

VFD

RECOMMEN- DATIONS

VARIABLE FREQUENCY DRIVE

Flygt



ITT Industries
Engineered for life

VARIABLE FREQUENCY DRIVE

The synchronous speed of an induction motor is primarily a function of the number of poles and the frequency:

$$n = 120 \cdot \frac{\text{frequency}}{\# \text{ of poles}} [\text{rpm}]$$

A slip between actual and synchronous speed is generated by the applied load torque. This slip is usually small, typically 1-3% of synchronous speed. A way to achieve a variable speed motor is to vary the frequency. Such a device is called a frequency converter. Frequency converters, also called variable speed drives, are usually installed to allow for a better process control and to save energy. The usage of variable frequency drive (VFD) control in pump applications is becoming increasingly common. The cost of a VFD has decreased over the years while the performance has improved. A modern VFD is a compact, well-developed unit which is relatively easy to install.

Unlike an old VFD, the modern version does not require as much power margin (de-rating) and so does not affect the induction motor to the same extent, this is due to the fact that VFD switching frequency is higher today. The high switching frequency however, induces transients which can lead to other problems such as nuisance tripping of control equipment. This effect can be minimized by using shielded cables and appropriate

filters. Despite the non-ideal VFD problems with clogging of the pump and sedimentation in pipe systems (due to low velocities) are more likely to occur when the speed of the pump is reduced.

Pumping with variable frequency drives can be separated into two cases.

- A variable continuous flow is required by the process. The normal way to control the flow is by throttling. The use of VFD control will, in all cases, lead to an energy reduction.
- VFD vs. on/off regulation. Variable speed drive is used to reduce losses whilst pumping. The effect of a VFD depends upon the system. Systems with a high percentage of friction losses relative to the static head are suitable for VFD operation. More pure lift systems, on the other hand, are not generally suitable for variable operation. The frequency normally decreases when the speed is reduced and there is a risk that the pump will operate outside allowed operational range. A thorough system analysis has to be performed in order to determine if variable speed control can be economically beneficial. Waste-water pumping is a typical application where VFD and on/off control have to be compared.

For more information, see Flygt brochure "Economical aspects of variable frequency drives in pumping stations".

BASIC PRINCIPLE OF A VFD

In theory the basic idea is simple, the process of transforming the line frequency to a variable frequency is basically made in two steps.

1. Rectify the sine voltage to a DC-voltage.
2. Artificially recreate an AC-voltage with desired frequency. This is done by chopping the DC-voltage into small pulses approximating an ideal sine wave.

A VFD consists basically of three blocks: the rectifier, the DC-link and the inverter.

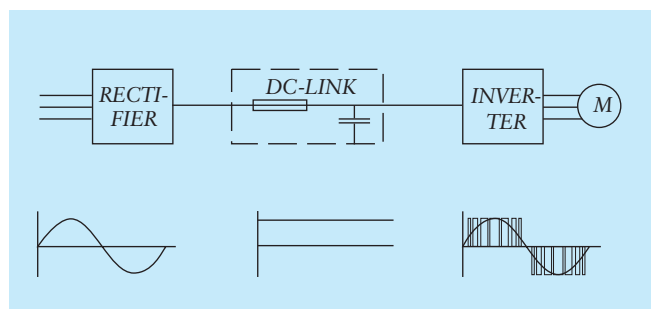


Fig 1. Schematic functions of a VFD

There are three different types of VFDs:

- VSI - Voltage Source Inverter, e.g. PWM.
- CSI - Current Source Inverter.
- Flux vector control.

The CSI has a rough and simple design and is considered to be very reliable, but the output signal means a lot of noise. Furthermore the CSI induces high-voltage transients in the motor. The flux vector control is a more sophisticated type of VFD which is used in applications where the speed should be controlled very precisely, e.g. paper mills. This type is expensive and pump applications cannot take advantage of its benefits. The most common type of VFD, and the one recommended by Flygt, is the PWM – Pulse Width Modulation.

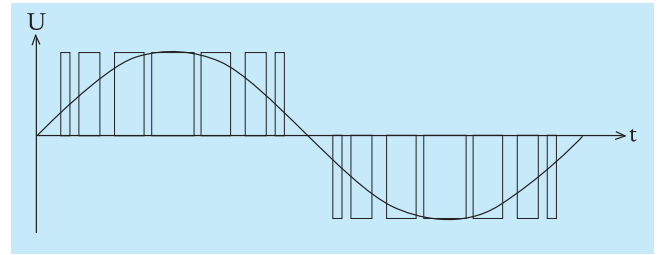


Fig 2. Schematic signal from a PWM-type VFD

The PWM-type VFD normally uses a constant voltage which is pulsed with integrated bi-polar power transistors (IGBT). The sine wave is generated by varying the width of the pulses. The frequency which the transistors are turned on and off by, is called switching frequency. The higher the switching frequency, the better the reproduction of the ideal sine wave.

SYSTEM

The affinity laws state that the flow is proportional to impeller speed at a specific point on the pump curve. Head and NPSH are proportional to the square of the speed, while the power is a cubical function of the speed. The hydraulic (pump) efficiency remains constant when the speed is reduced.

Affinity laws:

$$\frac{Q_1}{Q_2} = \left(\frac{n_1}{n_2} \right) \quad \frac{H_1}{H_2} = \left(\frac{n_1}{n_2} \right)^2$$

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2} \right)^3 \quad \frac{\eta_1}{\eta_2} = 1$$

Ex. A centrifugal pump with nominal frequency 50 Hz is running at reduced speed, 35 Hz. The best hydraulic (pump) efficiency point for the nominal curve is 74 % at a flow of 93 l/s and a head of 9.3 m. Power in best efficiency point (BEP) is 11.5 kW. New BEP is calculated:

- Flow decreases proportionally to the frequency:

$$Q = \frac{35}{50} \cdot 93 = 65.1 \text{ l/s}$$

- Head is reduced to

$$H = \left(\frac{35}{50} \right)^2 \cdot 9.3 \approx 4.6 \text{ m}$$

- Power drops to

$$P = \left(\frac{35}{50} \right)^3 \cdot 11.5 \approx 3.9 \text{ kW}$$

- Hydraulic (pump) efficiency remains the same, 74 %.

All points on the pump curve will move along second degree curves with constant efficiency towards the origin of the co-ordinates when the frequency is reduced.

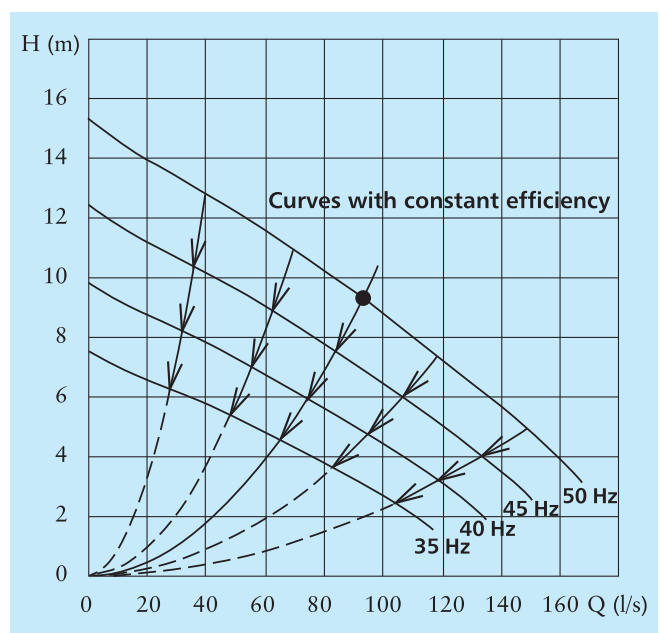


Fig 3. Frequency-regulated pump curve.

The actual duty point is always the intersection between the pump curve and the system curve. The hydraulic (pump) efficiency in systems with a static head will change when the frequency is reduced. The system curve for a system with a static head does not coincide with the constant efficiency curves. The duty point will move along the pump curve, towards the left side of the pump and efficiency curves, (see fig 4 and fig 5).

The system curve for a pure loss system will coincide with a constant efficiency curve, the hydraulic (pump) efficiency will remain constant when the frequency is reduced.

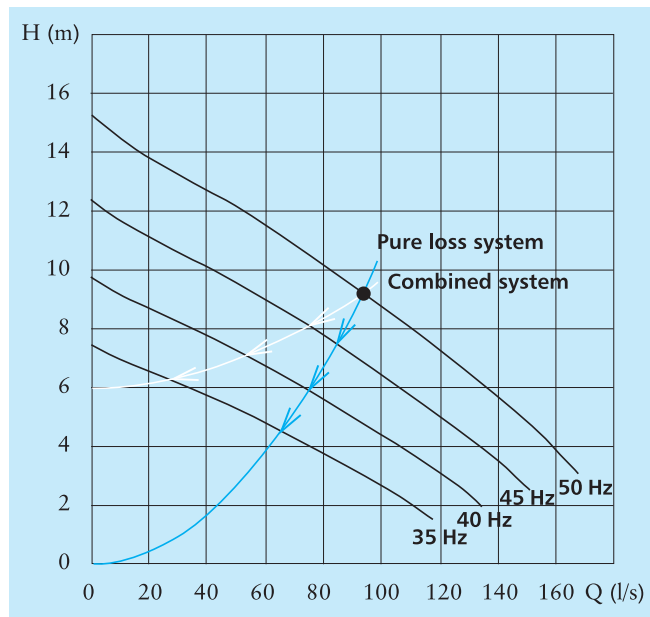


Fig 4. System duty-point movement for a lift system and a pure loss system.

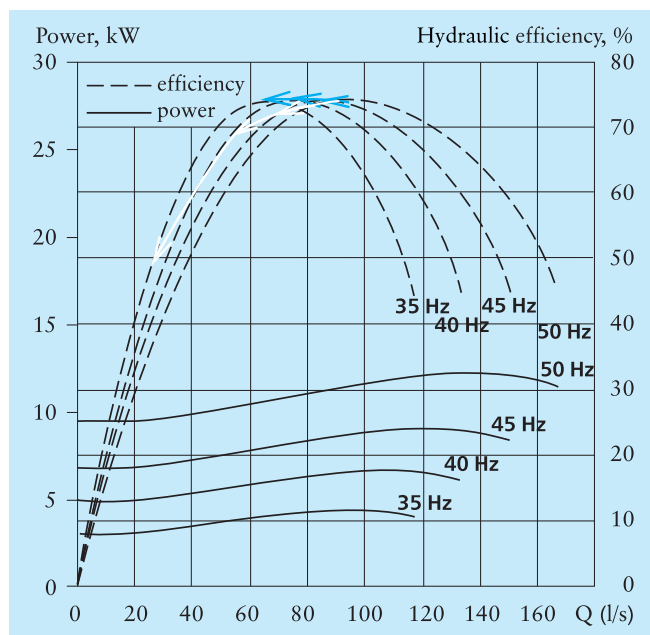


Fig 5. System duty-point movement for a combined system and a pure loss system shown in an efficiency and power diagram.

Ex. The same pump in the previous example is installed in a lift system with a static head of 6 m. The duty point for full speed is the same as BEP, 93 l/s at 9.3 m (eff. 74 %) What happens to the duty point when the pump frequency is regulated down to 35 Hz?

- Flow decreases to 26 l/s, (see fig 4).
- Head is reduced to 6.4 m, (see fig 4).
- Shaft power drops to 3.4 kW (see fig 5).
- Hydraulic (pump) efficiency is not constant, dropping to 50 % (see fig 5).

It is worth noting that the pump stops delivering flow at 32 Hz in this application.

It is recommended, when selecting a pump for VFD duty, that it has its full speed duty point on the right hand side of the BEP. This is due to the fact that the duty point moves towards the left hand side of the efficiency curve when the speed is reduced. Thus, hydraulic (pump) efficiency initially will increase when the frequency is reduced, and the rapid efficiency drop on the curve will not occur until the speed is reduced further.

Some of Flygt's pump curves are partially limited due to power or hydraulic limitations causing vibrations induced by re-circulation in the impeller. This will not disappear when the speed is reduced, and minimum allowed flow will be proportional to the frequency. The power reduction is dramatic when the frequency goes down, even though total efficiency drops. The power limitations disappear quickly.

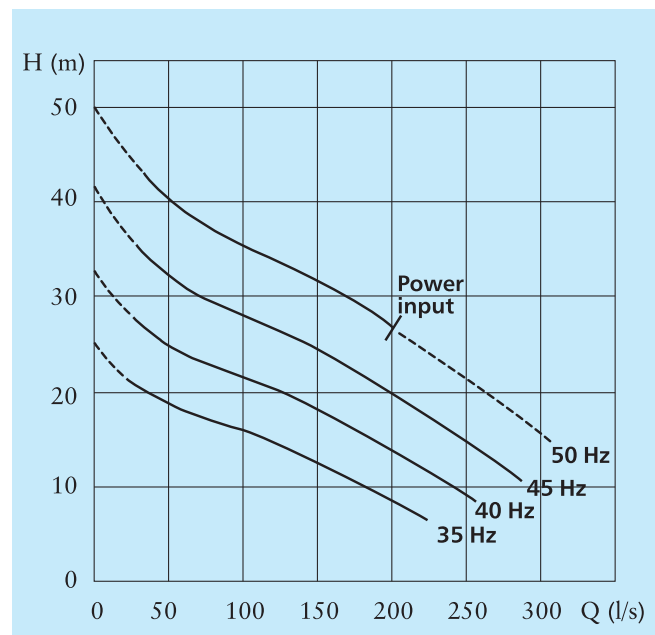


Fig 6. Change of upper and power limitation when frequency is reduced.

The maximum allowed output power (nominal rated power) will decrease when frequency and input voltage are reduced. See section “Motor characteristics” for more detailed information regarding voltage control. The load torque (power) will however be reduced much faster. It is important when selecting a pump with an oversized impeller which cannot, due to power limitations, be run at nominal (e.g. 50 Hz) frequency to compare the output power at desired max. frequency with the max. allowed output power at the same frequency.

There are two standard ways to control the VFDs when running several pumps with parallel connection in the same system: separate and common control. Separate control means that one pump is running at reduced speed and the rest are running at full speed. With common VFD control, all pumps are running with reduced speed at the same time. Separate VFD control is in general

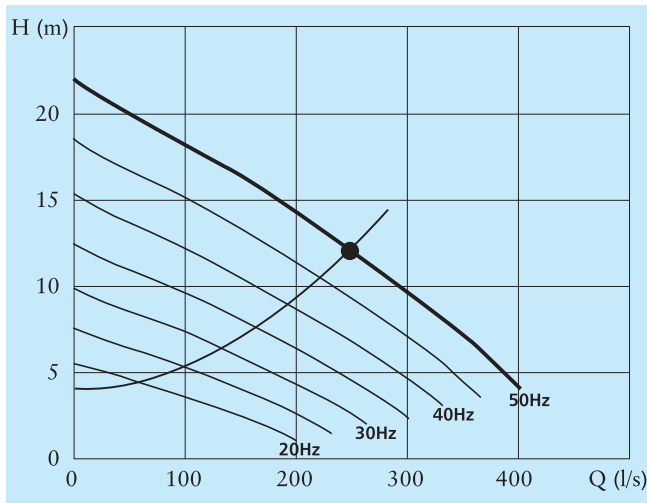


Fig 7. Common VFD control.

MOTOR CHARACTERISTICS

The characteristics of an electric motor will change when the frequency, and thus the speed, is reduced. The output torque from the motor is for a normal motor slip, a function of input voltage and frequency.

There are two standard ways to control the output voltage from a VFD. Voltage that is proportion-

$$T \approx k \cdot \left(\frac{U}{f} \right)^2$$

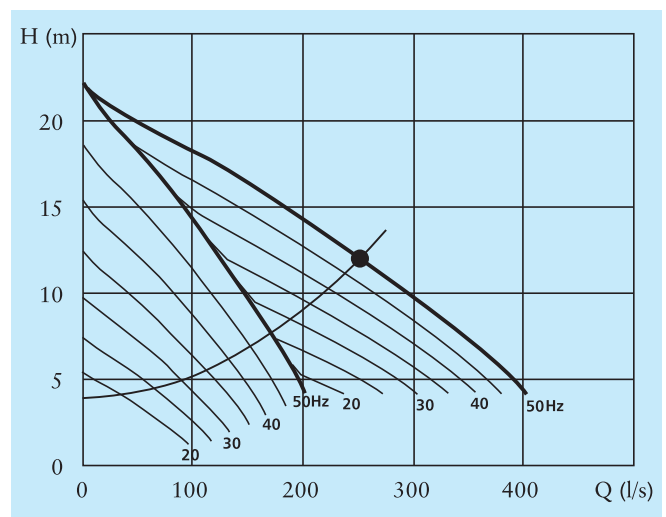


Fig 8. Separate VFD control.

most economical, but there are cases where common control can be a better choice.

The change of total efficiency when the speed is reduced is not only due to system duty point movement, even if it contributes to a major part. Motor and VFD efficiency will also be changed when the frequency is reduced.

nal to the frequency and voltage proportional to the square of the frequency. The available motor torque remains constant when the frequency is reduced, if a VFD with an output voltage proportional to the frequency is used. Having voltage proportional to the square of the frequency implies that torque is proportional to the square of frequency.

A pump represents a cubical load, the load curve is shown in fig 9. The diagram shows how

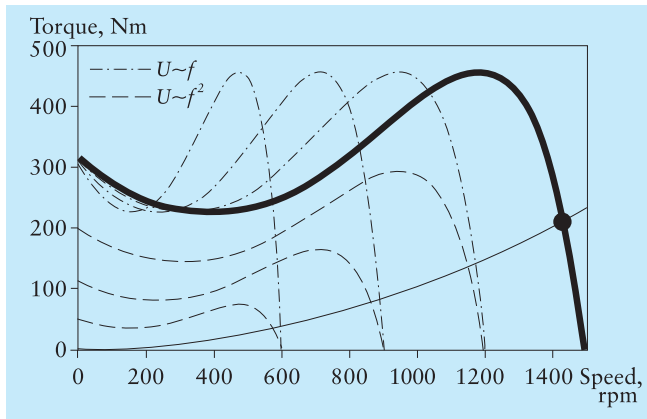


Fig 9. Motor duty-point movement.

the duty point, the intersection between the motor torque curve and load curve, moves down on the right flank of the torque curve for $U \sim f$ when the frequency is reduced. The duty point at nominal

VFD INFLUENCE ON INDUCTION MOTORS

An induction motor feels most comfortable when it is supplied from a pure sine voltage source which mostly is the case with a strong commercial supply grid. In a perfect motor there are no harmonics in the flux and the losses are kept low. When a motor is connected to a VFD it will be supplied with a non-sinusoidal voltage, this signal is more like a chopped square voltage. A square-shaped signal contains all orders of harmonics.

As these harmonics will induce additional heat losses that may require the induction motor to be de-rated, a margin between maximum output power and nominal-rated output power is required. *The required power margin depends upon the application and the supplied equipment. When in doubt contact the local Flygt engineering office for details.*

The performance of the VFDs has improved over the years and is still improving, and the out-

put signal is looking more and more like an ideal sine wave. This implies that a modern VFD with high switching frequency can run with a low or no power margin whatsoever, while an old one might need a margin of 15%. Unfortunately the extensive work needed to develop VFDs' ability to reduce losses in the motor and in the VFD, tends to emphasize other problem areas. VFDs with high switching frequency tend to be more aggressive on the stator insulation. A high switching frequency implies short rise time for the pulses which leads to steep voltage transients in the windings. These transients stress the insulation material. *Flygt recommends reinforced stator insulation for voltages 500 V and above.*

This problem can also be solved partially by adding an output filter to the VFD. See section "Noise suppression" for more details.

SIZING CRITERIA

The data needed to determine the correct size of a VFD are:

- Motor kVA rating.
- Nominal voltage
- Rated current
- Ratio max. torque/nom. torque

If the ratio between peak torque and nominal torque, T_p/T_n , is greater than 2.9 it might be necessary to choose a larger VFD. There are basically two reasons why a motor can have a ratio greater than 2.9:

1. The motor has a high magnetisation level
2. The motor has been de-rated.

RUNNING ABOVE NOMINAL FREQUENCY

Sometimes there is a desire to run the pump at frequencies above the nominal commercial supply frequency in order to reach a duty point which would otherwise be impossible. Doing so calls for extra awareness. The shaft power of a pump will increase with the cube of speed according to the affinity laws. Ten percent over-speed will require 33 % more output power. Roughly speaking the temperature will increase by approx. 80%.

There is however, a limit to what we can squeeze out of the motor at over-speed. Maximum torque of the motor will drop as a function $1/F$ when running above nominal frequency. This is due to the fact that the VFD output voltage has reached its full value at nominal frequency and cannot be further increased. The area above nominal frequency is denoted as the field weakening range. The motor will be overloaded and drop out if the VFD can't support it with a voltage that corresponds to that needed by the torque. In reality the VFDs' over-current protection will trip after a short while if we try to run the pump too far into the field-weakening range. Running above nominal frequency is not recommended, but if required, use the following guidelines:

- Check rated power. Shaft power will increase to the power of three according to affinity laws.
- Check that the VFD is dimensioned for the load increase. Current is higher than nominal rated current (for nominal frequency) in this case.
- Change "Base frequency" of the VFD. Base fre-

quency is the frequency where the VFD output voltage is the same as supplied nominal line voltage.

- If possible, select a machine designed for a higher frequency. When running a pump designed for 50 Hz operation above nominal speed, select a 60 Hz motor.

NPSH-required increases, according to the affinity laws, when running above nominal frequency. Always check that NPSH-available is greater than NPSH-required in order to avoid cavitation.

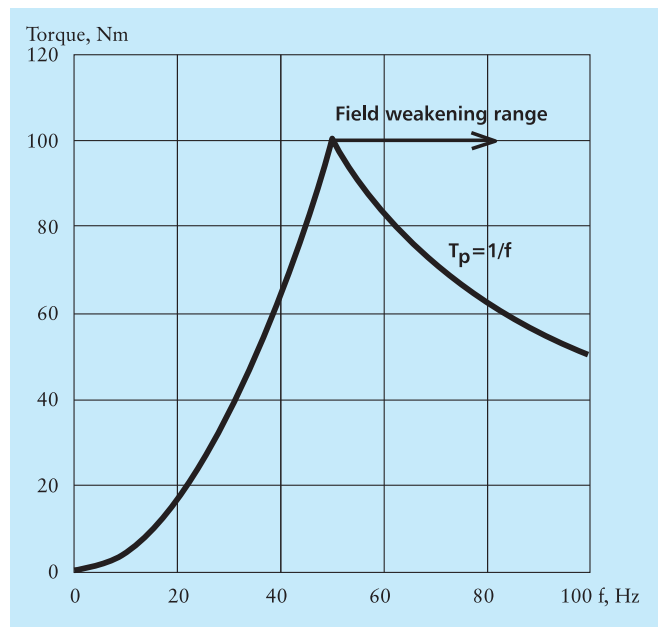


Fig 10. Maximum torque as function of speed

COOLING

There are four cooling systems available for a Flygt pump:

- Cooling by surrounding media, water/air.
- Integrated cooling. Water is pumped through a cooling jacket with back vanes on the impeller. The water flows with rotation in the cooling jacket which surrounds the stator house, e.g. medium and large C pumps.
- Axial-flow cooling. The motor is cooled by the pumped media, the water flows along the outside of the stator house, e.g. Flygt's B, PL and LL pumps.
- External cooling.

The integrated cooling system of Flygt's larger pumps has many advantages. One restriction however is that the pump must not run at too low speeds unless it's working in clear water. The cooling is adequate, but sediment may accumulate and the risk of clogging in the cooling system is higher when the speed is reduced. When the pump is sped up again and retains nominal speed, the efficiency of the cooling system is lower and the motor can overheat.

The critical minimum speed is different for different pumps, but a rule of thumb is that no adverse effects are likely to occur for speeds high-

er than 35 Hz for 2- and 4-pole machines, and 40 Hz for higher pole numbers. Another restriction is that the speed of the pump must not be too low when it's started for the first time after service – or a longer stop. This is due to the fact that all air in the cooling jacket has to be evacuated.

Contact the local Flygt office for detailed information regarding minimum and start-up speed for evacuating air in the cooling jacket.

Axial-flow cooling efficiency decreases rapidly when the flow goes down. The cooling efficiency

is not a function of speed, it's a function of flow and the flow is dependent upon the system characteristics. Axial-flow pumps are often installed in lift systems and are therefore not suitable for operation with variable speed drive.

Pumps cooled with surrounding media and pumps with external cooling are generally not affected by VFD duty.

The thermo-contacts should always be connected regardless of whether the pump is VFD-controlled or not.

CLOGGING

Waste-water pumping stations are in general designed for peak flows which occur approx. 5 % or less of the time. Pumps operated on VFDs run at reduced speed almost all the time. Lower flows result in lower velocities in the sump and a higher risk for sedimentation. Sizeable clusters of large particles may build up in the sump. Eventually they will break loose and may cause clogging in the impeller. The risk of clogging is generally higher in dry installed pumps. Sedimentation may build up in the inlet pipe, large solid particles can easily get stuck in the 90° inlet bend leading into the pump.

When running at reduced speeds, the available energy for the impeller to keep itself from clogging, decreases rapidly. Available energy in the impeller is proportional to the square of speed. The available impeller energy will drop 75% when the speed is reduced from nominal speed to half speed (see equation).

The distance from the leading edge of the impeller or propeller blades to the point where the flow becomes turbulent, will increase when the pump is running at reduced speed. This fact increases the risk of catching long fibrous materials on the leading edge. The pump is less effective in

$$T = \frac{I_p \cdot \omega^2}{2} \quad \text{Where} \quad \begin{array}{l} T = \text{Energy} \\ I_p = \text{Polar moment of inertia} \\ \omega = \text{speed [rad/s]} \end{array}$$

carrying away solids and clogging materials, when the velocity of the liquid is decreased. Long fibrous materials are more likely to catch on vanes when the velocity of the pumped media is low.

The rapid acceleration at start-up of on/off controlled pumps, effectively removes initial clogging in the pump. There is also a natural back flush when the pump stops, which prevents clogging. VFD-controlled pumps are, as mentioned above, seldom running at full speed. They are often running continuously and cannot gain from the on/off controlled pumps' benefits. This can be handled by adding a cleaning sequence 1-2 times per hour, where the pumps start and stop at full speed a couple of times. It is important that the ramping time at start and stop is short.

When running multiple pumps in continuous duty, it is possible that one particular pump handles the small flows and runs almost all the time with reduced speed. The risk for clogging and sedimentation is higher for this pump. This can be avoided by alternation of the pumps.

VIBRATIONS

Pumps running with variable frequency drives, excite a broader range of frequencies. The probability of exciting one of the system's natural frequencies, increases when running pumps with variable speed drives. This can lead to problems with vibrations and noise, especially in stations with dry installed pumps. If one of the system's natural frequencies is in the duty range of the VFD, this fre-

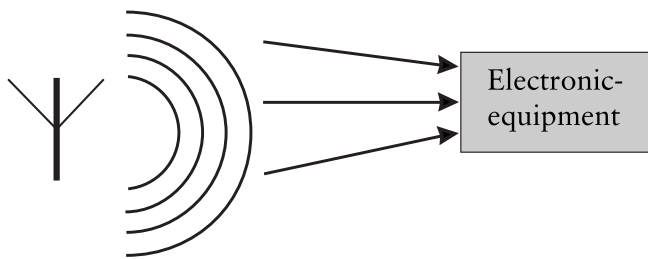
quency can be blocked in the VFD control unit. Most modern VFDs have this blocking function.

Some of Flygt's pump curves are dashed at low flows (close to shut-off head). Running the pumps in this area can cause vibration problems.

See Flygt brochure "Design recommendations for pumping stations with dry installed submersible pumps" for more detailed information.

EMC

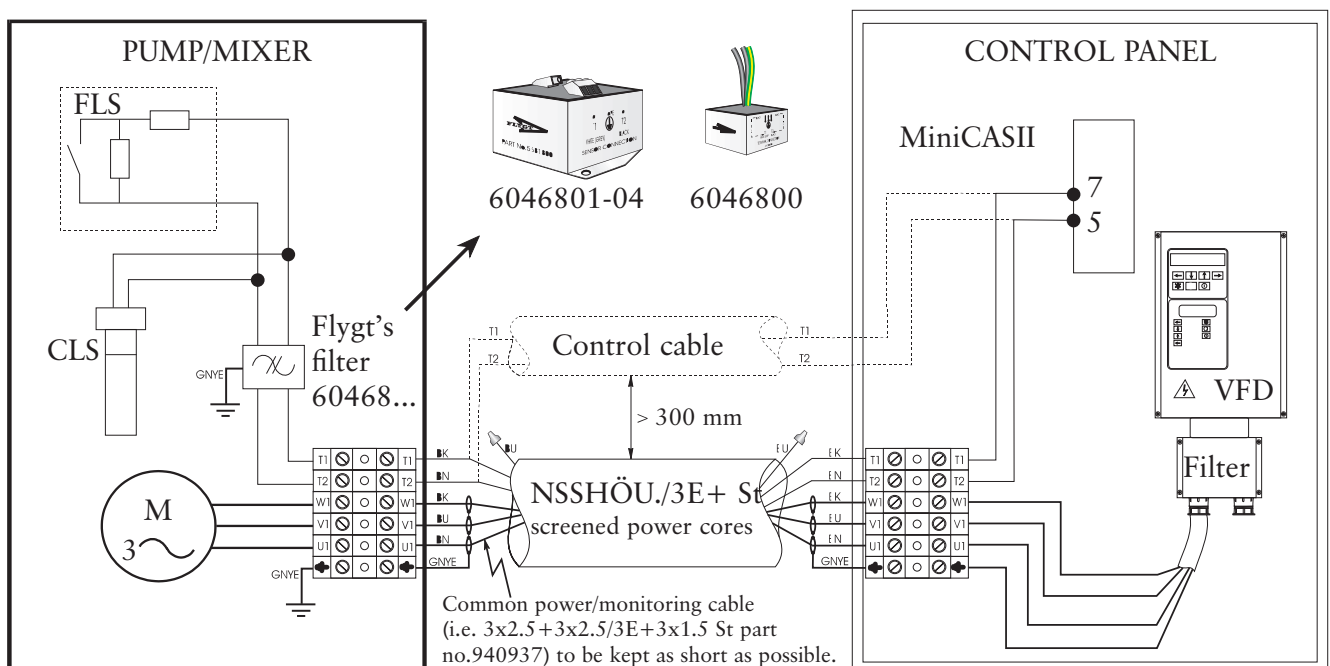
EMC stands for Electromagnetic Compatibility. It is the ability for electrical/electronic equipment to operate without problems in an electromagnetic environment. Likewise, the equipment must not disturb or interfere with any other product or system. Electrical equipment should be immune to high-frequency and low-frequency phenomena. Interference from the surrounding area with equipment comes from transients, voltage fluctuation, high frequency signals, static electricity etc.



The high frequency emission from a source should not exceed a level which prevents other equipment to operate as intended. Interference to the surrounding area from an electronic equipment such as a VFD can be produced by very fast switching components (triacs, IGBTs) in the frequency converters' control system. The high-frequency interference can propagate by conduction and radiation.

The EMC requirements must be followed when offering and selling both pumps and complete systems with control equipment on the European market. All Flygt pumps are CE-marked according to the EMC-directive, and the VFD that goes with the system should also be CE-marked. The inter-connecting cable between the pump and the VFD, has to be shielded in order to make the VFD pass the EMC-tests.

NOISE SUPPRESSION

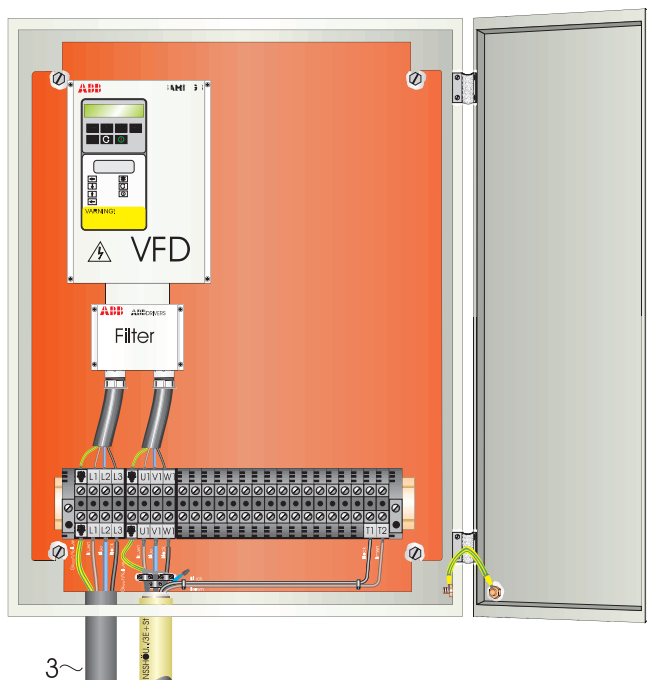


Overview noise suppression

CABLE

Shielded power and monitoring cables should be used wherever possible. The recommended shielded cable supplied by Flygt is the NSSHÖU heavy duty rubber cable. Contact the local Flygt office for more information. Separate power and monitoring should be used wherever dual cable entry is

provided in our pumps (e.g. 3140 and large pumps). The power cable and monitoring cable should run in separate cable ducts with a distance of at least 300 mm between them. The length of the cable should be kept as short as possible, and should not in any case exceed 40 m.

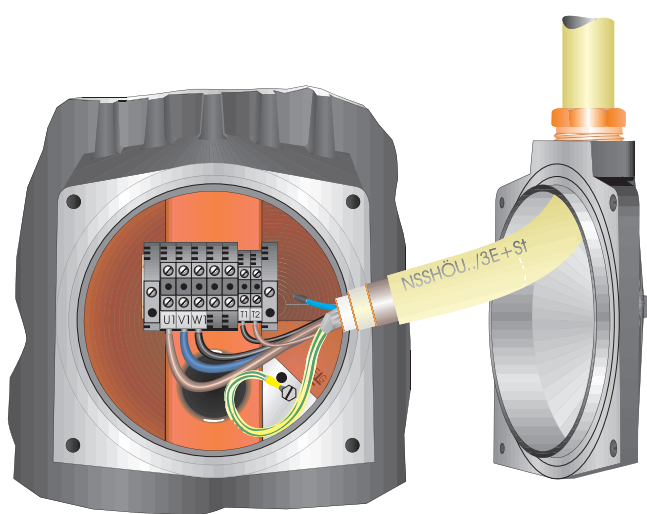


Installation of monitor cables in electrical cabinet.

The monitoring cables in the electrical cabinet and in the pump/mixer junction box, should be kept as far away as possible from the power cables.

FILTERS

Interference from a variable frequency drive may cause nuisance tripping of monitoring equipment and electronic sensors. This occurs when the pilot cable is in close proximity to the power leads. This nuisance tripping may be suppressed by connecting a suitable filter between the monitoring conductors (T1, T2) and ground (PE). The filter should ideally be located in the pump/mixer junction box.

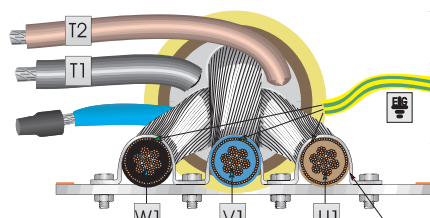


Filter installed in pump-junction box.

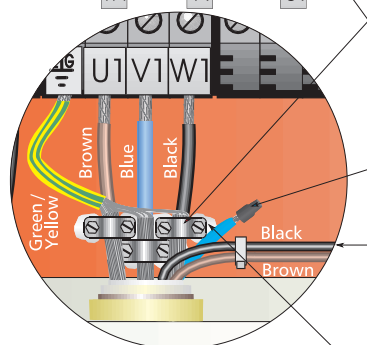
An output filter can be placed on the output signal from the VFD. This filter reduces the noise in the output signal. A lower or no power margin (de-rating) can be acceptable, if this filter is included in the installation. Problems with nuisance tripping are also reduced.

INSTALLATION

Cubicle connection.



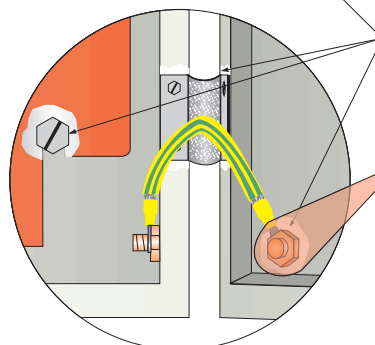
Power conductor screen twisted together and connected to PE.
Use a Green/Yellow shrink tube over the conductor.



Earthing clamps

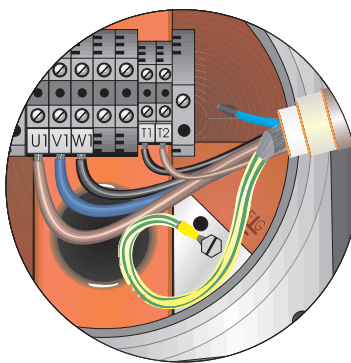
Cut the blue control wire and isolate the end.

Control wires:
T1-black
T2-brown



Scrape off the paint under earthing clamps, hinges and screws.

Spray scraped parts with colour or Tectyl.



Pump-junction box.

Power conductor screen twisted together and connected to PE.
Use a Green/Yellow shrink tube over the screen conductor.

Installation guidelines

