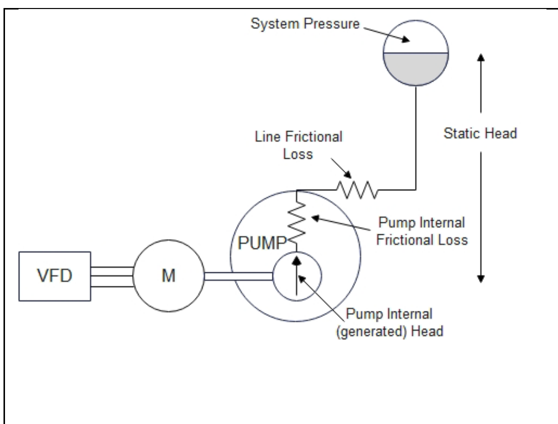
Peter Morgan's Response

I thought I would add a little to the conversation based on the modelling I have just started and some of my previous and earliest experience with pump control.

Ironically, my first task in the mid1970s (yes, that long ago) as a young systems engineer was to model and report on the behavior of the control system for feedwater control, where the electrodes of a liquid rheostat in series with a wound induction motor with slip rings were positioned to vary pump speed. Yes, it could be made to work! with the controller deadband providing a solution to the limit cycle occurring due to backlash and stick-slip. Since then, fluid couplings and VFDs have provided alternative methods for pump speed/flow control but in each case, the installed characteristics should be understood before choosing equipment. Although VFDs are complex systems, the limits of operation and performance issues are commonly due to their misapplication.

A little analysis of the hydraulic equations for the variable speed pump in the delivery of flow to the system can shed light on the reason for the distinct difference in behavior between flow control in systems where the pump is delivering flow into a system with high system pressure and/or high static head and when it is delivering flow into a low-pressure system. Common examples of each of these systems are the high-pressure feedwater supply system for a power boiler and a low-pressure product pipeline. Figure 1 and Figure 2 show each system schematically and the in-service characteristics.

For the power boiler (without a feedwater regulating valve in this example), the pump has to deliver enough head (proportional to speed squared) to overcome the drum pressure, the static head, the pressure drop in the economizer and evaporator (proportional to flow squared) and the pump internal pressure drop (proportional to flow squared). Before the pump delivers any flow at all, the pump internal generated pressure must match the system pressure plus the static head. In the example, with a system pressure of 1000 psi and a static head of 44 psi (100 ft elevation difference between pump and drum), the pump wouldn't deliver flow until it reached 82% speed (see Figure 1). It goes without saying that a non-return valve in the line is a must in this case.



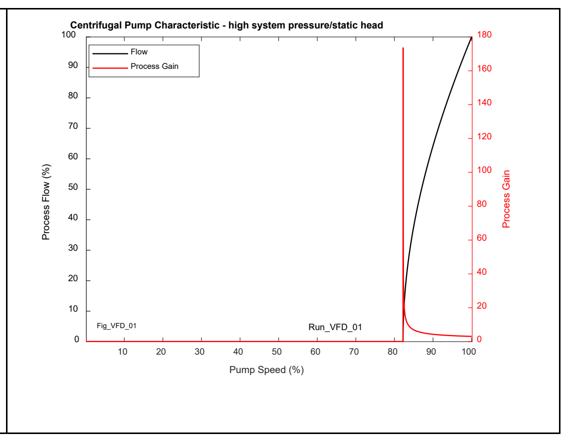


Figure 1 Schematic and in-service flow characteristics for a high-pressure system.

For the low-pressure system with little static head and the line discharging to a surge tank for instance, the pump only has to develop enough head to overcome the pressure drop in the line and pump internal pressure drop to establish a flow.

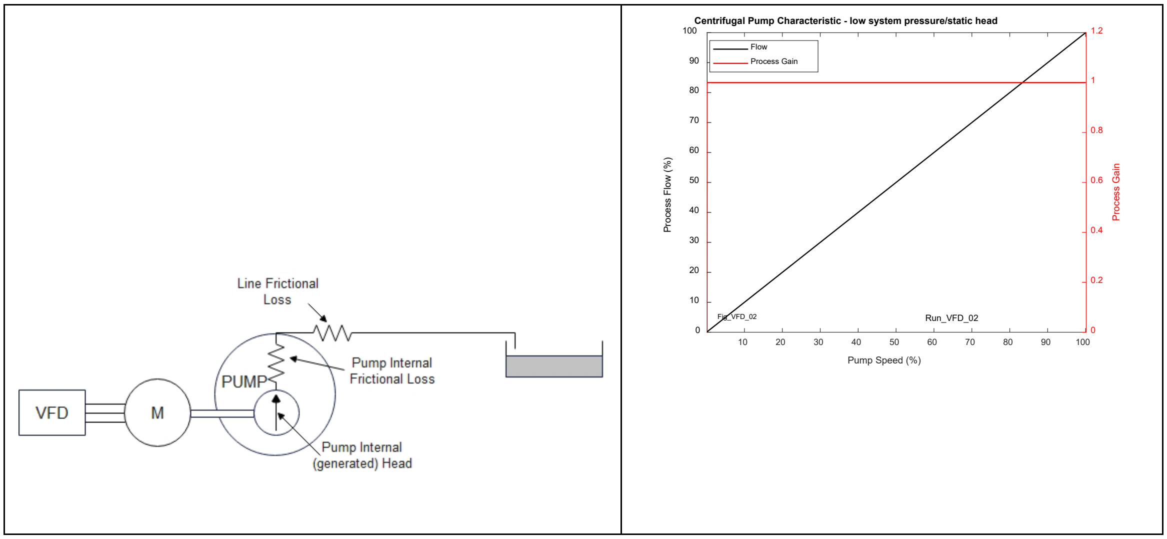


Figure 2: Schematic and in-service flow characteristics for low -pressure system.

For the control engineer, the difference in behavior is salient and, in the case of the high-pressure system, presents a challenge in achieving high turn down with precise and stable control at lower flows.

Why the difference in characteristics? Sometimes this is explained as being due to a convergence of the characteristics of the line and those of the pump but this isn't a particularly helpful explanation. For the centrifugal pump, the developed head is proportional to the speed (N) squared, for a small change in speed (δN), the change in head (δP_p) is then proportional to N_0* δN (where N_0 is the initial speed). For the frictional pressure drop (pump internal pressure drop and line pressure drop) for a small change in pressure drop, the change in flow (δQ) is proportional to $\delta P_f / Q_0$. Since the change in pump internal head is balanced by the backpressure due to the frictional losses, by substitution, the change in flow (δQ) for a small change in pump speed is proportional to $N_0 / Q_0 * \delta N$.

Not surprising then, for a low-pressure system, when the speed and flow both start at zero, the flow increases linearly with the speed so that the process gain is constant, but for the high pressure system, when the flow is zero and the speed 82% (in this example) before flow begins to increase, the process gain is very high (theoretically infinite) only then reducing as speed and flow increase.

For the high-pressure system, while the reduced speed range does not inherently pose a challenge for control (except for resolution), that the gain at flows less than 30% increases significantly means that gain adaptation is difficult to reliably apply. Since the system pressure can vary with load and the static pressure varies with load and temperature, the point at which flow is established by the pump varies and can add uncertainty to low-load operation. Since in the high-pressure system, the effective range of speed adjustment is low, the quantization of the analog output from the controller can have a greater effect on flow control in the high-pressure system than on the low-pressure system and that the D/A converter at the analog output for pump speed control should be 12 bit or more.

So, having made much of the issues with pump speed control with high-pressure systems, is there a solution? Fortunately, there is, and it involves adding a valve downstream of the pump. Although I have found references to schemes involving programmed adjustment / split range operation of the valve and pump speed, I have so far not found much evidence of successful implementations of these schemes.

On the other hand, I do have experience using the valve directly to control flow and modulating pump speed to maintain constant differential pressure across the valve. This is the common practice for boiler feedwater control and has the benefit of providing efficiency gains, low valve wear and high turndown while allowing the use of a linear valve. This and other possible alternatives for flow control using a variable speed pump, either as the only means of flow control or in combination with valve adjustment, will be the subject of a planned study by Greg McMillan and me, with an article forthcoming soon.

About the Authors

Erik Cornelsen is an Automation and Process Control Engineer at DPS Group, a leading system integrator based in Scotland. With over a decade of experience, Erik has worked and lived in six countries, contributing to diverse industrial sectors, including food and beverages, logistics, and construction materials. He holds a Master's Degree in Mechanical Engineering from INSA de Lyon (France) and is a Chartered Engineer, a member of the Institution of Mechanical Engineers (UK), and an active member of the ISA.

ISA Fellow **Gregory K. McMillan** https://www.linkedin.com/in/greg-mcmillan-5b256514/ retired as a Senior Fellow from Solutia Inc. in 2002 and retired as a Senior Principal Software Engineer in Emerson Process Systems and Solutions simulation R&D in 2023. McMillan is the author of more than 200 articles and papers, 100 Q&A posts, 80 blogs, 200 columns, and 20 books. McMillan received the ISA Lifetime Achievement Award in 2010, the ISA Mentor Award in 2020, and the ISA Standards Achievement Award in 2023. He was also one of the first inductees into the *Control Global* Process Automation Hall of Fame in 2001.

Michael Taube https://www.linkedin.com/in/michaeltaube/ is a principal consultant at S&D Consulting, Inc. Serving the greater Process Industries as an independent consultant since 2002, he pursues his passion to make things better than they were yesterday by identifying the problems no one else sees or is willing to admit to and willingly "gets his hands dirty" to solve the problems no one else can. Due to the continued occurrence of individual injuries & fatalities as well as large-scale industrial incidents, he collaborates with Operational Excellence & Safety Culture Experts to promote a real and lasting cultural shift in the Process Industries to help make ZERO Incidents a reality. He graduated from Texas A&M University in 1988 with a Bachelor of Science degree in Chemical Engineering.

Matthew Howard is the Pulp Mill Area Systems Manager for Sappi North America, Somerset Mill, Skowhegan, Maine, a large fully integrated pulp and paper manufacturing facility. He is responsible for multiple DCS systems maintenance and integration. He prefers to use his UMaine Chemical Engineering and technical background to implement process improvements with or without capital investment. Informed by an early stint as a frontline supervisor, he also strives to steadily improve the operator effectiveness of his plant following the ISA101, Human-Machine

Interfaces, and ANSI/ISA-18.2-2016, Management of Alarm Systems for the Process Industries standards.

ISA Fellow **Michel Ruel** is a recognized expert in process control and control performance monitoring and a frequent speaker. Now retired, he led a team that implemented innovative and highly effective control strategies across a wide range of industries, including mining and metals, aerospace, energy, pulp and paper, and petrochemicals. An accomplished author of numerous books and publications, Ruel is also a software designer specializing in instrumentation and process control. He is the founding president of Top Control Inc. and has contributed to projects in multiple countries.

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