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JOHN BROOKS COMPANY - WHITE PAPER

VFD SELECTION FOR VARIABLE AND FIXED SPEED PUMPING APPLICATIONS

SIZING, HARDWARE SELECTION, CONTROLS & SOFTWARE

This white paper discusses the following selection criteria for VFD's in pumping applications.

- Sizing VFD's and motors for different pump applications.
- Variable Torque (Normal Duty) VFD rating for centrifugal pumps compared to Constant Torque (Heavy Duty) VFD rating for positive displacement pumps.
- Comparing the common NEMA Enclosure ratings for VFD's and considerations for heat dissipation
- Optional and auxiliary hardware for VFD's and where they should be applied.
- VFD control Inputs and Outputs (I/O) and their uses for pump applications.
- Different VFD control modes for pumping application and where they should be applied.

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APPLICATIONS

Pressure Wash

Lift Stations

Variable Speed Pressure Boost

Booster Pumps

INTRODUCTION

Variable Frequency Drives (VFD's) are often used in pumping applications where the speed of the pump needs to be constantly ramped up or down to maintain a set discharge pressure with varying system conditions. A common example is a pressure wash system feeding several spray guns that open and close on demand. In this application VFD's provide considerable energy savings compared to running the pump at full speed and bypassing excess flow through a pressure relief valve.

VFD's are also used to drive a pump at a fixed speed other than the motor's synchronous speed to allow flexibility in the pump performance when design conditions are uncertain. A common example is a centrifugal drainage pump were the system curve or the required flow rate is not certain, or may change over time. Other applications requiring a direct drive motor can use VFD's to reduce the speed of the motor to meet the duty point.

For either fixed speed or variable speed applications, a number of criteria should be considered when selecting a VFD and motor. Basic criteria such as selecting the VFD to meet the motor full load amps (FLA), and ensuring the motor is inverter duty rated are well known. This white paper discusses selection criteria which may not be as well understood by those involved in selecting or sizing VFD's for pump applications. The first two points discussed focus on sizing VFD's and pump motors properly, the third and fourth points focus on VFD hardware and components, and the last two points focus on VFD control and software features.

Sizing Motors and VFDs - Available Horsepower and Torque

Direct Drive Systems

When sizing a motor and VFD in a direct drive system the motor horsepower may need to be significantly higher than the break HP of the pump. The motor is capable of producing a relatively fixed torque at speeds from near 0 to 60Hz. The motor is not able to produce a fixed HP at reduced speeds. The typical speed, HP and Torque relationship for a VFD is shown in figure 1 below.

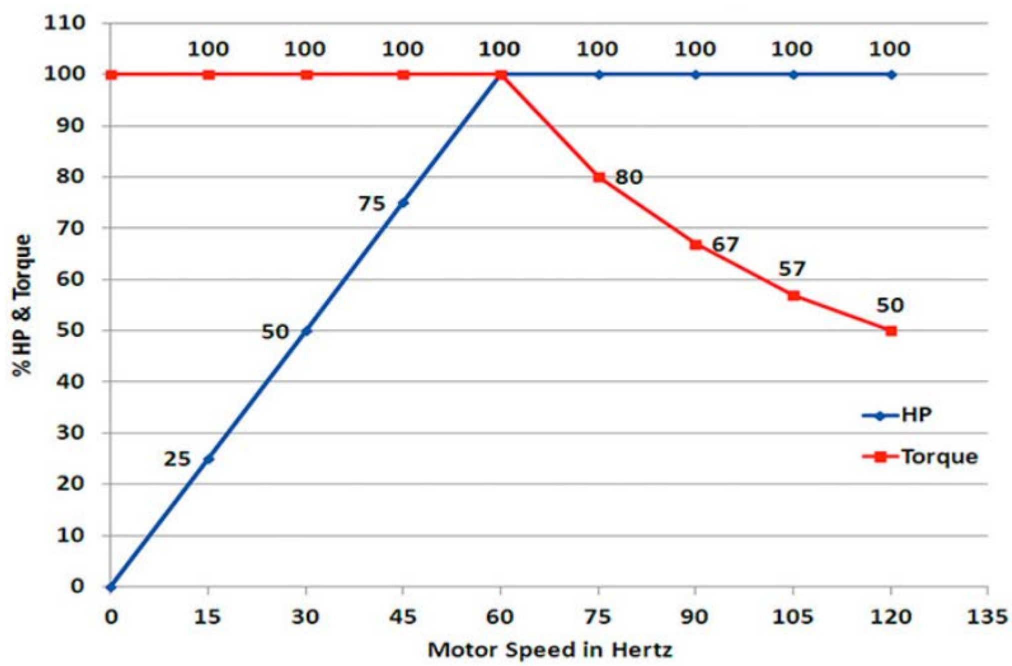

Figure 1: Available Power and Torque vs Motor speed

The motor and the VFD must be selected to provide at least the required HP (and torque) at all operating speeds.

The available HP at a given operating speed is calculated as:

Available HP = Motor Nominal HP x Motor operating RPM / Motor Nominal RPM.

If the pump duty point is 1380RPM then the available HP from a 10HP 1765RPM motor is:

Available HP = 10 HP x 1380RPM / 1765RPM.

= 7.8 HP

A detailed example with calculations is included in appendix A. As explained in the example, if the BHP were 6.5HP at 1380 in the above example, over speeding the motor slightly with the VFD may be preferable to permit the use if a 7.5 HP 1380RPM motor and VFD and a more cost effective solution.

The motor manufacturer should be consulted when over speeding a motor, however typically a 2 pole 3600 RPM motor can be operated up to 75Hz and a 4 pole 1800RPM motor can be operated up to 135Hz.[1]

Belt Driven or Gear Box Systems

When using belt drive systems or a gear box with a variable speed pump application such as a pressure wash system, it is best to size the sheaves or gear box ratio so that the peak HP required is as close as possible to the motor nominal speed.

For example, if a pump's maximum required HP is at a pump speed of 875 RPM and a 1750 RPM motor is being used then the sheave or gear box ratio should be 2:1. At lower speeds the available HP will reduce proportional to the motor speed. Typically the power (HP) required by the pump will reduce either proportional to the pump speed (constant torque loads such as a positive displacement pump) or proportional to the cube of the pump speed (variable torque loads such as centrifugal pumps governed by the affinity laws). For both constant torque and variable torque loads the motor will not be overloaded at reduced speed provided the peak HP required is at the motor nominal speed, which can be achieved by selecting the proper sheave or gear box ratio.

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[1] https://deltaautomation.wordpress.com/2014/03/11/operating-motors-at-higher-speeds-than-their-nameplate-speed-can-it-be-done/

CONSTANT TORQUE VS VARIABLE TORQUE AMPERAGE RATINGS

As described above, VFD's can provide relatively constant torque at speeds from near 0 to 60Hz. This may lead to confusion regarding the constant torque (CT) and variable torque (VT) amperage rating of a drive. These ratings are determined by the maximum over-amperage rating the drive can sustain for short periods of time, typically experienced when starting the pump. These ratings are not determined by the VFD's ability to provide constant torque at all speeds.

Constant torque loads such as positive displacement pumps starting against full system pressure require a higher torque to start the pump than a variable torque load such as a centrifugal pump starting against little discharge pressure. The required torque is directly related to the amperage drawn by the motor, and it is for this reason that constant torque loads require VFD's that can provide higher starting amps for a short period of time.

The typical over amperage requirements for CT and VT ratings of VFD's are listed below.

CT or Heavy duty rating: 150% for 60 seconds, 200% for 3 seconds

VT or Normal duty rating: 110 - 120% for 60 second81s, 150% for 3 seconds

Some manufacturers list both the variable torque amp rating as well as a lower constant torque amp rating for the same drive. These are also referred to as normal duty (ND) and heavy duty (HD) rating by some manufacturers.

500-690V - Three Phase

Electrical Data					Mechanical Data				Purchasing Data
Current (A)		Built-In Dynamic Braking	Maximum Applicable Motor		Frame	Weight (lb)	Degree of Protection	Dimensions (in) H x W x D	Part Number
			ND*	HD*					
ND*	HD*		HP	HP					
22	19	Optional	20	15	D	75	NEMA 1	21.7 x 11.8 x 12.0	CFW110022T6ONBZ
27	22	Optional	25	20	D	75	NEMA 1	21.7 x 11.8 x 12.0	CFW110027T6ONBZ
32	27	Optional	30	25	D	75	NEMA 1	21.7 x 11.8 x 12.0	CFW110032T6ONBZ
44	36	Optional	40	30	D	75	NEMA 1	21.7 x 11.8 x 12.0	CFW110044T6ONBZ
53	44	Optional	50	40	E	141	NEMA 1	26.6 x 13.2 x 14.1	CFW110053T6ON1NBYZ
63	53	Optional	60	50	E	141	NEMA 1	26.6 x 13.2 x 14.1	CFW110063T6ON1NBYZ
80	66	Optional	75	60	E	141	NEMA 1	26.6 x 13.2 x 14.1	CFW110080T6ON1NBYZ
107	90	Optional	100	75	E	141	NEMA 1	26.6 x 13.2 x 14.1	CFW110107T6ON1NBYZ
125	107	Optional	125	100	E	141	NEMA 1	26.6 x 13.2 x 14.1	CFW110125T6ON1NBYZ
150	122	Optional	150	125	E	141	NEMA 1	26.6 x 13.2 x 14.1	CFW110150T6ON1NBYZ
170	150	Standard	150	150	F	370	IP20	48.6 x 16.9 x 14.2	CFW110170T6ONBYZ
216	180	Standard	200	200	F	370	IP20	48.6 x 16.9 x 14.2	CFW110216T6ONBYZ
289	240	Standard	300	250	F	370	IP20	48.6 x 16.9 x 14.2	CFW110289T6ONBYZ
315	289	Standard	300	300	G	569	IP20	49.8 x 21.1 x 16.8	CFW110315T6ONBYZ
365	315	Standard	350	300	G	569	IP20	49.8 x 21.1 x 16.8	CFW110365T6ONBYZ
435	357	Standard	450	350	G	569	IP20	49.8 x 21.1 x 16.8	CFW110435T6ONBYZ

* ND - Normal Duty

- 110% during 60 seconds every 10 minutes
- 150% during 3 seconds every 10 minutes

* HD - Heavy Duty

- 150% during 60 seconds every 10 minutes
- 200% during 3 seconds every 10 minutes

Notes: The maximum motor power ratings listed above are based on WEG 2 and 4 pole motors. For motors with different numbers of poles (ie. 6 and 8 poles), other voltages and/or from other manufacturers, specify the VFD through the motor rated current.

Figure 2: Variable Torque / Normal Duty (ND) and Constant Torque / Heavy Duty (HD) amp ratings for CFW-11 WEG VFD

There are other load ratings for VFD's such as Extended Torque (ET) and Constant Power (CP), but these are seldom applicable to pumping applications.

When sourcing a VFD for a constant torque pumping application the VFD supplier should be consulted to ensure the VFD's amperage rating is the constant torque or heavy duty rating. Failure to do so could result in current overload or torque limit shutdown alarms.

Enclosure Ratings and Heat Dissipation

NEMA and IP Enclosure Ratings

Electrical Enclosures are rated according to either the NEMA or IEC IP standard according to the level of protection the enclosure provides against dust and debris, water, ice, and corrosion. NEMA also rates enclosures for hazardous areas which are designed to contain an internal explosion without causing an external hazard, or prevent an explosion.

This paper will focus on the NEMA rating system. Further information about comparisons between NEMA and IP ratings can be found at:

https://www.nema.org/Products/Documents/nema-enclosure-types.pdf

The higher the degree of protection provided by the enclosure, the more difficult heat dissipation becomes. Figure 3 below provides a listing of the most common NEMA ratings for VFD's and the degree of protection they provide.

Provides a Degree of Protection Against the Following Conditions	1	4	4X	3R	12
Access to hazardous parts	X	X	X	X	X
Ingress of solid foreign objects (falling dirt)	X	X	X	X	X
Ingress of water (Dripping and light splashing)	...	X	X	X	X
Ingress of solid foreign objects (Circulating dust, lint, fibers, and flyings **)	...	X	X	X	X
Ingress of solid foreign objects (Settling airborne dust, lint, fibers, and flyings **)	...	X	X	X	X
Ingress of water (rain, sleet, snow)	...	X	X	X	...
Ingress of water (Hosedown and splashing water)	...	X	X	...	...
Oil and coolant seepage	...	...	..	...	X
Oil or coolant spraying and splashing	...	...	...	...	...
Corrosive agents	...	...	X	...	...
Ingress of water (Occasional temporary submersion)	...	...	...	...	...
Ingress of water (Occasional prolonged submersion)	...	...	...	...	...

Figure 3: Common VFD NEMA ratings [2]

All VFD's generate considerable heat from the high frequency switching and control circuits which are inherent to their operation. The majority of this heat is dissipated either by air movement (convection) or conduction through the enclosure walls or a heat exchanger or heat sink.

[2] https://www.nema.org/products/documents/nema-enclosure-types.pdf

Comparing VFD Enclosure Ratings

NEMA1 and NEMA12 rated enclosures are not required to be air tight, and typically inexpensive fans are used to blow the surrounding air through the VFD and carry the heat away to the surroundings. Provided the surrounding air is not above 30C-40C, utilizing convection is the most effective means to dissipating large amounts of heat. As a result, NEMA1 and NEMA12 VFD's are the most cost effective design particularly for VFD's rated 30amps and above.

Figure 4: NEMA 1 rated VFD with open slats for ventilation

NEMA4 and 4X enclosures typically need to be air tight to provide wash down protection against hose directed water. These air tight enclosures typically rely on conduction only to dissipate heat, which is significantly less effective than convection. This significantly limits the amp rating of NEMA4 and 4X standalone VFD's. Typically, the maximum size for a standalone NEMA4, or 4X VFD is in the 30-40amp range regardless of voltage.

If a NEMA4 VFD larger than 40amps is needed a separate enclosure can be provided with an open-style or NEMA 1 VFD installed inside. Many open or NEMA1 VFD's have a removable NEMA4 keypad that can be mounted on the front of the front of the enclosure. The enclosure may include one or more of the following heat dissipation methods:

- An oversized enclosure to allow conduction through a greater surface area.
- Air to air heat exchangers or heat sinks to further improve conduction from the inside the enclosure
- Special NEMA4 or 4X rated fans to blow air through the enclosure which can dissipate considerable heat (convection).
- Air conditioning units with refrigerant circuits.

Figure 5: NEMA4X rated VFD, and Custom NEMA 4 enclosure with NEMA 1 VFD (NEMA4 keypad).

NEMA 7 (explosion proof) enclosures can be used if a VFD needs to be installed in a classified area containing explosive gases or dust. The term explosion proof is somewhat misleading. The thick walls of an explosion proof enclosure do not prevent an explosion, rather they contain the explosion within the enclosure. If gasses enter the enclosure through failed conduit seals or other means the VFD can cause an explosion inside and will be destroyed, but the flames will not reach the outside atmosphere and cause a larger explosion. Explosion containing enclosure may be a more suitable term for NEMA7 rated enclosures.

Figure 6: NEMA 7 Enclosure containing VFD, NEMA4 Air Purge Panel

An alternate solution is to pressurize a NEMA4 rated enclosure with a non-explosive gas, typically compressed air. This ensures that no explosive gases will enter the enclosure. This solution may be more cost effective than a NEMA7 rated enclosure, but needs to include a pressure switch to verify positive pressure is maintained in the enclosure and a means to automatically power down the VFD if the air pressure is not maintained. Typically it is more cost effective and safer to simply install the VFD outside the classified area.

Other factors affecting heat dissipation

It is important to remember that whether the heat is dissipated by convection or conduction, the temperature for the surrounding air will influence the temperature within the VFD enclosure. Most VFD's are rated for an ambient temperature of 40C, but it is best practice to keep the ambient temperature well below the maximum limit.

Ambient temperature measurements and calculations should be made to determine the maximum expected temperature. The heat load from nearby equipment (e.g. boiler) or from sunlight exposure also need to be considered when determining the cooling requirements for a VFD.

If the ambient temperature will be 40C or above specialty VFD's with oversized cooling equipment and internal components with higher temperature ratings are available, but these are costly. Alternately, cooler air from another location can be blown through the VFD. It is typically more cost effective to simply move the VFD to a cooler location.

ADDITIONAL HARDWARE FEATURES

There are several protective devices available to protect both the VFD and the motor it serves:

- **Fast acting semiconductor Fuses:** These special fuses protect a VFD from catastrophic failure if there is an electrical short somewhere in the VFD or motor circuit.

- **Local Disconnect:** A local disconnect is useful when servicing the motor, particularly when the feeder panel is far away from the VFD.

- **Line reactor:** A line reactor helps protect a VFD from poor power quality, either from poor utility power or electrical disturbances caused by nearby equipment (e.g. another VFD). A line reactor is recommended whenever there are two or more VFD's in close proximity.

- **Load reactor:** A load reactor is recommended to protect the drive and motor when the wire length from the VFD to the motor is between 100-500, or 300-500 feet (depending on the motor). These are typically installed external to the drive. [3]

- **dV / dT filter:** Similar to a load reactor, but used when the wire length from the VFD to the motor is between 500-1000 feet.[3]

Some higher end VFD's offer some of these features integral to the VFD. Cost effective VFD's typically do not and these features would need to be installed in a custom VFD enclosure, or external to the VFD.

[3] https://www.rae.ca/wp-content/uploads/Line%20Reactor%20White%20Paper%20AN0032.pdf

I/O Requirements

The majority of VFD's incorporate a means to manually start and stop the motor with a keypad, and manually adjust the speed with a keypad or potentiometer. Most VFDs can also integrate into a control systems to automate these functions.

Virtually every VFD has some inputs and outputs (I/O), and higher-end VFDs have multiple I/O's and full-feature communications ports. These can be connected to an external PLC control system, or pressure and flow measuring devices to automate motor speed commands as well as START / STOP commands.

Discrete I/O and Their Uses

Discrete inputs interface the VFD with control devices such as pushbuttons, selector switches, flow switches, pressure switches, current transducer switches, and PLC digital outputs. These signals are typically used for functions such as start/stop, forward/reverse, external fault, preset speed selection, and fault reset.

Discrete outputs can be transistor, frequency pulse or relay types. Typically, transistor and frequency pulse outputs drive interfaces to PLCs, motion controllers, pilot lights, and auxiliary relays. Relay outputs are capable of higher voltage and amperage switching and are can be used to control electric valves, alarm horns or other devices.

Analog I/O and Their Uses

Analog inputs interface the VFD with control devices such as pressure transmitters, level transmitters, flow transmitters and PLC analog outputs. The most common signals are 4-20ma signal and 0-10VDC.

These analog signals are used for adjusting the speed of the motor by either:

a) Adjusting the VFD speed directly proportional to the analog input signal (e.g. 5VDC = 50% speed, 10VDC = 100% speed).

b) Adjusting the VFD speed to maintain the analog signal at a certain level through Proportional-Integral-Derivative (PID) control built into the VFD's software. A typical example is connecting a pressure transmitter to an analog input to ramp the motor speed up and down as the pump discharge pressure signal falls and rises around a fixed pressure set-point.

Analog outputs are typically 4-20ma or 0-10VDC. These are used to transmit the actual motor speed, current output, voltage output, or motor torque. These are useful measures to log for monitoring processes, preventative maintenance, or fault diagnostic purposes.

VFD Control Modes

VFD control mode choice greatly depends on the application. The four common VFD control modes are volts-per-Hertz (V/Hz), volts-per-Hertz with encoder, sensorless vector (sometimes called open-loop vector), and closed-loop vector control.

For most pump VFD applications V/Hz and sensorless vector provide sufficient accuracy. These two methods are explained below.

Volts-per Hz (V/Hz) Control Mode

V/Hz control is the simplest motor control method and is often used as a "plug and play" VFD. There is no motor tuning required, and minimal parameters that need to be adjusted in the VFD control menu (e.g. Motor FLA, Voltage and RPM).

However V/Hz control provides the lowest speed regulation accuracy (+/- 2-3%), and limits the motor's starting toque to 150% at low speed (0Hz-3Hz). This limited starting torque is more than enough for most variable torque applications such as centrifugal pumps, but may be insufficient for constant torque applications such as positive displacement pumps.

The most common V/Hz control is a simple two point straight line relationship between applied voltage (V) and motor speed (Hz). For example a nominal 600V / 60Hz drive operating at half speed (30Hz) will output 300V to the motor. This is suitable for positive displacement constant torque loads where the power required increases linearly with speed, but is also often used with centrifugal pump variable torque loads.

Some VFD's incorporate 3 to 5 point V/Hz curves to more closely match the power requirements of a centrifugal pump operating on a system curve.

Sensorless Vector (Open Loop) Control Mode

Sensorless-vector control mode has more accurate speed regulation (+/- 0.2%) compared to V/Hz control, and is able to provide more dynamic motor control in applications where the speed is constantly changing (e.g. PID speed control).

Sensorless-vector control is also more complex than V/Hz control, and typically requires a tuning exercise where the motor is uncoupled from the pump, jogged by the VFD, and then coupled back to the pump. This tuning allows the VFD to "learn" the characteristics of the motor. Some VFD's also offer a motor tuning that does not require the motor to be uncoupled, but this method is less accurate.

If speeds lower than 3Hz, or if high starting torque are required then sensorless vector may be required. Sensorless vector is also often required to provide the accuracy and dynamic response needed to automatically adjust the motor speed in response to a pressure, flow, or level transmitter signal as opposed to operating at a fixed speed.

Many VFD's offer both V/Hz and sensorless vector control. Because sensorless vector requires the tuning process, most pump application VFD's ship out with V/Hz control and are only changed to sensorless vector if required during field testing.

CONCLUSIONS

Pump speed control through Variable Frequency Drives offers many benefits. Among these benefits are considerable energy savings, extending the life of the motor and pump by soft starting, allowing motors to be cycled on and off frequently without overheating, and flexibility in the pumping rate if conditions change during the life of the pump, and many others.

Care must be taken when sizing a VFD and motor to ensure there is sufficient power available at reduced motor speeds. The available power from the motor is proportional to the operating speed of the VFD.

Different pumping applications require different VFD's, features, and control strategies:

- Centrifugal pumps require Variable Torque or Normal Duty rated VFD's while positive displacement pumps require the higher rating of Content Torque or Heavy Duty rated VFD's.
- There are a wide variety of NEMA enclosure ratings available depending on the environment that the VFD will be installed in.
- There are several optional hardware features that may be needed to protect the VFD or motor in certain circumstances.
- There are a variety of input and output options to interface the VFD with control systems, flow switches, pressure switches, or other sensors.
- V/Hz control is sufficient for manual speed adjustment or constant speed applications, whereas Sensorless Vector Control is often needed for applications where the VFD speed is constantly changing to maintain a certain process parameter (e.g. discharge pressure or flow rate).

Appendix A – Sizing Samples

Example 1 – Sizing VFD at reduced motor speed (Torque method)

Consider a centrifugal or positive displacement pump application where the duty point speed of the pump motor is 1380RPM and the duty point power required on the pump curve is 6.5HP. A 1765RPM motor with a VFD to reduce its speed to 1380RPM is being considered. What size motor and VFD should be selected?

Torque, power and speed are related as in equation 1 below:

Power (HP) = Speed (RPM) x Torque (ft-lbs) / 5250 (1a)

Or alternatively

Torque (ft-lbs) = 5250 x Power (HP) / Speed (RPM) (1b)

For this example the maximum / duty point torque required at the pump shaft is:

Torque (ft-lbs) = 5250 x 6.5HP / 1380RPM

= 24.7 ft-lbs

If a 1765RPM motor is to be used, the minimum power required is:

Power (HP) = 1765RPM x 24.7 ft-lbs / 5250

= 8.3 HP

A 10HP motor would need to be used, with a 10HP VFD.

In direct drive systems it may be preferable to over speed the motor slightly than to select a motor with the next higher speed. For example, take the same application as above. If a 1155 RPM motor is selected, a 7.5HP motor and smaller 7.5HP VFD can easily meet the duty point by over speeding the motor to 1380 RPM or 71.7 Hz.

The available torque from a 7.5HP, 1155 RPM motor at 1380 RPM is:

Torque (ft-lbs) = 5250 x 7.5HP / 1380 RPM

= 28.5 ft-lbs

This exceeds the torque required to turn the pump (24.7 ft-lbs). The 7.5HP 1155RPM motor operating at 1380RPM with a 7.5HP VFD is sufficient for this application.

The motor manufacturer should be consulted when over speeding a motor, however typically a 2 pole 3600 RPM motor can be operated up to 75Hz and a 4 pole 1800RPM motor can be operated up to 135Hz so long as the power and torque requirements of the pump at the higher speed do not exceed the motors rated HP and torque.[4]

Example 2 – Sizing VFD at reduced motor speed (alternate method)

For the same pump as in example 1, the VFD and motor can be sized without getting into the torque calculation by using the motor power available to motor speed relationship shown in figure 1. This method is simpler to apply.

The **available power** from a VFD driven motor at a speed less than 60Hz is proportional to the motor speed:

$$\text{Available Power (HP)} = \frac{\text{Nominal Power (HP) x Operating Speed (RPM)}}{\text{Nominal Speed (RPM)}} \quad \textbf{(2a)}$$

Or alternately we can replace the available power with the required power (6.5HP) and rearrange the equation to calculate the minimum nominal (nameplate) power required at the reduced speed:

$$\text{Minimum Nominal Power (HP)} = \frac{\text{Required Power (HP) x Nominal Speed}}{\text{Operating Speed (RPM)}} \quad \textbf{(2b)}$$

[4] https://deltaautomation.wordpress.com/2014/03/11/operating-motors-at-higher-speeds-than-their-nameplate-speed-can-it-be-done/

For this example the required power from the pump curve is 6.5HP, the nominal speed is 1765RPM, the operating speed is 1380RPM, and the minimum nominal power for the motor and VFD is:

$$\text{Nominal Power (HP)} = 6.5\ HP \times 1765\ RPM / 1380\ RPM$$

$$= 8.3HP$$

A 10HP motor would need to be used, with a 10HP VFD.