Understanding Pump Curves
Presenter: Michael Stroh – Application & Project Engineer, Sulzer Pumps
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OWEA-S: Understanding Pump Curves
The **Static Head** is the total vertical distance that the liquid must be pumped.

The Static Head is measured from the starting water level surface to the discharge water level surface.

The Static Head is normally expressed in “Feet” in the wastewater industry, meaning feet of water column.
The Dynamic Head is determined by analyzing the losses in the entire piping system at various flow rates. The losses are based on the configuration of the piping system. All pipe and fittings through which the water flows must be taken into account.

The Dynamic Head of a system is computed for multiple flow rates, and plotted along with the Static Head to produce a System Head Curve or simply System Curve.
The **Design Flow** is determined by the pumping requirements of the station.

The **Design Head** is determined from the System Curve. The intersection point of the Design Flow and the System Curve provides the Design Head.

The whole purpose of the System Curve is to provide the **Total Head** for a particular system, at any flow rate.
The Pump Curve is then plotted on the same graph as the System Curve.

The intersection point of the Pump Curve and the System Curve defines the Flow and Head at which the pump will operate in this particular system.

The pump will *always* runs at this intersection point. It is physically impossible for the pump to operate at any other point.
Most pump stations actually have a System Curve that continuously changes during the pumping cycle.

This change results from changing static head while the pump is emptying the wet well.

The full range of possible System Curves are normally represented by two curves, one at each extreme of the possible static head.
Understanding Pump Curves

When the Pump Curve is added to the graph, the range of possible operating points during a pumping cycle can be seen.

The pump will operate the higher flow, lower head point at the beginning of the pumping cycle.

The pump will operate at the higher head, lower flow point at the end of the pumping cycle.
Most commonly however a single system curve is provided, and we select the pump with the understanding that it may run a little left or right of the given intersection point.
An actual pump curve for a 12” pump with a 450mm diameter impeller, showing Q-H, P2, and Hydraulic Efficiency.
A duty point of 4500 gpm at 80 feet (40 feet static head) has been added.
Because the impeller is oversized for the duty point, the actual flow and head will be 4712 gpm at 83.7 feet... the intersection point between the pump curve and system curve.
Trimming the impeller to 440 mm shifts the performance curve down so that it intersects the system curve at the duty point.
For most wastewater pumps, the flow limits for smooth reliable operation is from 50% of BEP flow to 125% of BEP flow.
Summary

- The System Curve is a combination of static and dynamic head.
- The static component is based on the vertical distance that the liquid must be pumped (change in elevation).
- The dynamic component is based on pipe and fitting size, quantity, and interior roughness of the material.
- It provides a means of selecting pumps by predicting the Total Head at any flow rate.
- The pump always operates at the head and flow corresponding to the intersection of the System Curve and the Pump Curve.
- When selecting wastewater pumps, the rule of thumb is stay in the range of 50%-125% of BEP flow. Going outside this range is possible, but more detailed analysis of the application is necessary.
Understanding VFD Curves
Primary Benefits of Variable Speed Pumping

There are three primary reasons to use a VFD to control pump speeds:
- Control the output of the pump for process reasons (flow or pressure)
- Reduce energy consumption
- Manage starting current

Secondary reasons to use a VFD can include:
- Manage water hammer
- Improve Power Factor
- Precision control of wet well levels
- Managing stations with wet wells that are too small
Affinity Laws

The Affinity Laws predict the performance of a centrifugal pump at differing speeds:

- The change in flow is proportional to the change in speed:
  \[
  \frac{Q_1}{Q_2} = \frac{n_1}{n_2}
  \]

- The change in head is proportional to the square of the change in speed:
  \[
  \frac{H_1}{H_2} = \frac{n_1^2}{n_2^2}
  \]

- The change in power is proportional to the cube of the change in speed:
  \[
  \frac{P_1}{P_2} = \frac{n_1^3}{n_2^3}
  \]

Q = flow
H = head pressure
P = power
Affinity Laws

Since we don’t know the exact speed the submersible pump is turning at any VFD output frequency, it’s common to substitute the frequency ratio for the speed ratio:

\[
\frac{n_1}{n_2} = \frac{F_1}{F_2}
\]

\[
\frac{1780 \text{ rpm}}{1483 \text{ rpm}} = \frac{60 \text{ Hz}}{50 \text{ Hz}}
\]

n = rotational speed
F = output frequency of the VFD
Calculating Using the Affinity Laws

Therefore, for a pump delivering 2000gpm at 100feet, with a BHP of 67hp, reducing the speed from 60 Hz to 50 Hz:

\[
\begin{align*}
\frac{60 \text{ Hz}}{50 \text{ Hz}} &= \frac{2000 \text{ gpm}}{1667 \text{ gpm}} \\
\frac{60 \text{ Hz}^2}{50 \text{ Hz}^2} &= \frac{100 \text{ ft}}{69.4 \text{ ft}}
\end{align*}
\]

- \(Q\) = flow
- \(H\) = head pressure
- \(P\) = power
Calculating Using the Affinity Laws

Reducing the frequency (and rotational speed) from 60Hz to 50 Hz, or about 16.7% results in:

- A flow reduction of 16.7% to 1667 gpm
- A head reduction of 30.6% to 69.4 feet
- A power reduction of 42.1% to 38.8 hp

Of course the pump will not necessarily run at this new flow and head. The actual new operating point depends on where the system curve intersects with the reduced speed pump curve.
Example pump, 8" discharge, 4 pole, 115 HP, full speed curve
Understanding VFD Curves

Reduced speed curves are parallel to the full speed curve, and follow the affinity laws.

Flow reduction is directly proportional to the speed reduction.

Head reduction is proportional to the square of the speed reduction.

Reduced speed curves shown in 5 Hz increments.
Understanding VFD Curves

Lines of constant efficiency added to the curve
Example system curve added

Full speed duty point is 3600gpm at 95 feet, with a 30 foot static head

Pump performance at any speed can be determined by the intersection point of the system curve and appropriate reduced speed pump curve
The same pump with a slightly different system curve

Full speed duty point is still 3600gpm at 95 feet, but now with an 85 foot static head
First Rule of Thumb

First rule of thumb:

Applications where the static head is greater than 50% of the total head are not usually good applications for VFD variable speed pumping. This is because:

- Since the system curve is very flat, the pump efficiency at the reduced speed operating point falls off rapidly. The opportunity for energy savings at reduced speed is minimal.
- Since the system curve is very flat, there is very little useable speed reduction range.
- Pump rotational speed at reduced speed, lower flow conditions remains very high, resulting in high energy recirculation cavitation, which can damage the pump.
Understanding VFD Curves

10" pump selection with 25 ft static head, 6 pole 115hp motor

![Graph showing VFD Curves with pump selection point indicated]
10” pump selection with 25 ft static head, 6 pole 115hp motor

Useable speed adjustment range down to below 30 Hz (about 800 gpm)

Efficiency increases as the pump is slowed down, to a max of 80.4% at 2100 gpm, then begins to fall

Efficiency falls to 65% at 800 gpm
10” pump selection with 60 ft static head, 6 pole 115hp motor
10” pump selection with 60 ft static head, 6 pole 115hp motor

Useable speed adjustment range down to about 42 Hz (about 1100 gpm)

Efficiency increases as the pump is slowed down, to a max of 80.4% at 2800 gpm, then begins to fall

Efficiency falls to 60% at 1100 gpm
Second Rule of Thumb

Second rule of thumb:

*For variable speed applications, select pumps with the full speed operating point to the right of BEP whenever possible.*

- Selecting to the right of BEP improves efficiency at reduced speed since the intersection point with the system curve moves toward BEP when slowing down.
- Variable speed applications often allow the use of smaller, less expensive pumps.
- Smaller pumps and selections right of BEP provide the best opportunity for energy savings at reduced speed (where the pumps run most of the time).
- Check NPSH margin for all selections, especially when selecting to the right of BEP!
Establishing Minimum Speeds

The minimum speed the pump can run in a VFD application is dependant on several factors:

- Fluid velocities through the pump and the piping systems. For normal wastewater you must maintain 2.5ft/sec in horizontal runs and 3ft/sec in vertical runs to keep solids suspended.

- Meet the pump manufacturer’s minimum flow requirements for the selected pump to avoid damaging recirculation cavitation. This can range from 20% of BEP flow to 50% of BEP flow, depending on the impeller design and operating speed.

- Maintaining high enough rotational speed to keep the motor’s cooling system functioning. The min speed for proper cooling system operation depends on the type of cooling system provided.
Clogging issues with pumps on VFDs

Pumps running on VFDs are more prone to clogging than constant speed pumps. This is because:

- At reduced speed, fluid velocities through the impeller and in the piping can drop significantly allowing rag material to build up
  - At reduced speed, material moves more slowly through the impeller and volute and can build up, creating a clog.
  - In the impeller, the natural scouring action which aids in rag handling can be greatly reduced
  - Material can build up in the discharge piping, and eventually back up into the pump
  - In dry pit, material can build up in the suction piping, and overwhelm the pump with solids when the speed is ramped up
Other Important VFD setting and operational parameters

Modern VFDs have many configuration options that must be set during startup. Setting these parameters properly can make the difference between a good VFD pumping system, and a poor one.

- Constant torque/variable torque: Centrifugal pumps are variable torque machines, so this parameter should always be set to variable torque.

- Acceleration and deceleration ramp: Initial ramp setting should be 10 sec for both accel and decel. This should be tuned to field conditions with the understanding that shorter ramp times are usually preferable (especially with systems that have a high percentage of static head). If water hammer is not an issue, coast to stop is preferred over controlled deceleration.
**Understanding VFD Curves**

**Other Important VFD setting and operational parameters**

- **Slip compensation:** This parameter should be turned OFF unless the pump manufacturer specifically states that it should be on for the particular application. Slip compensation attempts to run the motor at full synchronous speed by increasing the max frequency above 60 Hz. This can cause overload and overheating of the motor.

- **Minimum frequency:** This must be set to an appropriate frequency to meet the minimum flow requirements of the system as previously discussed. Failure to set the minimum frequency to an acceptable level can cause the level controls or an unsuspecting operator to run the pump continuously at shutoff head; damaging the pump.

- **Maximum frequency:** This should be set to the name plate frequency of the motor (60Hz in N. America) to prevent over speeding of the pump. Only set the max frequency above 60Hz if recommended and approved by the pump manufacturer.
Understanding VFD Curves

Other Important VFD setting and operational parameters

- Speed control settings: The control system should be set to ramp up the pump to full speed and allow it to stabilize before dropping it down to level control speed. This is normally accomplished through the PLC or controller rather than through the VFD settings. Systems that ramp up to control speed directly without a short run at full speed are more likely to clog.

- Parallel pumps on VFDs: When multiple identical pumps are run in parallel on VFDs, all pumps must be run at the same speed. If a VFD pump is to be run in parallel with a constant speed pump, the VFD pump must be run at full speed. Exceptions can be made to the above rule if a detailed analysis of the pump curves and system curve has been performed, and it is found that the slower running pump will be running at an acceptable point on the curve.
Summary

The general rules of thumb for selecting variable speed pumping systems are:

- Applications where the static head exceeds 50% of the duty head are not usually good applications for variable speed pumping
- Select pumps so that the primary, full speed duty point is to the right of the pump’s BEP (but watch NPSH margin)
Summary

Some other guidelines:

- Allow about a 5-10 percent motor power reserve at full speed to account for extra heat generated in the motor.

- Use motors that are acceptable for VFD service, and use appropriate filters for long cable runs to prevent damage to the motor.

- Size and select VFD and Motor combinations with an emphasis on current, not horsepower, to be sure the VFD has adequate output capability for the application.

- Carefully consider operational parameters for VFD stations to minimize the possibility of clogging.

- Apply VFDs only where there is a real benefit in efficiency or process control. Don’t fall for the argument that VFDs *always improve* the efficiency and performance of pump systems, it’s simply not true. Some systems can benefit, but many cannot.
The End