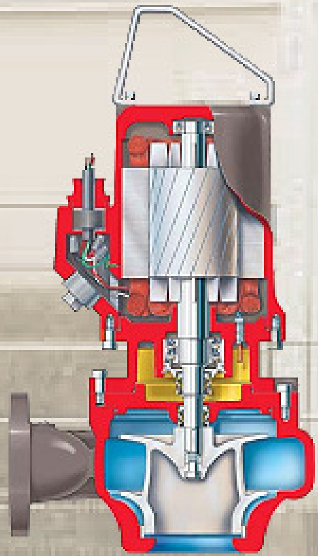
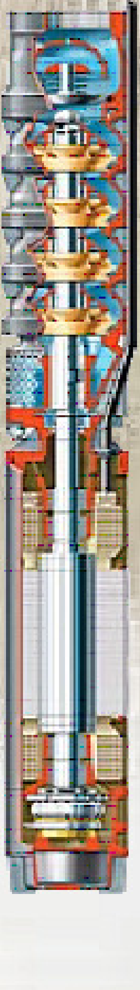
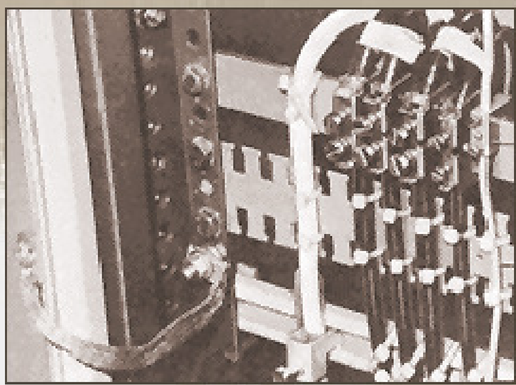
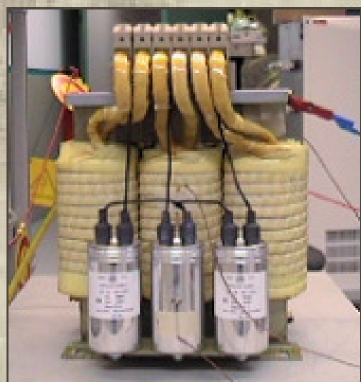
VARIABLE SPEED ELECTRO SUBMERSIBLE PUMPS





A GUIDE TO THE SPECIFIC APPLICATION OF VSD'S FOR BOREHOLE AND WET-WELL PUMPS





GAMBICA

Europump

GENERAL

- Modern electro submersible pumps fall into two basic families, open well and deep well, which may both benefit from the application of a variable frequency drive.
- The pumps are normally designed around an electricity supply from a conventional power supply network, and so some additional specific requirements may apply when a variable frequency drive is used.
- The additional effects are dependent on the motor physical frame size, on the supply voltage, and on the cable system.
- For a VFD the acceptable cable length to meet the EMC class may vary from 10 m to 200 m. Operation with longer cables will generally require special measures, please pay special attention to voltage drop.
- For dry or oil filled motor types with cable runs of less than 30 m the effects are usually minimal, and no additional provisions need to be made.
- For longer cable runs, additional components may need to be added to ensure satisfactory operation.
- For borehole type pumps an output sinusoidal filter is generally required.
- In all cases the experience of the manufacturer should be sought to ensure system compatibility.

MOTOR SELECTION

- Failure due to bearing currents is seldom encountered, but for security of operation the following should be observed.
  - Adhere strictly to the motor and inverter manufacturers' recommendations regarding the installation, cabling and grounding.
- Motor insulation levels can be a more difficult area, and the following general guidelines are suggested, which will depend on the Supply Voltage
- For supply voltages of 400 V it is important to ensure that the motor insulation meets the requirements of Figure 1-1 (Pale blue curve)
  - Note that some motors < 7.5 kW may not meet this level and some filtering in the output of the inverter may be required.
- For supply voltages of up to 500 V it is important to ensure that the motor insulation meets the requirements of Figure 1-1 (Green curve)
- For supply voltages of up to 690 V it is important to ensure that the motor insulation meets the requirements of Figure 1-1 (Mauve curve)

CONVERTER SELECTION

- A variable frequency drive incorporates an inverter, which is a source of current.
- Many electro submersible pumps will have current ratings which do not correspond to "conventional" motors, always ensure the converter output has sufficient voltage and current for the pump.
- For solid handling pumps, overload conditions may occur, requiring intermittent high current.
- A converter will be designed for a specific EMC category, and long cable runs can overload the conducted emissions filters.
- An EMC plan may be required to confirm compliance with the essential requirements of the European Directive.
- Always adhere strictly to the motor and inverter manufacturers' recommendations regarding the installation, cabling and grounding.

APPLICATION SPECIFIC NOTES

Applications with "long" cable lengths

- The definition of "long" depends on the motor rating and type, and may vary between 10 m for very low power systems to 200 m or more for higher powers.
- Always refer to specific manufacturers' technical documentation for these applications.

Active rectifier drives

- For drives with PWM active rectifier (regenerative and/or low harmonic), the effective peak motor voltage can be raised by up to 15%, and this should be considered when selecting motor insulation.

Potentially Explosive Atmosphere approval (ATEX)

- The application of a variable frequency drive to an "Ex" motor may invalidate the certification – refer to Chapter 7 of this guide.

Alternative Approaches

- It may not be possible to follow the above recommendations, for example, because the variable frequency drive is to be retrofitted to an existing pump, or data is not available for the unit concerned. In these cases additional preventative measures may be recommended and options are detailed in Chapter 6.

CONTENTS

Chapter 1 INTRODUCTION

1.1 Objectives of the guide

Variable Frequency Drives in pump systems are now a mature technology, which can generate large benefits to the user in cost savings and reliability improvements, in the right applications.

It has been recognized by industry that the majority of **new** pump sets sold complete with Variable Frequency Drives (VFDs) rarely have any technical issues, when installed in accordance with the appropriate instructions. It has also been recognized that some types of pump sets already in service can be vulnerable to certain phenomena when trying to retrofit Variable Frequency Drives .

This Guide should be read in addition to the Existing Europump/ Hydraulic Institute Guide on Variable Speed Pumping see www.europump.org or ISBN 1-85617-449-2. Which amongst other items includes sections on pumps, systems, motors, variable speed drives and control methods, which start with the basic principles, but progress to more advanced and detailed concepts. At all times the importance of understanding the process requirements and system design are emphasised, and the interrelation of the various elements is fully explained.

1.2 What are the issues?

Because of their physics of operation, VFDs introduce additional electrical stress on motor windings. In some cases, this added electrical stress can cause a low energy partial discharge effect which gradually degrades the insulation system until premature failure occurs.

For detailed descriptions, reference should be made to the GAMBICA/REMA Technical Report Number 1[1]. This document explains the phenomena and describes the potential solutions available. For standard air cooled motors, this guide provides simple guidance - for voltages up to 500V, standard stock motors may be used without problem and for voltages above 500V, special measures are needed such as enhanced motor insulation systems or output filters on the VFD etc. For retrofit applications or where the motor characteristics are not known, VFD related measures such as output reactors or du/dt filters are usually employed.

However, for applications with borehole type pumps, the motor characteristics are relatively undefined in relation to repetitive pulse withstand capabilities on VFD operation. Users are therefore unclear on the measures necessary to ensure extended motor lifetime.

Some pump manufacturers claim to meet "IEC 60034-25 curve A" (GAMBICA/REMA Technical Report No 1 Figure 21 reproduced here as

Figure 1-1) whereas other pump manufacturers recommend the use of a du/dt filter as standard (although this adds extra cost, size and losses into the VFD solution).

It is not uncommon with borehole pumps for the cable between the motor and the drive to be 100m+ therefore VFDs would often require output reactors or sine filters. These are quite effective at reducing the rate of voltage change (du/dt) and the peak motor voltage. For EMC issues refer to Chapter 5

[1] Available from www.gambica.org.uk

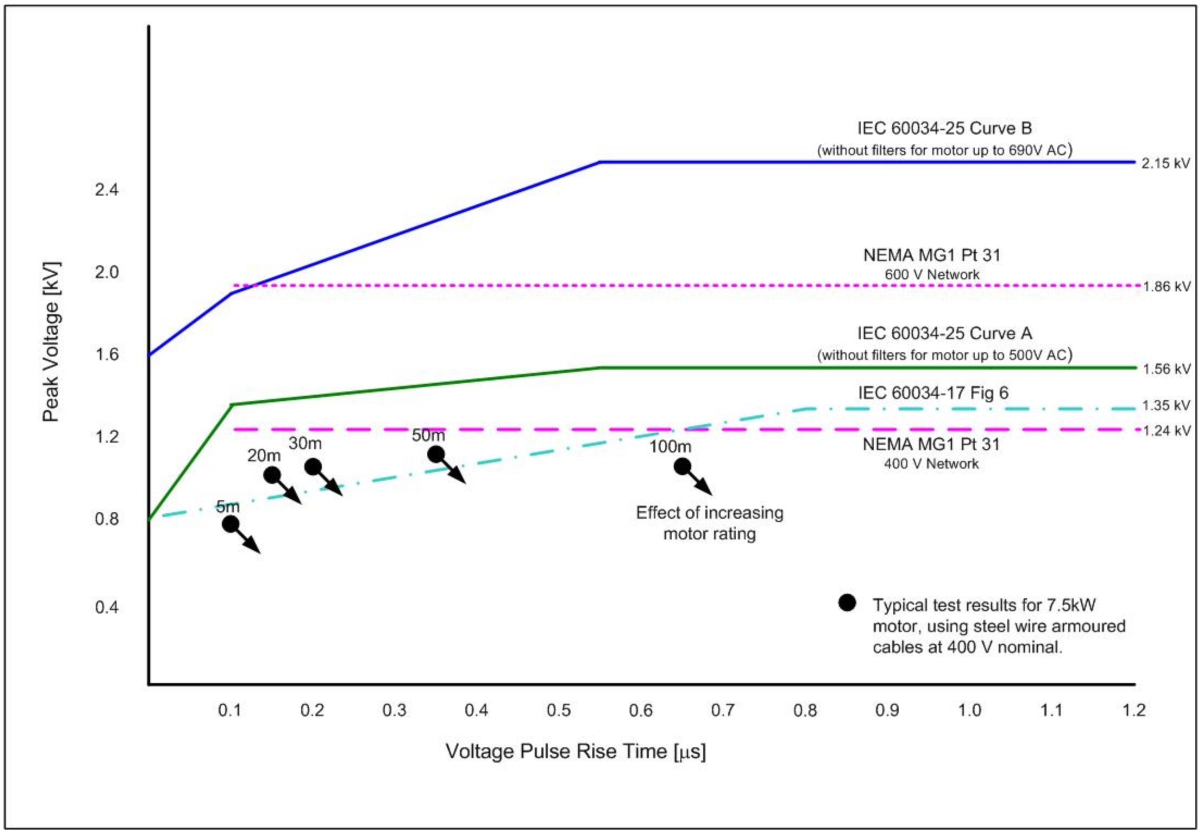


Figure 1-1
Voltage withstand curve

1.3 Who is affected?

The Guide is addressed to the cover application issues that can occur in Submersible Pumps installations when variable frequency drives are used. It will help the manufacturers to design a motor suitable for a VFD power supply. It will also help the user to understand the requirements and its cost implications.

The guide is addressing issues for “borehole” as well as “sewage" type electro-submersible pumps.

Certain aspects may be more important for one type as for the other. If that is the case the guide will make the reader aware of the fact.

This guide is also intended to assist decision makers, specifies, technicians, manufacturers and other involved personnel in the running and maintenance of submersible pump-sets.

1.4 Acknowledgements

The International working group was formed from members of the Pump, and Drives industry and it is to these individuals we are all indebted for this guide.

The Chairman and the Secretary of the working group are indebted to all the team members for their contributions.

In particular a special mention should be given to: -

Geoff Brown – ABB
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Jeremy Wilkinson – Siemens
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Ruhan Agar – Alarko-Carrier

Frank Ennenbach
Approvals Manager
ABS Group
(Chairman of the Drives Group)

Steve Schofield
Technical Director
BPMA
(Secretary of the Drives Group)

A special acknowledgement should be give to members of Gambica (UK Drives Industry Association) for their contribution to the guide.

Chapter 2 BENEFITS AND POTENTIAL DRAWBACKS

When designing a system to utilise variable frequency technology there will be some benefits that are relatively easy to quantify, some which are less tangible and some potential problems, which must be avoided.

This section also provides extensive practical considerations, which will assist in achieving successful VFD installations.

2.1 Benefits to The User

- Energy saving

  If there is a requirement for a velocity, head or flow variation use of Variable Frequency Drives can provide energy saving options. In such installations savings of between 30% and 50% can be achieved.

- Improved process Control

  By matching pump output flow or pressure directly to the process requirements, small variations can be corrected more accurately by variable speed drive than by other control forms, this improves process performance. There is less likelihood of flow or pressure surges when the control device provides rates of change, which are virtually infinitely variable.

- Reduced stagnant water (buffer volume) storage in pressurised systems.

- Good supply side displacement power factor at all loads, power factor compensation is unlikely to be required, unlike a network connected fixed speed motor.

- Open-loop designs can run without any speed sensor. Few pump applications require the degrees of control accuracy where closed loop control is justified.

- Low inrush current from the supply network on starting. Soft starting and stopping reduces stress on the motor, pump, coupling and supply network.

- Integrated diagnostics (if available) and protection helps reduce and identify faults. VFDs can incorporate several types of dedicated pump and motor protection, (e.g. overload, under-load, loss of phase, under/over voltage, etc)

2.2 Potential Drawbacks of Variable Frequency Drives

- Pulse Width Modulation (PWM) Variable frequency converters can be fitted to most existing motors in Europe and other areas, which use a network with ≤ 500 V, however specialist advice on cable length, voltage spikes, motor insulation and other technical issues is required.

- Because many standard drives use a simple diode input bridge, there may be some undesirable network harmonic distortion.

- The high rate of switching in the PWM waveform can occasionally lead to problems.

- Potential differences can be induced between the shaft and frame of motors, potentially leading to circulating currents, which can damage bearings and even impellers; unless corrective measures are implemented.

- High rates of voltage change can also lead to radio frequency interference, unless special care is taken in installation. This interference can be conducted to the feeding supply network, or radiated from the cable installation.

- The VFD will have losses, and the ventilation requirements for the electronics can be an important issue.

- The VFD will generally require installation in a clean environment because electronics are less able to cope with corrosive and damp locations.

- For a motor in a hazardous area the VFD must be installed in a safe environment, which can lead to long cable runs.

Chapter 3 ESSENTIAL MOTOR REQUIREMENTS

3.1 General

The development of the squirrel cage induction motor, with its associated insulation system, has generally been for sinusoidal supplies. Its design is well proven and inherently robust leading to long reliable service with minimum maintenance.

3.2 Motor Insulation Life

Practical life expectancy of insulation systems, and hence motor life, can be many years with ultimate failure likely to be through thermal and mechanical degradation of the insulating materials, not by short-term direct electrical breakdown.

When a fixed speed motor is started direct on line, the powerful magnetic fields will move the stator coils back and forth, and high inrush currents which cause very rapid thermal expansion, compared to the surrounding iron stator core, which has a much lower thermal time constant. These effects can put a substantial strain on the impregnation and support structure. During a VFD start the coils are not subjected to such mechanical stresses.

With a VFD the voltage is generated by a series of short duration pulses, which can cause the motor insulation to deteriorate, and particular concern may be due to a high rate of voltage rise, which can allow up to 85% of the voltage to appear between the first and second turns of a winding. Each voltage peak can cause a small breakdown called a partial discharge (PD) in any of the air filled voids in the insulation materials. Winding materials may be classified by their partial discharge inception voltage. VFD operation puts a higher voltage stress on motor insulation system because of this reason it is recommended to have either reinforced insulation system or alternatively a filter between motor and VFD. See clause 6.4.

Requirements for motors are established internationally in the IEC 60034 series of standards. These cover aspects of performance, starting characteristics, thermal classifications, mechanical protection, safety, insulation level by dielectric test etc.

Developments in the materials and varnishes used in motor insulation systems have improved the thermal, mechanical and dielectric characteristics considerably beyond the minimum requirements of those standards and overall, the standard induction motor is well able to withstand the voltage waveforms encountered with the majority of VFD outputs.

3.3 Standard Motor Insulation Systems

Motor insulation is generally only defined by the thermal capability, ie Class B, Class F or Class H. These classes do not define the electrical capabilities of the insulation system used.

Motor winding life is generally anticipated to double for every 10^0C reduction in operating temperature, and a VFD using flux optimisation techniques will optimise this effect.

There are two main types of winding, broadly classed as random wound and form wound.

- Lower power motors are generally random wound, i.e. with coils in which the turns of round section wire are randomly located in the coil forming process.

- For larger powers, form windings are often utilised where the pre-formed coils are layered up uniformly - usually with rectangular section conductors.

3.3.1 Dry or Oil Filled Motors

The essential elements of both random and form wound insulation systems consist of:

- Phase to earth insulation - slot liner and closure.
- Phase to phase insulation - slot separator and end-winding.
- Inter-turn insulation - slot and end-winding.
- Impregnating varnish - slot and end-winding

Typical phase to earth and phase to phase insulation will be polyester film/meta aramid paper composites with inter-turn insulation provided by multi-layer polyester/polyamide-imide enamel on the conductor or alternatively mica/polyester wrapped film in the case of rectangular form wound turns.

Impregnating the winding, typically with polyester resin meeting thermal class F or H provides mechanical strength with overall electrical insulation and resistance to environmental contamination.

Figure 3-1
Example of Dry Random Wound Motor

3.3.2 Wet Wound Motors

The characteristic of these motors are that the winding wire is in direct contact with the motor fluid. Hence motor fluid acts as an electrolyte the insulation of the winding wire is the sole barrier between live wire and ground.
The insulation can be extruded onto the wire or it may be wrapped.
Most common insulation materials used:

- PVC (65^0C) Poly Vinyl Chloride
  Extruded as single layer
- PE/PA (85^0C) Poly Ethylene/ Polly Amid (nylon)
  PE extruded around the copper for insulation, PA (conductive) extruded on top to give mechanical strength.
- PP Poly Propylene
  Extruded as single layer
- PEEK
  Wrapped onto the wire

Wet wound motors are made with standard insulation material like slot insulation, slot wedges and phase insulation around the coil heads, but the main scope of these materials are to give mechanical protection against wear.

A wet wound motor is a dynamic construction where windings are loose. The windings move when energised or exposed to vibrations from the pump.

The insulation material is relatively thick and due to this the size of the slots in this kind of motors are relative big - slot filling fairly low.

Figure 3-2
Example of Wet Wound Motor Under Construction

3.4 Enhanced Motor Insulation Systems

For dry type motors to withstand the higher stresses due to supplies greater than 500V and up to 690V, an enhanced random wound motor insulation system will involve further reinforcement of slot liners, slot closures, slot separators, inter-phase barriers, end winding bracing, etc, and possibly the use of special winding wire.

This is completed by a multiple impregnation regime. In the case of a form winding, standard windings having mica/polyester wrapped conductors, will normally meet enhanced insulation requirements.

3.5 Special Operating Conditions for Electro Submersible Pump Motors

Common facts

- Extreme running hours
    - Often continuous operation (8000 hours/year) with focus on operational costs[2]
    - Applications with very limited operation (flood /storm water control) and focus only on capital cost.
- Reduced torque and power demand of rotodynamic pumps cause little or no problems with motor cooling at reduced speed for submerged units.
- If no non-return valve is installed in the discharge “turbining” (reverse rotation) may occur on shut down

3.5.1 Submersible motors

The following points require consideration:

- No rigid fixing to a base plate or foundation (e.g. duck foot bend, pipe shaft) which may result in higher vibration level (typically up to 11 mm/s) see Figure 3-3
- Low moment of inertia
    - very high rates of acceleration and deceleration (e.g. a 400 kW pump direct on line start takes less than 2 s)

2 Refer to Europump LCC Guide ISBN I-880952-58-0

- Large temperature gradients inside motor
    - (e.g. difference between end winding and slot up to 40 K)

- No mandatory frame size / high power density

- Special choice of standard bearings which bear high hydraulic forces and mechanical seals may result in higher friction losses

- The flow rate must be adequate to cool the motor and achieve minimum flow through pump

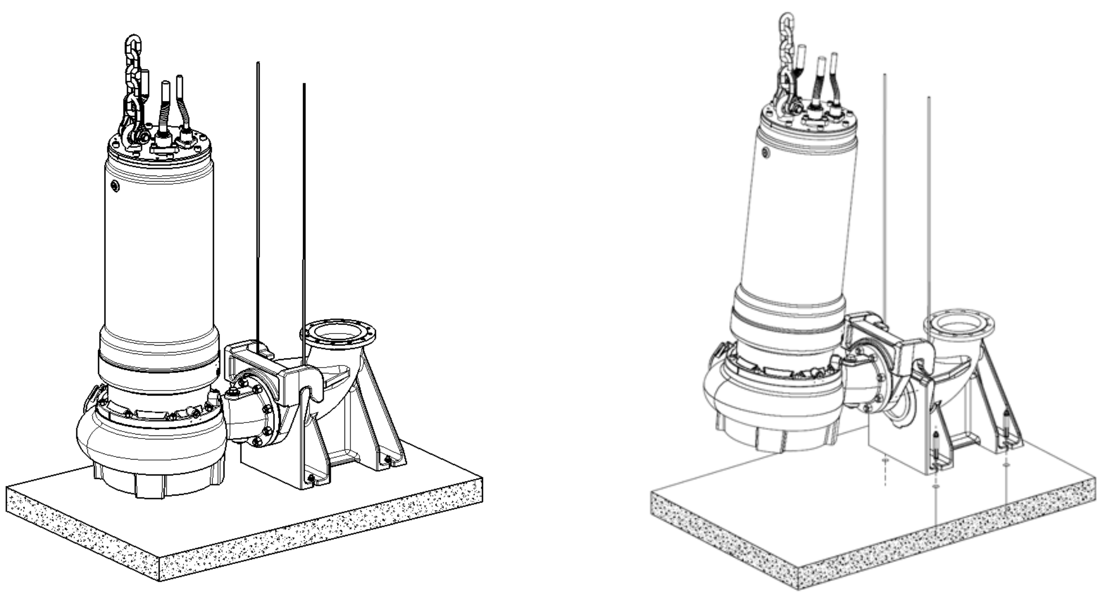

Figure 3-3
Duck Foot Arrangement

3.5.2 Deep Well Motors

- No rigid fixing on a base plate or foundation
    - higher vibration level

- Long and slim design
    - Critical speed considerations
    - Torsional vibration considerations

- Very special fluid lubricated journal bearings

- “pulling costs” (removal/re-installation) may exceed pump costs, leading to lack of maintenance

3.6 Motor Bearings

Bearings are used to support axial and radial forces in rotating elements.

3.6.1 Overview of Bearing Types in Pump Applications

Different pump and motor types will have different requirement characteristics.

3.6.1.1 Borehole Type Submersible Motor

Submersible pumps for pure water from 4” up to 24” have journal bearings.

The pump will also have a thrust bearing which is generally of tilting pad design, high initial rates of acceleration are required to establish lubricant films in the bearings.

These types of bearing are not vulnerable to bearing currents caused by VFDs.

3.6.1.2 Sewage Pumps

Sewage pumps typically use following types of bearings on the drive side:

- Single row deep groove ball bearings
- Single row angular contact ball bearings
- Double row angular contact ball bearings

On the non drive side mostly single row deep groove ball bearings are installed. Single row cylindrical roller bearings may also be used.

These standard types of bearings are normally not resistant to bearing currents associated with VFDs

3.7 Danger of Motor Bearing Failures

Along with other aspects such as EMC and peak voltage stress, there is increasing concern amongst users that VFDs may reduce the lifetime of the motor bearing elements due to undesired currents circulating through the bearings.

At first the situation is confusing, because reports from industrial applications are very different and they also differ from country to country. Market dominating conventional motor manufacturers give varying recommendations

From experience of pump manufacturers over the last years there had been cases of reduced bearing lifetime with dry installed pumps, but there had been practically no reports about submersible motor pumps and there is a technical background for this situation.

3.7.1 Technical Reasons for Motor Bearing Currents

A full description is detailed in the Gambica/REMA Technical report No 2, and a summary is given below.

3.7.1.1 Motor Magnetic Asymmetry

The issue of induced shaft voltages and attendant bearing currents has been well known for over 70 years in mains fed motors and was attributed to stator / rotor magnetic asymmetries. All rotating electric motors potentially suffer from this phenomenon.

The North American guidelines contained in NEMA MG1 require the shaft voltage to be less than 1V rms, however, reports of typical shaft voltage reveal values between 3 and 45V. Shaft voltages increase with motor frame size.

Shaft voltages try to drive a current through an electric circuit consisting of shaft, bearings and motor housing. The oil or grease film of bearings is an insulator with a typical breakdown voltage of between 3 and 30V. This limits or even prevents bearing currents in mains fed motors.

Large motors, with a rating of some hundred kW. are often equipped with insulated bearings especially for ungrounded (delta connected) mains operation.

Experience, especially with VFD operation shows, that low speed applications suffer more from shaft voltage than ones with higher speed. The reason is that breakdown voltage depends on rotational speed. The thickness of oil or grease film wedge between rolling elements and race way of bearings reduces with decreasing speed.

3.7.1.2 Common Mode Voltage Asymmetries / Fast Switching Transient Effects

In VFD operation the situation is more complicated.

Main components of an inverter are fast switching semiconductors (IGBT). They can only produce a "square" output voltage waveform, which has no effective neutral point. this allows a “common mode” voltage to cause a magnetic field to establish across the moto.r There is a tendency that the rotor of an induction motor will become electrically charged against the stator, due to this field. at a frequency related to the inverter switching frequency. These High frequency rotor voltages seek to return to ground and one path may be offered by motor bearings. In addition capacitively coupled voltages can reach high instantaneous values which exceed the insulating capabilities of the bearing oil or grease film. They do not usually have enough energy to damage bearings directly.

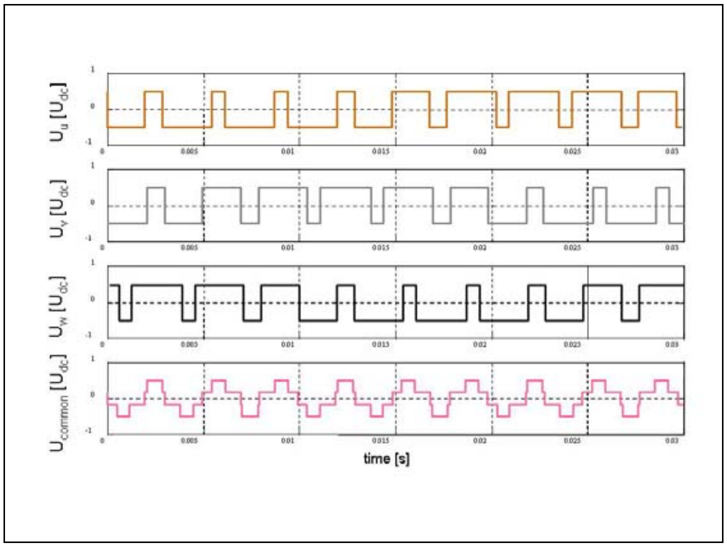

Figure 3-4
Formation of Common Mode Voltage from Phase Voltage Pulses

3.7.1.3 Damage Mechanism

Bearing problems may arise if low voltage, high energy traditional shaft voltages and capacitively coupled high frequency rotor voltages work together. High capacitive voltages break through oil or grease film. The created conductive channel is then used by shaft voltage to drive a high current.
High currents through bearings generate sparks between rolling element and race way, which cause small craters as initial damage.

3.7.2 Preventive Measures against Bearing Currents

There are some commonly recognized preventive measures against bearing currents which are presented below.

3.7.2.1 Electrical Installation Procedures

Good practice installation techniques are essential in any case to avoid potential problems with EMC. The same principles conveniently reduce the bearing currents. The principle is to ensure the lowest possible impedance path on the shield connection to avoid stray currents travelling through the bearings back to ground. Potential equalization techniques should be applied between the VFD and the motor. This technique dramatically reduces the chance of shaft grounding currents.

Submersible motors apply this highly beneficial measure automatically!

Water around the motor housing is a perfect EMC shield and it equalizes electric potential of all metal construction elements.

3.7.2.2 Use of Insulated Bearings

The traditional technique of insulating one bearing normally the None Drive End (NDE) is used to reduce the problems associated with mains frequency bearing currents associated with magnetic asymmetries.

If the rotor can be adequately isolated from the stator by the motor bearings, the high frequency rotor currents will seek to find the lowest impedance ground.

Effluent and Waste Water pumps are usually close coupled with a common shaft for motor and pump.
Therefore electrical potential equalization of the motor shaft is generally achieved by immersion in a conductive fluid (usually water). Any shaft currents traverse through the water and not through bearings! Thus insulated bearings are not needed for them.

Grounding by water is harmless, if protective ground and potential equalization are connected as required by operating instructions and local installation regulations.

In case of dry installed standard motors, shaft currents could possibly traverse through metallic couplings to the load. In the case of centrifugal pumps one achieves a benign grounding by water. In case of other driven working machines without grounding lifetime of its bearings may be compromised. In addition the use of insulated bearings at the motor Drive End (DE) may encourage circulating currents.

If a dry installed centrifugal pump and its VFD driven motor are coupled by an insulating coupling with rubber elements, then the motor does not benefit from grounding by water. In such cases motor bearing failures are reported. The use of insulated NDE bearings makes sense here and shall be done as recommended in VFD handbooks.

3.7.2.3 Modification of Inverter Waveform

A range of standard inductors and filters (ranging from simple du/dt filters through to sinus output voltage filters) are often applied for other reasons - for example:

a) To mitigate capacitive cable charging currents due to long motor cables
b) To reduce motor peak voltages
c) To minimize motor audible noise

Although not their primary design purpose, these measures will also have a beneficial effect in reducing possible bearing currents.

3.7.2.4 Modifications in Semiconductor Pulse Characteristics

Modern inverters use semiconductor switching rates between 2 - 20kHz. Most inverters allow the switching frequency to be modified.
Higher switching frequencies result in greater parasitic coupling between the stator and the rotor.
A simple compromise is to reduce the switching frequency of the output transistors to the lowest level acceptable by other criteria (performance, motor heating, audible noise etc).

3.7.3 Bearing Failures

With the improvements in motor construction techniques, the motor bearings have become the elements most likely to require early attention. Naturally, motor bearings fail for a variety of reasons mainly mechanical. Rated examples of failure mechanisms are:

a) Misalignment of shaft (not applicable for submersible motor pumps)
b) Excessive loading
c) Incorrect lubrication
d) Thermal environment (seldom applicable for submersible motor pumps)
e) Excess vibration (important for submersible motor pumps)
f) Bearing quality
g) Bad handling
h) Bearing currents

3.7.4 Conclusion

- Mechanical issues remain the major cause of bearing failure.
- "Best practice" mechanical and electrical installation techniques are the most important measure in mitigation premature failures.
- ***Because of special electrical grounding conditions insulated bearings are not essential for submersible motor pumps operating with frequency converter.***

Chapter 4 OPERATIONAL ISSUES

4.1 Over Speed /Under Speed Operation

By definition a VFD is able to operate a motor at speeds other than the motor nominal speed. The effects on the motor and pump need careful consideration. It is required that limits identified in both the pump and motor manufacturers operating and maintenance manuals shall be adhered to.

4.1.1 Over Speed Operations - General Considerations

- Increased loading on system components such as motor, VFD, bearings, couplings, etc increased noise in dry installed applications
- Increased vibration, or excitation of reed frequencies
- Increase in abrasion and wear
- Risk of cavitations due to the reduction in Nett Positive Suction Head available (NPSHa)
- Effect on mechanical seals and potential shaft critical speeds
- Adverse effects on pumping system due to increased pressure
- Characteristics of the pumped liquid can limit maximum pump speed

4.1.2 Particular Considerations

Above nominal speed the torque available will drop as the variable frequency drive cannot increase its output voltage beyond its input voltage. The motor then becomes progressively under fluxed. This is known as field weakening, although in the right circumstances a motor may be run above its nominal speed.

As described earlier in this guide, with rotodynamic pumps relatively small speed changes can have a major effect on parameters such as power absorbed, Nett Positive Suction Head required (NPSHr) etc.

Generally VFDs will be used to reduce speed from the nominal, however if there is adequate motor power available the drive may be used to increase speed. In this case there are a number of precautions, which must be considered:

There will be a change in the noise output from both the pump & the motor as the speed is changed. With higher speed, greater noise and potentially greater vibration will occur
If the pump is handling liquid containing abrasive particles, an increase in flow will result in a corresponding increase in abrasion and wear

With increasing speed, the user must ensure that the NPSHa at the pump is still at an adequate level to prevent cavitation. This must be checked, since the pressure drop along the suction pipe will increase as the flow/velocity increases, which will cause a reduction in the NPSHa to the pump. The situation is further exacerbated by the fact that the pump will also require more NPSH when running at higher speeds

4.1.3 Under Speed Operation – General Precautions

- In the case of a high static head, the risk of moving to shut off/opening point (closed valve) can cause a no flow through the pump.
- Particulates may come of suspension
- Balancing issues for lower speed
- Gas seals can limit minimum pump speed
- Minimum cooling flow for the motor may not be achieved at lower speeds
- Can cause excessive thrust bearing wear if the motor is not turning fast enough to ensure an adequate film of fluid between the thrust bearing face and thrust pads

4.1.4 Particular Considerations

Lower speed generally benefits energy savings and maintenance costs but the following precautions must be considered:

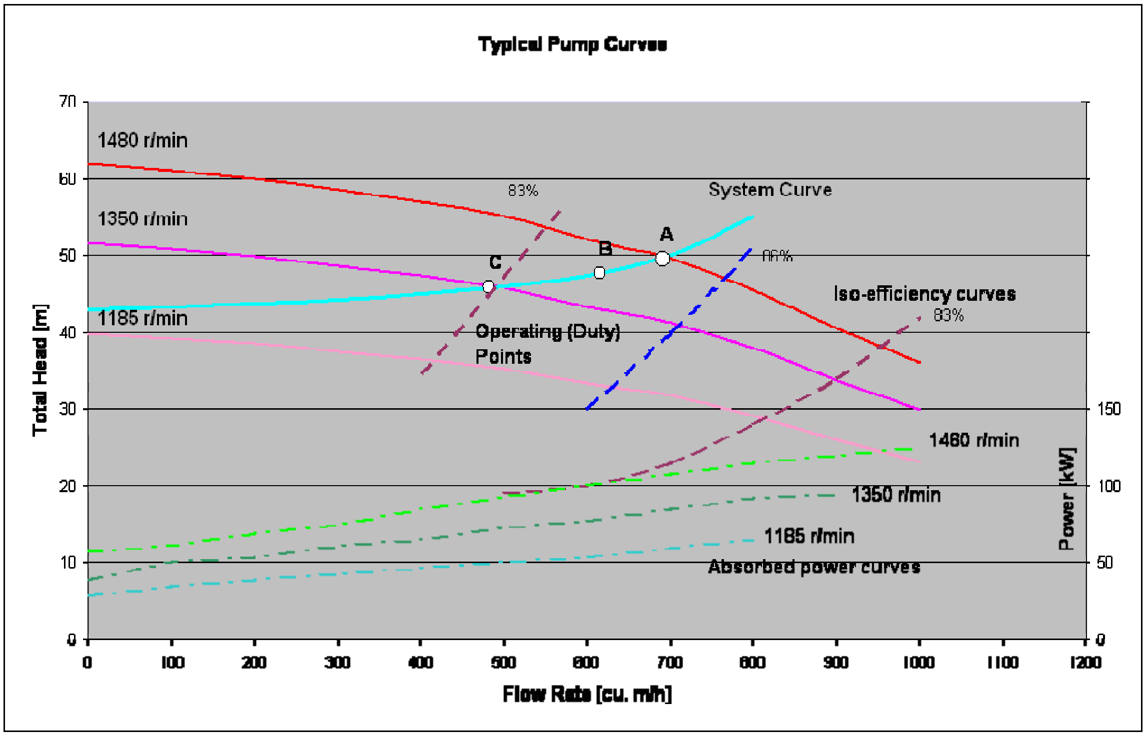

Figure 4-1
Example of the effect of pump speed change with a system with high static head.

In the case of relatively high static head, care has to be taken that the pump is not operated in inappropriate regions. As shown in Figure 4.1, a relatively minor decrease in speed can move the operating point close to shut off head. If the pump is operated in such a region for a long period of time it will have severe consequences for the life of the equipment

If pump speed is reduced in some applications, particulates may come out of suspension and cause problems

A minimum speed limit applies if pumps have a balance disc or drum (generally multi-stage pumps) as unacceptable wear can occur

Gas seals have minimum peripheral speed and pump flowrate requirements, check with manufacturer

4.2 Hydraulic Problems Caused By the Use of VFD's

Pumps have historically been designed for single speed operation with the majority of pump types being able to accept differing sizes of impeller.

Varying the impeller size or trimming the impeller has the similar effect to varying the speed of the motor.

The majority of pump manufacturers will accept a 15% impeller trim. Whilst in the first instance the trim may be regarded as the equivalent of varying the speed, excessive trims do change the hydraulic condition within the pump which could lead to reduction in efficiency and instability in operation.

The use of variable speed drives avoid this problem, however varying the speed of the pump can include other problems which are primarily associated with the type of system into which the pump is pumping.

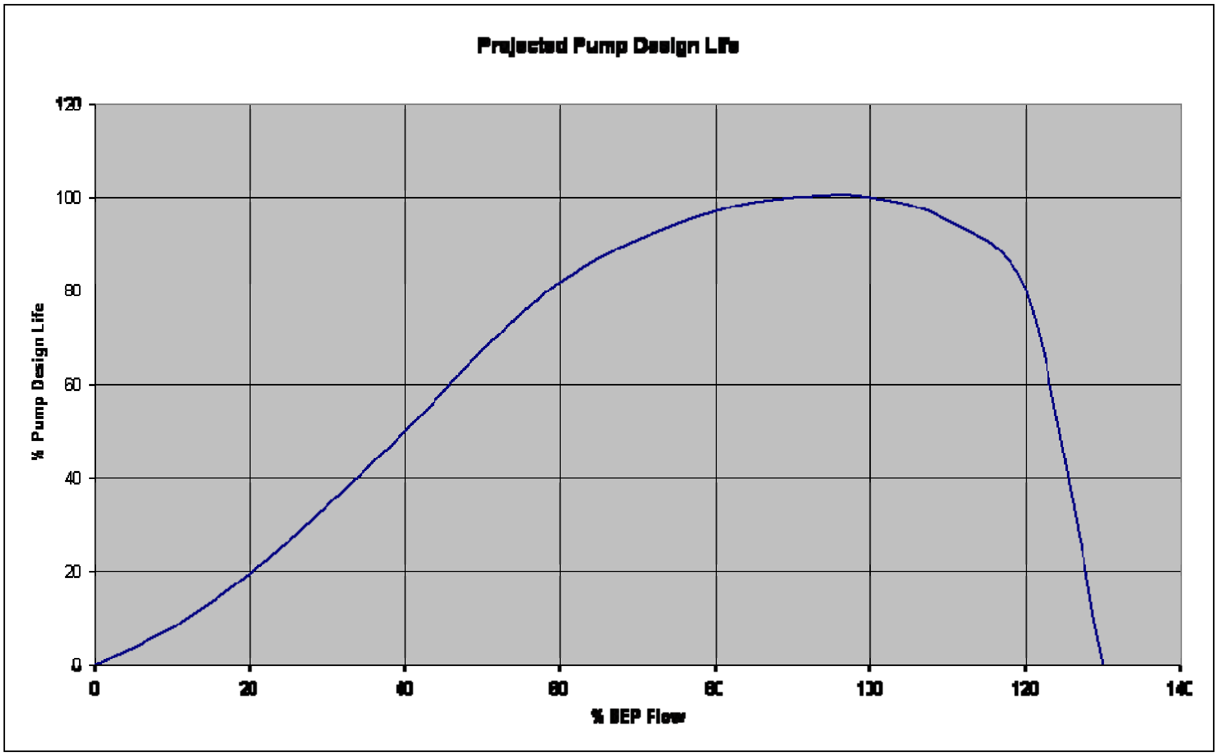

Figure 4-2
Projected %Pump Design Life vs % Flow Rate

These problems include:

Low or No Flow Operation - this is a destroyer of pumps.

If a pump is operating in this region then the pump and motor will potentially suffer damage from overheating, overloaded bearings and excessive cavitation.

Figure 4-2 gives the projected life of a pump based on its % flow and its theoretical life. This life may vary dependant upon the fluid being pumped from a 100,000 hours for a large water pump to a few 100 hours for pumps pumping aggressive fluids.

Following are examples of variable speed inducing low flow.

4.2.1 Tank Emptying Operation

A pump is pumping out of a tank which has a variable input. This may typically be a sewage pumping station or return water from process plants. There is a great temptation to provide the very simple control philosophy of maintaining a fixed level in the tank. This is acceptable provided that the inflow meets the minimum flow requirements of the pump.

If this inflow falls below the minimum flow requirements then the pump could be severely damaged or destroyed. An actual example was where a sewage pump was operated at such a low speed that the head generated was such that the non-return valve failed to open and the pump overheated and was totally destroyed.

The solution to this problem is to determine the minimum acceptable running speed of the pump and to use this as the minimum speed setting for the drive.

This running speed should be determined from the following considerations. Firstly the safe minimum flow through the pump, typically 25% of design flow and secondly the minimum acceptable pumping efficiency typically 80% of Best Efficiency Point (BEP).

4.2.2 Parallel Operation

Here there are two separate conditions one, where two or more variable speed pumps are operating in parallel and the second is where one or more variable speed pumps are operating in parallel with a fixed speed pump.

Case one

Some control systems are designed so that the first pump runs up to maximum speed and the second pump is started and runs at a speed to meet the demand. This means that one pump will run at high flow and the second pump will run at varying flow. The varying flow may be such that the minimum flow is not achieved. The solution is that when the second pump is started then both pumps should run at the same speed. This of course is provided that both pump characteristics are the same. Complications do arise if firstly the pumps are not identical and secondly if the pumps are the same but one is badly worn, however, this solution does tend to offer additional energy savings.

Case two

The pumping system consists of a fixed speed pump, and a variable speed pump. In this case a typical system may be such that the fixed speed pump is started first and when the duty requirement is greater than the duty of the first pump then the variable speed pump will be started. Again there is a distinct possibility that the variable speed pump may be asked to run below the minimum acceptable speed. In addition the opposite combinations may occur when the variable speed pump may be over speeding and cause the fixed speed pump to fall back on its curve and in the worst instance suffer low or no flow conditions.

The solution to this problem is not easy and sometimes may not be solved without installing variable speed drives on each pump.

4.3 Resonance and Rotor Dynamics

4.3.1 Rotor Dynamics

The risk of the rotating element in the pump or motor, encountering a lateral critical speed, increases with the application of a VFD. Lateral critical speeds occur when running speed excitation coincides with one of the rotor's lateral natural frequencies. The resulting rotor vibration may be acceptable or excessive depending on the modal damping associated with the corresponding mode.

Additionally, drive-induced torque harmonics may result in resonance conditions with torsional rotor dynamic modes.

Typically sewage type submersibles are designed to operate well below critical speed, however due to the small diameters many borehole pumps will operate above the first critical speed.

4.3.2 Precautions

- Lateral and torsional rotor dynamic analyses allow the calculation of rotor natural frequencies under operating conditions over the entire applicable speed range. Lateral modes are typically damped and the acceptability of a particular design depends on a combination of available modal damping and separation between natural and excitation frequencies

- Torsional modes have little damping, the acceptability of the design may be proven by means of a forced response analysis and comparison of calculated stresses to allowable stresses

- Three basic corrective actions or a combination thereof, can be applied if a resonance situation exists and associated vibration levels are excessive:

    - Locking out of certain speeds or speed ranges from the continuous operating speed range, this is achieved in the drive software, however this can limit the operational flexibility

    - Detuning a resonance condition by means of changing the excitation frequency

    - Reducing excitation levels by means of improving balance, alignment etc. or by means of changing impeller/diffuser or impeller/volute configurations

4.3.3 Structural resonance

Resonance conditions can result in excessive vibration levels, which in turn are potentially harmful to equipment and environment, particularly with vertical and large rotodynamic pumps.

Pumps, their support structure and piping are subject to a variety of potential structural vibration problems (resonance conditions). Fixed speed applications often miss these potential resonance situations, because the common excitation harmonics due to running speed, vane passing frequency, etc., do not coincide with the structural natural frequencies. For VFD applications, the excitation frequencies become variable and the likelihood of encountering a resonance condition within the continuous operating speed range is greatly increased.

Pressure pulsations are the common excitation mechanism. These pressure pulsations may be further amplified by acoustic resonance within the pump or the adjacent piping.

4.3.4 Precautions

There are a number of analyses that can be performed in order to predict potential resonance situations:

- Hydraulic resonance calculations
- Passing frequency analysis
- Using finite element analysis to investigate structural resonance
- Modal testing of the physical machine can supplement the regular vibration test. Very often a pump intended for Variable Speed operation will only be tested at one single speed

4.3.5 Effects on Noise & Vibration when Varying Speed

The trend towards higher rotational speeds has an unfavourable effect on the noise developed by centrifugal pumps, since the overall dimensions of the machine are reduced and the energy conversion consequently takes place in a much smaller volume (increased power density).

An increase of 3 to 6 dBA in motor noise is generally apparent when dry installed motors are used in combination with Variable frequency converter drives. A change in switching frequency can potentially reduce the effects. However, the overall reduction in speed level normally leads to an overall decrease in noise levels.

Slow speed motors with high numbers of pole pairs may also have narrow band acoustic noise induced at points within the running range, when converter controlled. This is due to the small number of slot combinations available within the physical build of the motor, and is usually countered by using a motor wound for a lower running frequency. For example base speed of an 8 pole motor nominally 750 r/min at 50 Hz, when run at 30 Hz becomes 434 r/min.

The converter will also have associated electrical and cooling noise in the control room/panel

4.3.6 Resonant Vibrations in Vertical Pumps

Vertical pumps are more likely to exhibit operational zones of excessive vibration because of their lower natural frequencies.

It is normal practice to design pumps sets, such that NRF (Natural Reed Frequency) of the pump/motor unit has a separation margin of 20% above maximum operating speed and 20% below minimum operating speed.

Motors with different synchronous full speeds can be selected in order to achieve a non-resonance band of operation.

The pump may have different NRFs in the x and y directions. Both bands of speeds may be locked out on the VFD.

It is usually preferable to change the pump/motor structural stiffness to move the resonance band away from the operating zone. On the other hand, if the NRF is close to the minimum range of operating speed, the unit may be made more flexible.

4.4 Speed

Beyond base speed the torque available will drop as the VFD cannot increase its output voltage, and the motor becomes progressively under fluxed. This is known as field weakening.

4.4.1 Operating Motors above Base Speed

In some instances operating a motor above base speed is possible if the consequences are carefully examined. An example may be using a 4-pole motor with frequency doubled by the VFD instead of a 2-pole motor.

4.4.2 Low Base Speed Motors

For low base speed motors, limited number of slot combinations between the stator and rotor can lead to an acoustic resonant condition, and the associated very high levels of narrow band noise.

In some instances a motor designer may prefer to use a motor designed as detailed in Clause 4.3.5, which in addition to reducing the risk of narrow band noise, can also result in improved efficiency and power factor.

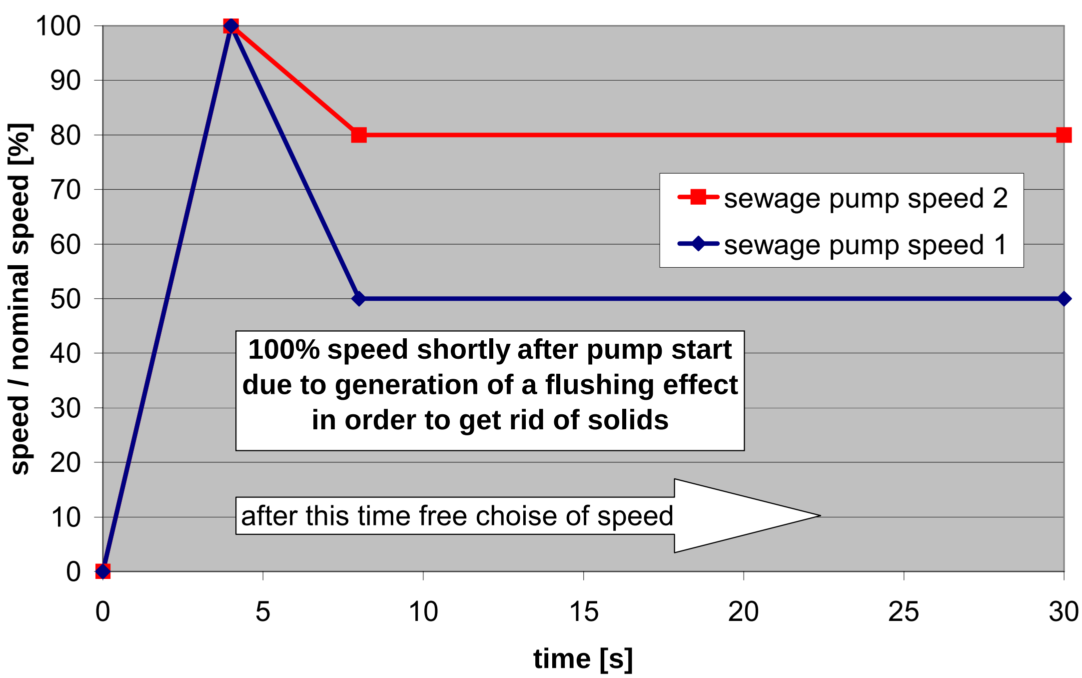

Figure 4-3
Typical Run up time for sewage pump

4.5 Run up Time

VFDs allow control of the run up (ramp times) to control the acceleration and deceleration rates of pumps.

In many cases it is important to ramp rapidly (typically 3- 5 seconds) to a minimum speed to establish a lubricant film in bearings and seals. This also ensures flushing of pipe work is carried out.

Many VFDs allow for two or more ramp rates, which allow fast ramp to establish lubrication, then a slower ramp to avoid surge in the discharge pipework.

The pump manufacturers' recommendation should always be sought.

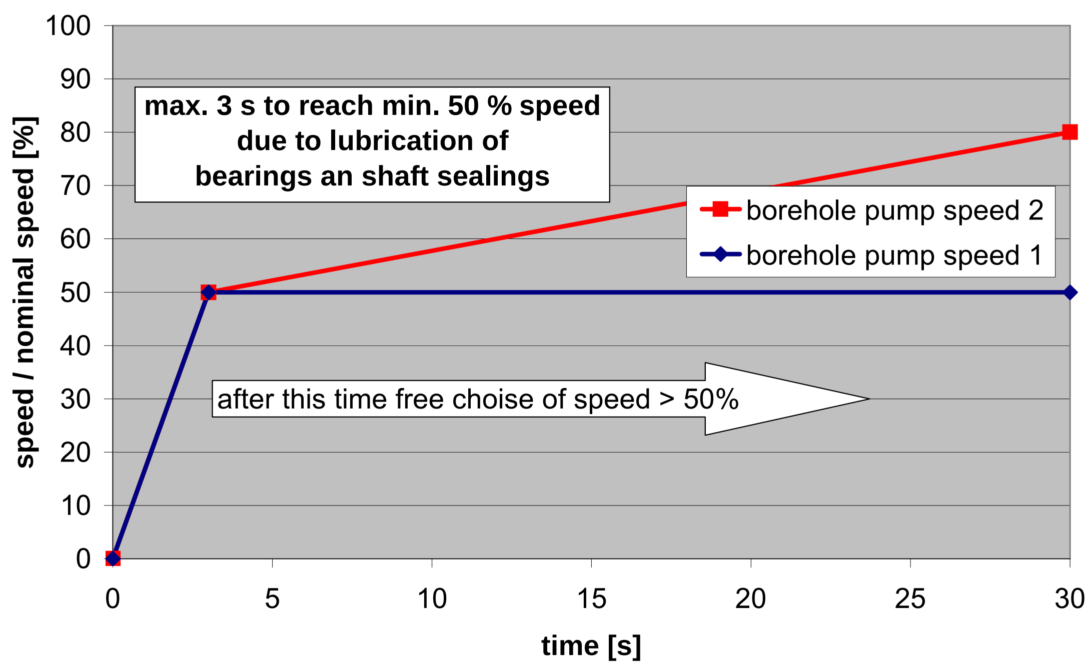

Figure 4-4
Typical Ramp Profile for borehole pump

4.6 Deceleration and Regeneration

In many cases when stopping, the column of fluid will pass back through the pump hydraulics and turn the motor into a generator. This can cause nuisance tripping of a VFD and careful consideration of the stopping mode is required. An active rectifier VFD may have facility to regenerate the power to the supply network. As an alternative a non-return valve can also be installed.

4.7 Further Issues

As described earlier in this guide, with rotodynamic pumps relatively small speed changes can have a major effect on parameters such as power absorbed, NPSHr etc.

Generally VFDs will be used to reduce speed from the nominal, however if there is adequate motor power available the drive may be used to increase speed. In this case there are a number of precautions, which must be considered:

- There will be a change in the noise output from both the pump & the motor as the speed is changed. With higher speed, greater noise and potentially greater vibration will occur
- If the pump is handling a liquid containing abrasive particles, an increase in flow will result in a corresponding increase in abrasion and wear
- With increasing speed, the user must ensure that the NPSHa at the pump remains adequate level to prevent cavitation. This must be checked, since the pressure drop along the suction pipe work will increase as the flow/velocity increases, which will cause a reduction in the NPSHa to the pump. The situation is further exacerbated by the fact that the pump will also require more NPSH when running at higher speeds
- Various mechanical constraints must also be checked:- If the speed (and so the power) is increased then bearings, flexible coupling, magnetic coupling, motor, etc must be checked to make sure they can operate with the increased loading
- Since a speed increase will also affect mechanical seals, the manufacturer should verify that they are still being operated within the allowable region
- In some instances where shear sensitive liquids/chemicals are involved, it is necessary to limit maximum pump speed

Lower speed generally benefits energy savings and maintenance costs but the following precautions must be considered:

- In the case of relatively high static head, care has to be taken that the pump is not operated in inappropriate regions. As shown in Figure 4-1 a relatively minor decrease in speed can move the operating point close to shut off head. If the pump is operated in such a region for a long period of time it will have severe consequences for the life of the equipment
- If pump speed is reduced in some applications, particulates may come out of suspension and cause problems
- A minimum speed limit applies if pumps have a balance disc or drum (generally multi-stage pumps) as unacceptable wear can occur
- Gas seals have minimum peripheral speed and pump flow rate requirements, check with manufacturer

Chapter 5 EMC AND INSTALLATION

5.1 EMC

Electromagnetic compatibility (EMC) is the ability of a system to operate satisfactorily in its intended electromagnetic environment, without disturbing or being disturbed by other users of that environment. Please refer to European Directive 2004/108/EC for guidance.

It is generally used to describe the effects of high frequency conducted and radiated emissions, although all emissions should be considered.

The effects of radiated emissions are of particular concern with both dry and wet well pumping installations; however, long cables lengths can also influence the performance of conducted emissions filters.

For a VFD the requirements are laid down in IEC/EN 61800-3

The basic principle utilised in achieving EMC is that Radio Frequency Interference (RFI) conducted emissions are filtered by an electrical network, and radiated emissions are contained within an overall earthed screen known as a “Faraday Cage”. In cases where high powers are involved, the conducted emission filtering may be achieved in the feeding transformer, by using an earthed screen between the primary and secondary windings.

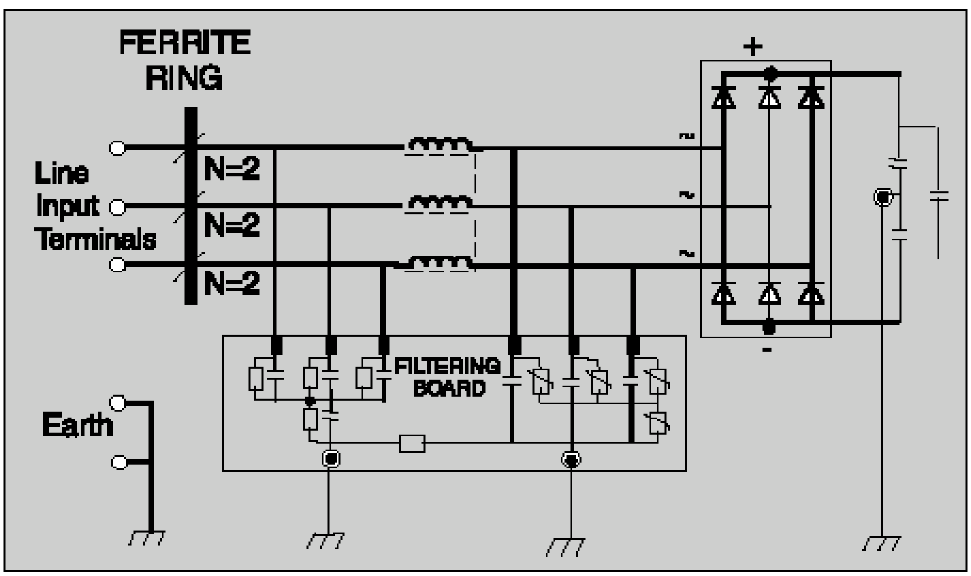

Figure 5-1
Typical Conducted Emissions Filter, Integrated into Drive Module

An examination of the structure of the filter will also indicate that the filter functions by passing the high frequency emissions to ground, which in turn may have an effect on any earth leakage protection used in the supply network.

5.1.1 Differences with Conventional Installations

In a conventional installation, and also in the majority of dry well installations, the motor is installed to a dry atmosphere with fixed cabling and earthing arrangements.

The converter is installed as a wall or floor mounted equipment, with a continuous cable run to the motor, allowing the Faraday Cage to be readily completed.

Generally, the cable length is greater than in conventional installations due to the distance between pump and cabinet.

In a submersible installation at least a part of the cable is flexible, and is designed to resist the effects of the pumped medium. In some cases the cable sheath is formulated to prevent leaching of chemical components to the pumped medium, such as potable water.

If the installation implies that the use of unscreened cables is required. The use of additional filtering .is mandatory in order to fulfill the EMC requirements

5.2 EMC and Shallow Installation

5.2.1 General

The term shallow installations is used for applications were the pump and motor are submerged in the pumped liquid at a depth of not more than 30m.

The ideal installation is where the system of pump, motor, cable and frequency converter is placed in a Faraday cage which totally screens all frequencies present in the system. In a typical pump installation this is usually very practical. Instead, each component of the drive system will be a part of the Faraday cage.

The VFD will require a Radio Frequency Interference (RFI) conducted emissions filter to meet the relevant standards, and the manufacturer will stipulate a maximum cable run length. If this length is exceeded the paragraphs detailing the requirements for deep well installations should be applied.

5.2.2 Cables

It is conventional to use screened cables to limit radiated emissions in accordance with the applicable standards. To minimize problems, the conductors in the cable should be individually screened. The ideal screen is a metallic foil wrapped around the conductors. In general, there are two types of screened cables see Figure 5-2:

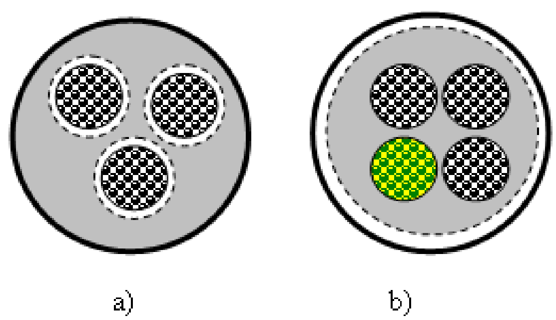

Figure 5-2
Screened Cable Types

In Case a) the cable cores are individually screened and the screens are grounded at the noise source end only, whereas in Case b) the screen is concentric around the whole cable, and is grounded at both ends.

The screen must have sufficiently low impedance at high frequency. A minimum of 2.5 mm^2 is generally adequate, and a guideline value is 0.1 Ω/m at 100 MHz.

If a separate conductor is used for protective earth/potential equalizing, it must be completely outside the cable screen or completely inside the screen and for higher powers symmetrical with the main cores. It must be connected to earth at the same place as the screen at both ends of the cable.

During operation, there will be high frequency currents in the screen of the motor cable, and to prevent interference from these currents double screen cables may be used. In that case, the outer screen should be connected to earth at both ends.

These high frequency currents will cause a loading on the VFD conducted emissions filter, and the maximum cable lengths given by the supplier must not be exceeded.

Any monitoring or signal cables should be placed in separate cable ducts and be no closer than 500 mm from the power cable (where possible). If crossing of cables cannot be avoided, the power and monitoring/signal cables should meet at 90° angle.

5.2.3 Pump Motor Cable Entries

In the ideal case, to ensure a complete Faraday cage the screen of the cable shall have 360° metallic contact to the motor / cabinet at the inlet. In the case of a submersible pump this may not be practical at the motor side.

The cable seals or bushings could preferably be made of a semi conductive material, but this is seldom or never used.

The screen and Protective Earth (PE) conductor shall be connected to earth as close as possible to the cable entry, i.e. the length of the conductor shall be minimized. The length of any unscreened cores inside the junction box should also be kept to minimum.

5.2.4 Local to Motor Isolation and Intermediate Junction Box

Where local to motor isolation is required for safety purposes, it is essential that the switch enclosure should be conductive, and form part of the "Faraday Cage" surrounding the entire drive system. This means that the cable screens should be correctly bonded/glanded to the enclosure.

In many cases the converter manufacturer will make recommendations regarding switching off the variable frequency converter, prior to opening of the switch contacts.

Figure 5-3
Local to Motor Isolator

5.3 EMC and Deep Well Installation

The network side of the VFD as for any other installation will require RFI filtering according to the VFD manufactures recommendation in order to reach the required emissions category.

The characteristic of most deep well installations is that long cables have to be installed between the VFD and the pump in order to reach the submersible motor.

Long cables on the motor side of the VFD equate to a high risk of transmission line "amplifier" effect meaning that damaging levels of transient voltage can be reached at motor terminals.

The recommendation is therefore to install the VFD as close to the well head as possible.

Also;

- Use unscreened cable as drop (down hole) cable.
- Use screened cable, steel tube (conduit or cable trunking with each section bonded to the next) as cable duct from outlet of the VFD cabinet to the well head in order to comply with the emission part of the EMC standard.
- Use sinus filter (LC filter) on the motor side of the VFD.
  - Sinus filters will have an associated voltage drop, see Clause 5.5,

The use of unscreened cables can pose a problem in relation to sensors - this can normally be overcome by using the best possible sinus filter and having the cables for sensors moved as far from the drop cable as possible, having a good screen on the sensors and ultimately put these cables into steel pilot tubes.

All above means are taken in order to minimize distance between VFD and submersible motor.

If screened cables are used pay attention to voltage drop created by the cable configuration - even big three phase submersible motor can be exposed to damaging under voltage.

5.4 Installation / Cabinet

The circuit before the point where supply power is connected to the VFD and where the filtering is installed is referred to as the clean side. The parts of the which can cause disturbances are described as the dirty side.

Enclosed wall mounted drives are designed so that the circuit to the output connection is the only dirty part. This is the case where the installation instructions of the drive are followed implicitly.

To be able to keep the clean side "clean" the dirty parts are segregated into a Faraday Cage.

The use of additional components, e.g. contactors, isolators, fuses, etc. in some cases makes it difficult to keep the clean and the dirty side separate.

Reliable high frequency/low impedance connections are essential to ensure proper functioning of the filter, therefore, where the filter is not integrated into the drive module, the filter manufacturers instructions must be followed, and they will typically stipulate.

- Filter shall be assembled on a metal plate with unpainted connection points all in accordance with filter manufacturer's instructions.
- The frames of the filter cubicle (if separate) and the drive cubicle shall be bolted together at several points. Paint shall be removed from all connection points.
- The input and output cables of the filter shall not run in parallel, and must be segregated.
- The maximum length of the cable between the filter and the drive must be according to the RFI-filter manufacturer's instructions.
- The filter must be earthed in accordance with the manufacturer's instructions. Note that the cable type and size are critical.

Where the VFD is an IP 00 open chassis converter, or if additional components are to be connected to the dirty side of an otherwise compliant unit, it is always necessary to provide an EMC enclosure.

For enclosed chassis modules where the motor connections are made directly to the converter output terminals and all the internal shielding parts are fitted, there are no requirements for special enclosures.

If drives are fitted with output switching devices, for example, then an EMC enclosure will be needed, as the integral Faraday Cage will no longer apply.

As a reminder, EMC is only one part of enclosure selection. The enclosure is sized according to several criteria:

- Safety
- Degree of Protection (IP Rating)
- Heat Rejection Capability
- Space for accessory equipment
- Cosmetic aspects
- Cable access

From the EMC point of view it means that the enclosure is sufficiently rigid and proof enough to be a part of the Faraday Cage. In general steel of less than 0.75 mm thickness will not prove adequate. In small systems, plastic boxes can also be used if they are coated inside with conductive paint. The paint must have metal to metal contact at each seam to other parts of the metal enclosure.

External safety switches may also be in plastic boxes if the boxes form a good Faraday Cage and are conductive inside, otherwise metal boxes should be used.

Specific requirements for enclosures may include

- Inside surface: not painted.
- Louvres and holes in steelwork..
- Doors:
    - Sealed with conductive gasket, and adequately earthed. Sufficient locks to seal and maintain high frequency earthing.
- Cover and glanding plates:
    - Metal against metal (not painted), all earthed.

A number of proprietary enclosure types are available, which use a variety of materials and methods of shielding against radiated emissions. The manufacturer's guidelines for construction and earthing must be followed.

As the cables are part of the overall installation they are also part of the Faraday Cage. To be able to meet the EMC requirements, power cables with good shielding effectiveness must be used.

The purpose of the shield is to reduce radiated emission. In order to be efficient, the shield must have good conductivity and cover most of the cable surface. If the cable shield is used as protective earthing, the shield cross area (or equivalent conductivity) must be at least 50 % of the cross sectional area of the phase conductor.

The motor cable should preferably be connected directly to the VFD and not via a terminal box. The motor cable screens and the Protective Earth conductor should be terminated at the VFD earth connector, not at the cabinet earth point. Where an intermediate terminal or safety switch box is required special care is required.

Conductive cable ducts trays or racks must be connected to earth, and all sections of the cable support structure must be properly interconnected.

The cables must not be bent too tightly as the screen may spread which will increase the HF emission.

A minimum bending radii is often stipulated by the cable manufacturer.

Bond all metallic panels of the cabinet

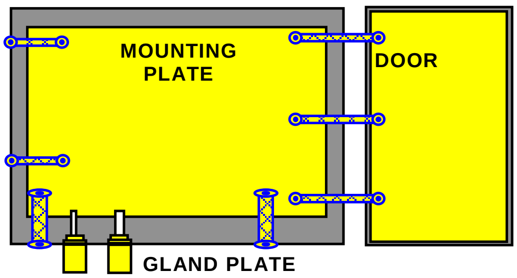

Figure 5-4
Enclosure Grounding Requirements

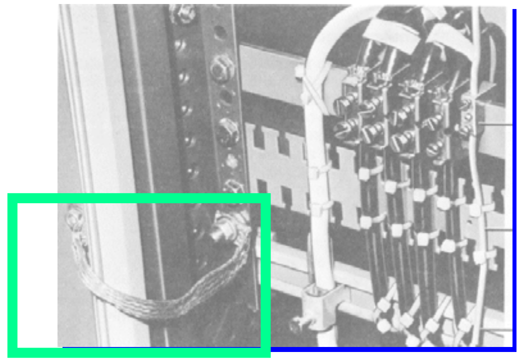

Figure 5-5
Braided Tinned Copper Earthing Straps Give Best Results

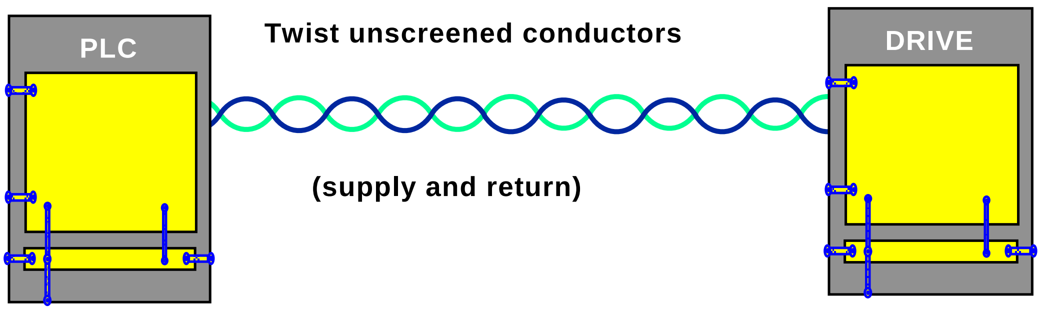

Figure 5-6
Twist all Control Cable Pairs

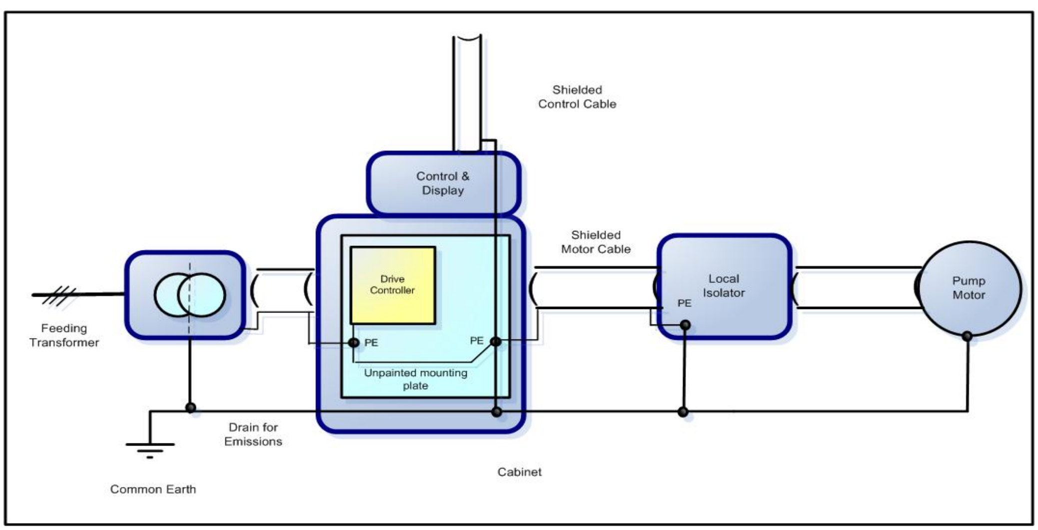

Figure 5-7
Install Equipotential Bonding

Examples of good EMC installation practice

5.5 Precautions with Long Cables

Where long cable runs are involved, the filtering capabilities of the VFD must be considered. Manufacturers recommend specific conducted emissions filters based on tests with maximum lengths of cables, and longer cables will cause reduced performance of the filter. In extreme cases the filters will overload and cease to function.

Two basic forms of output filtering can be utilised:-

- du/dt filters will reduce the rate of change of the voltage pulses and this will reduce the effects of long cables, however, there will still be a finite limit which should be detailed in the manufacturers' documentation.
- Sinus (or sinusoidal) filters are designed to produce a completely sinusoidal waveform, which has no distance limitation.

Both types of filters will have an associated volt drop, and care must be taken to ensure that the terminal voltage is within the tolerance for the specific pump motor. Sinus filters typically reduce the output by 40 V to 60 V, therefore the terminal voltage available to the motor will also require consideration

5.6 Common Aspects of Installation

A number of basic questions must be answered to achieve a satisfactory installation, including the following.

5.6.1 Electrical Safety

- Co-ordination with the protection provision
  - The drive should provide fast-acting short-circuit and earth-fault protection which protects the motor, cable and drive. Overload protection of the motor is also provided, usually within the drive. Provided this protection has been correctly arranged the cable rating needs only to match the motor continuous rating.
- Earth leakage protection
  - With RFI-filtering It is important to consider that the capacitance values and therefore the energy content and finally the effectiveness of Y-type capacitors used for the filters is limited by the normative requirements of safety standards, such as IEC 60065 in the case of plug-in apparatus.
  - If the leakage current through this RFI-filtering capacitance to earth is too high, the effectiveness of differential protection (earth fault protection) within these supply systems can be compromised. Safety requirements related to leakage current, including requirements for warnings, are given in IEC 61800-5-1.
  - In complex or essential processes, it is useful and state of the art to have a distributed isolated power supply system (IT Network). Even if, for example, the motors are exposed to high humidity, it may be necessary to continue the process in spite of one short circuit to earth. This short circuit is detected via an "earth fault monitoring system" and allows the whole process to be safely run until the next service interval
- Effects of harmonic currents.
  - The VFD produces a series of voltage pulses in the output, this results in a virtually sinusoidal output current. There is therefore normally no need for any special consideration in the motor circuit.
  - Local regulations and international standards (EN 50160, IEC 61000-2-2, IEC 61000-2-4, IEC 61000-3-2, IEC 61000-3-12, IEEE 519, ENA ER G5/4-1) regulate the levels of harmonic current or voltage allowed on the supply network.

- Voltage Rating
  - Experience has shown that for low voltage installations a cable rated 600/1000 V will provide adequate insulation.
  - The use of 300/500 V cables for 400 V networks is not recommended.
- Cables should always be cut to the correct length.
  - Spare cable must never be rolled up, this practice is not acceptable both for rating and EMC reasons.
- Cables should not be jointed with different types of cable, except at a single, purpose designed, junction box.

5.6.2 Circuit Protection

Most drive modules require circuit protective devices (fuses or circuit breakers) at the supply input. Their purpose is to provide protection from a catastrophic failure within the drive, which causes a fault between lines or to earth, or (rarely) a sustained overload.

These protective devices may sometimes also be used to protect the feeding cables.

Protection against drive or motor overload and against a short-circuit at the output is provided in the drive.

The drive supplier's recommendations must be followed. This is essential for the safety of the installation, and to maintain the validity of safety markings such as the CE mark, UL approval etc.

Care must also be taken to ensure that any stipulated protective device clearance time is achievable, as fault currents can be limited by "weak" supply networks

5.6.3 High Powers/Currents

When high powers are involved, and no sinus filter is fitted, and it is not possible to obtain an adequately rated single three-core cable, or the physical installation of such a cable is too difficult, the installation should be made in parallel three core cables, not in single core cables as shown in Figure 5-8.

This is to prevent circulating currents in the screens of single core cables, as the overall screen must be terminated at both ends.

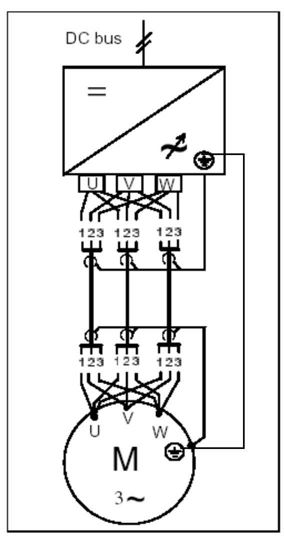

Figure 5-8
High Current Installation

5.6.4 Power Factor Correction

With a frequency converter, power factor correction capacitors must never be installed in the output side of the frequency converter.

The Variable frequency converter will always provide the reactive power required by the motor.

The network side power factor will depend on the rectifier type being utilised, and the specialist advice may be required.

5.6.5 Segregation

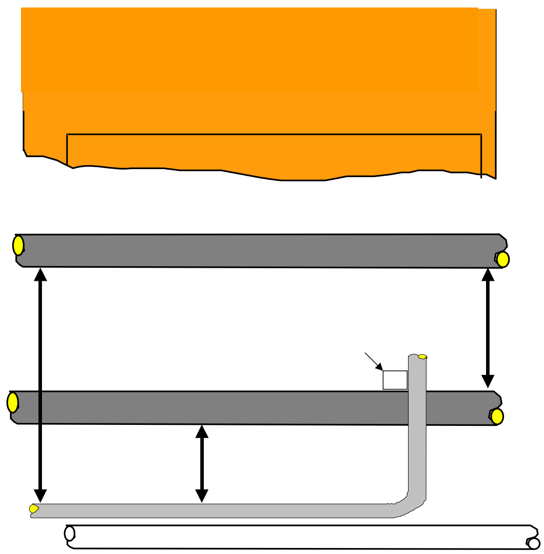

Figure 5-9
Recommended Segregation between cables

Many installers are reluctant to bond a cable screen at both ends due to a fear of circulating currents. Drive manufacturers are well aware of this, but have tested their products to meet the most stringent operating conditions.

They include instructions for appropriate mitigation measures, such as potential equalisation conductors in parallel with the screened cables.

The screen termination may only be omitted at one end if the signal at that end is galvanically isolated, and the manufacturer of the equipment specifically approves of this style of connection.

5.6.6 Earthing

Primarily the purpose of earthing is personnel safety. Irrespective of any other instructions all the conducting parts of the system must be earthed, ensuring that a safe “touch voltage” is not exceeded.

For electromagnetic compatibility it is also necessary to ensure that equipotential bonding is effective over a wide range of frequencies.[4] Further information on Earth Bonding and Electronics is also contained in EN 60204-1.

In order to limit the potential for a system to radiate noise, it is essential that all the parts share a common potential. Because of the high frequencies involved, this means that the conductors connecting them must have very low inductances. For this reason the conductors required from the safety point of view are often inadequate.

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[4] GAMBICA/REMA Technical Report No 2 covering Bearing Currents gives further information on the requirement for potential equalising.

It is also important that both the motor and driven machine share a common earth potential, and the drive and its controls share a common potential.

5.7 Protection of Submersible Motors

5.7.1 General

Installation conditions for submersible motor pumps often make it difficult to gain access on them.

Dismantling for inspection may be difficult and expensive (e.g. crane rental fee).

Consequently there is a need for information about the condition of the system and thus submersible motor pumps are often equipped with sensors for remote condition monitoring. These sensors must operate without disturbances caused by the VFD.

There are three parameters of special interest:

- Critical temperatures
- Water ingress into dry IP68 motors
- Vibration

Phase sequence and direction of rotation are normally monitored on a control panel or the VFD itself.

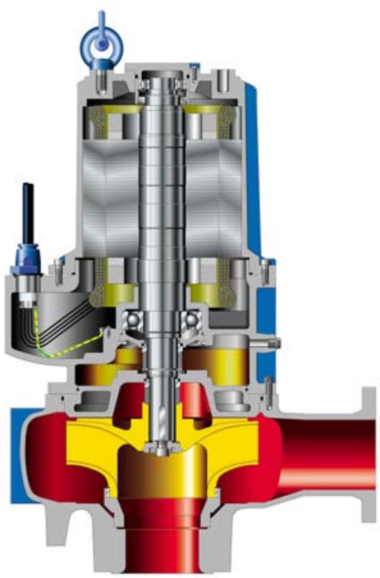

Figure 5-10

Figure 5-11

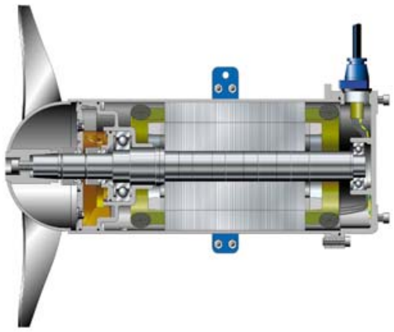

Figure 5-12

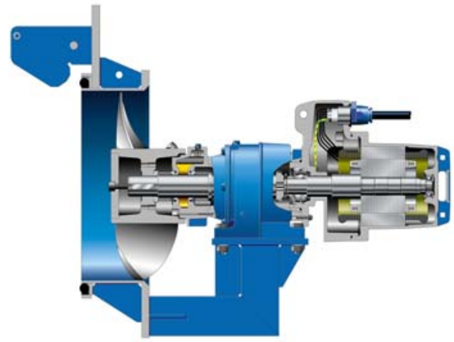

Figure 5-13

Figures 5-10 to 5-13 are Typical Submersible Motor Pumps with IP68 Motors

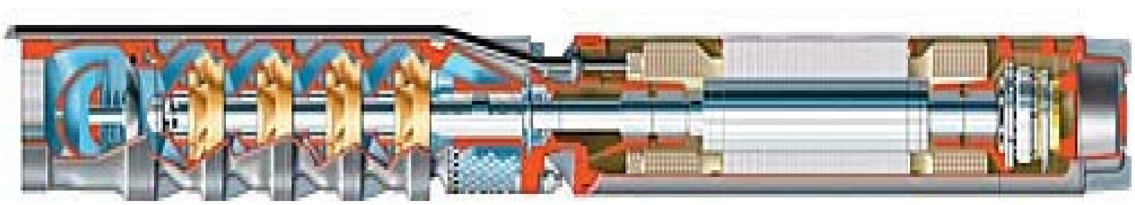

Figure 5-14
Typical Multistage Deep Well Pump-set

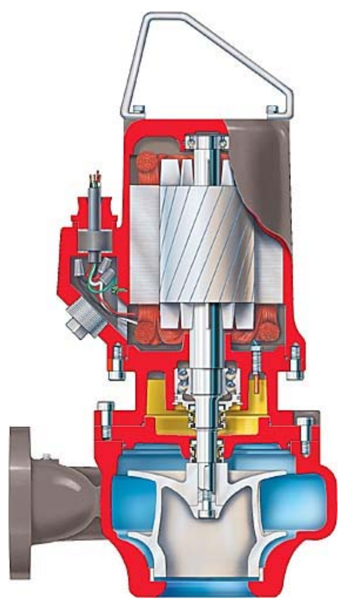

Figure 5-15
Typical Oil Filled Motor Sewage Pump-set

5.7.2 Sensor Types and Vulnerability

Typical sensors and their sensitivity regarding EMC will be considered in the following paragraphs

5.7.2.1 Motor Winding Temperature Sensor

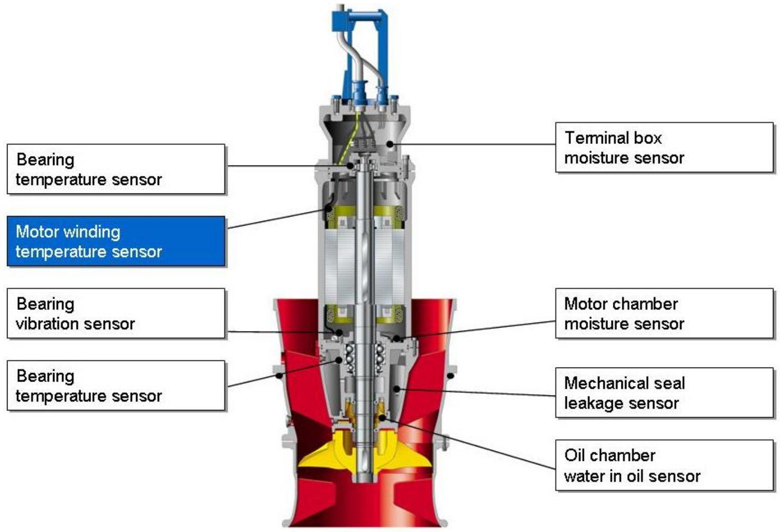

Figure 5-16
Motor Winding Temperature Sensor

Insulation of the motor windings is temperature sensitive. Ageing and lifetime depend extremely on temperature. Operating at 10^o Celsius above the thermal class temperature will halve winding lifetime! Therefore monitoring of motor winding temperatures is an important matter.

Pt 100 resistance temperature detectors (RTDs) are normally used only with high voltage motors (See comments regarding bearing temperatures).

For low voltage motors it is common practice to have simple yes / no information whether the thermal class temperature is exceeded or not.

Such sensors are little affected by VFD operation of pumps, and Positive Temperature Coefficient (PTC) thermistors are the most commonly used sensors, while bi-metal sensors (Klixon) are often used for small low cost pumps.

Over temperatures in motor windings may have different reasons:

- Mechanical overload
- Single phase operation
- Loss of coolant

5.7.2.1.1 Positive Temperature Coefficient Thermistor

- Temperature sensitive semi conducting resistance with positive temp. coefficient
- Inserted into motor winding
- Special monitoring relay mandatory
- Maximum operating and test voltage 30 V

Typical data for one PTC sensor is shown in Figure 5-18:

For protection of motor windings three PTC elements in series is normally used. This gives a higher safety and enables detection of single phase running.

EMC sensitivity:

- low, non critical

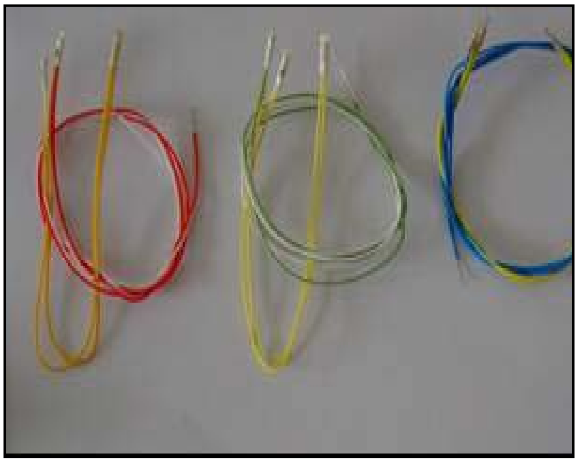

Figure 5-17
PTC sensors

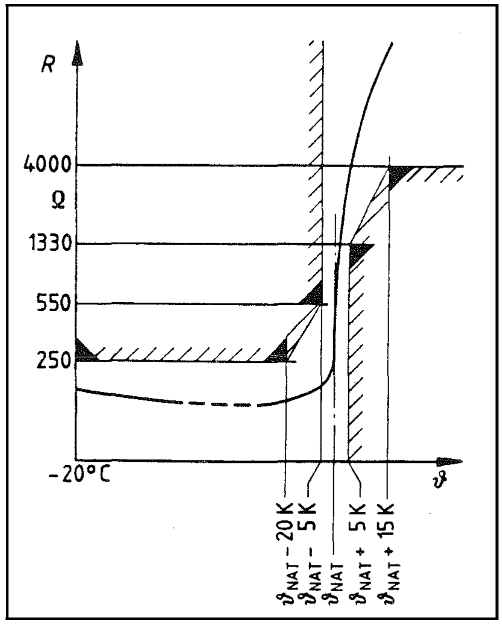

Figure 5-18
PTC characteristic acc. DIN 44082

5.7.2.1.2 Thermal (Bi-Metal) Contact

- Temperature sensitive mini switching contact
- Inserted into motor winding
- No monitoring relay necessary
- Potential free Normally Closed-contact (typical data 250 V AC; 2 Amp)
- Automatic reset, when temperature drops 30^0 K
- Closed temperature O.K., Open temperature too high

EMC sensitivity:

- low, non-critical

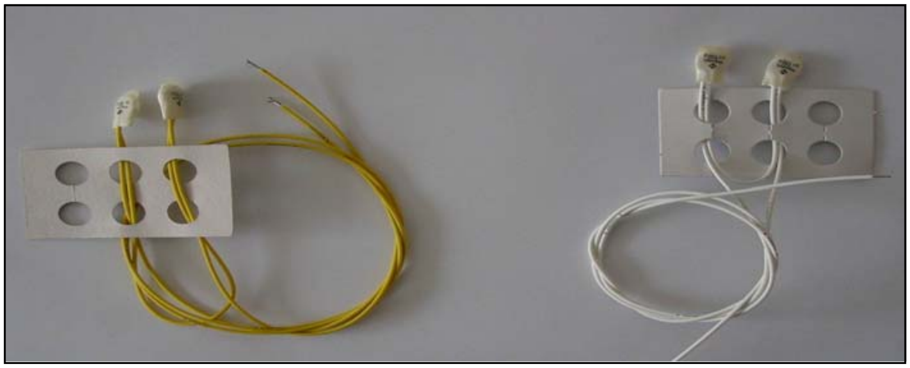

Figure 5-19
Thermal (Bi-metal) Sensors

5.7.3 Temperature Sensor as Pump Controller

Raw sewage pumps are often installed in a sump on a duck foot bend.

It is normal that water level should be lowered as much as possible for some time. Therefore the motor has to operate in a semi-submerged condition and loses it‘s water cooling, and therefore to reach thermal class temperature is normal and not a fault condition.

Bi-metal sensor switch the pump on and off automatically depending on water level and temperature.

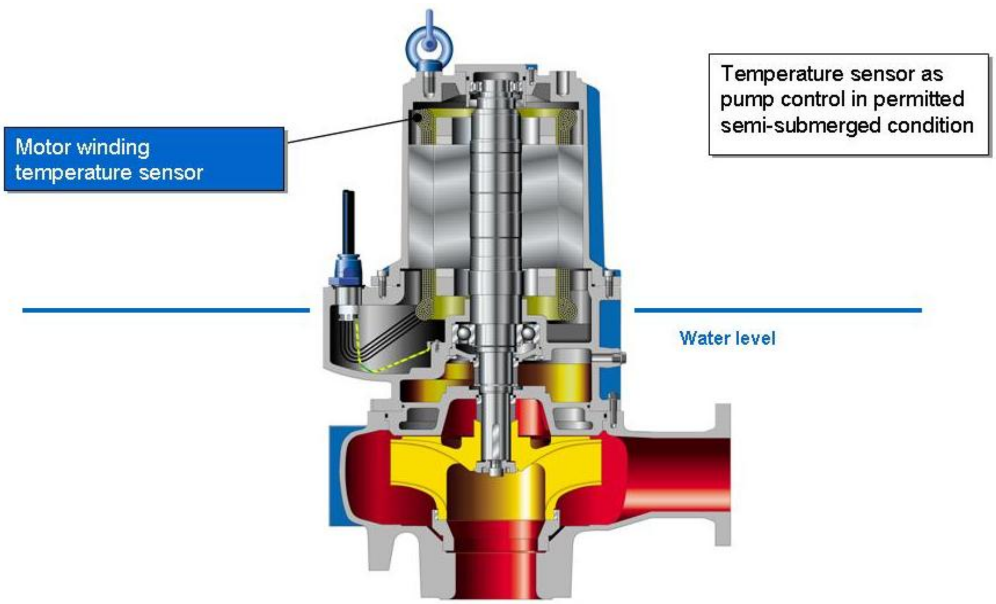

Figure 5-20
Semi Submerged Operation

5.7.4 Bearing Temperature Sensor

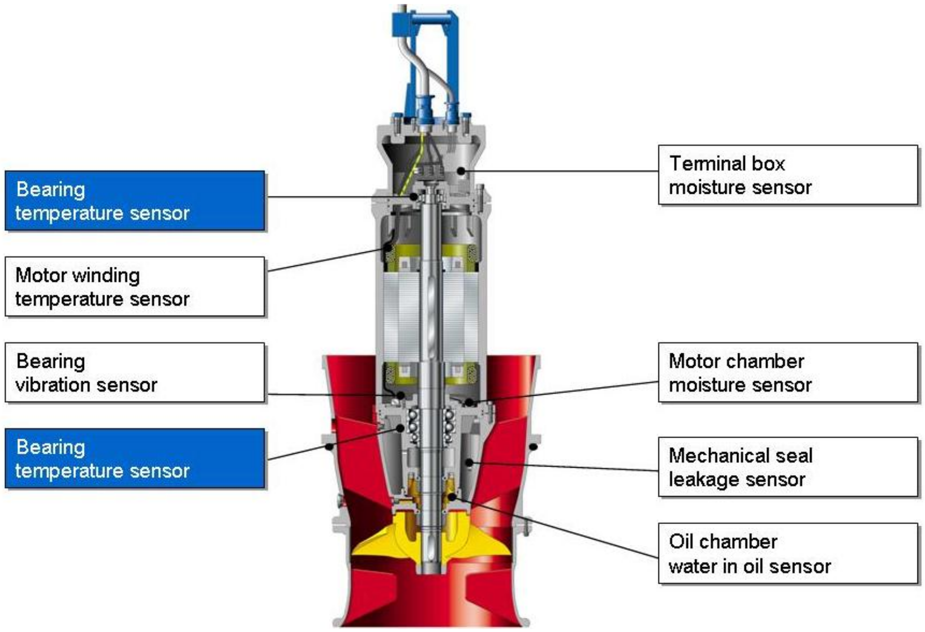

Figure 5-21
Bearing Temperature Sensor

Monitoring of bearings is a technology with long history. It is state of the art to nearly always use Pt 100 RTDs although other sensors such as PTC thermistors may also be suitable.

Pt 100s have the advantage that it is possible to record a trend of temperatures. Slowly increasing temperatures can be a sign for wear of the lubricant.

Typical sensor data:

- Pt 100 RTD
- M10 thread in bearing housing
- Analogue, continuous temperature signal, max. voltage 6 V
- Costly monitoring relay needed

Resistance varies by the relation $R = 100\,Ohm \bullet \left(1 + 0.00383 \bullet \frac{T}{°C}\right)$

- Test in workshop at 20°C gives 107.7 Ohm
- Typical Tripping value for motors with standard grease
  Limit = 110°C --> 142.1 Ohm --> stop
- Tripping value for submersible motors with high temperature grease.
  Limit = 130°C--> 149.8 Ohm --> stop
- Tripping limit for special hot water execution 150°C --> 157.0 Ohm --> stop

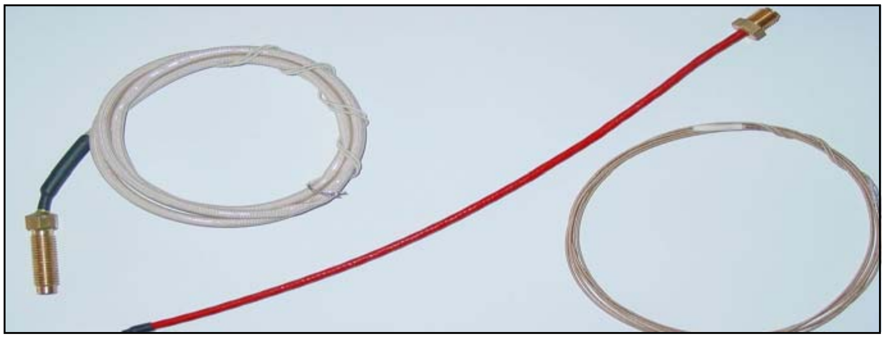

Figure 5-22
Pt 100 Sensors with Screw Housing for Bearing Monitoring

Four conductors wiring for compensation of cable resistance is not mandatory, since temperature deviations of less than 1^0 K have no significant negative impact on motor protection.

EMC Sensitivity:

- High

Screened (shielded) sensor cables and segregation from power cables are essential with VFD operation of pump.

5.7.5 Monitoring of Water Ingress in IP68 Motors

It is essential to keep an IP68 motor dry inside.

Unnoticed water ingress will damage winding insulation and also bearings after a short time.

There are several different possibilities for water ingress.

Three typical failures are:

- Mechanical shaft sealing
- Cable entry seals
- Motor housing rubber seals and O-rings

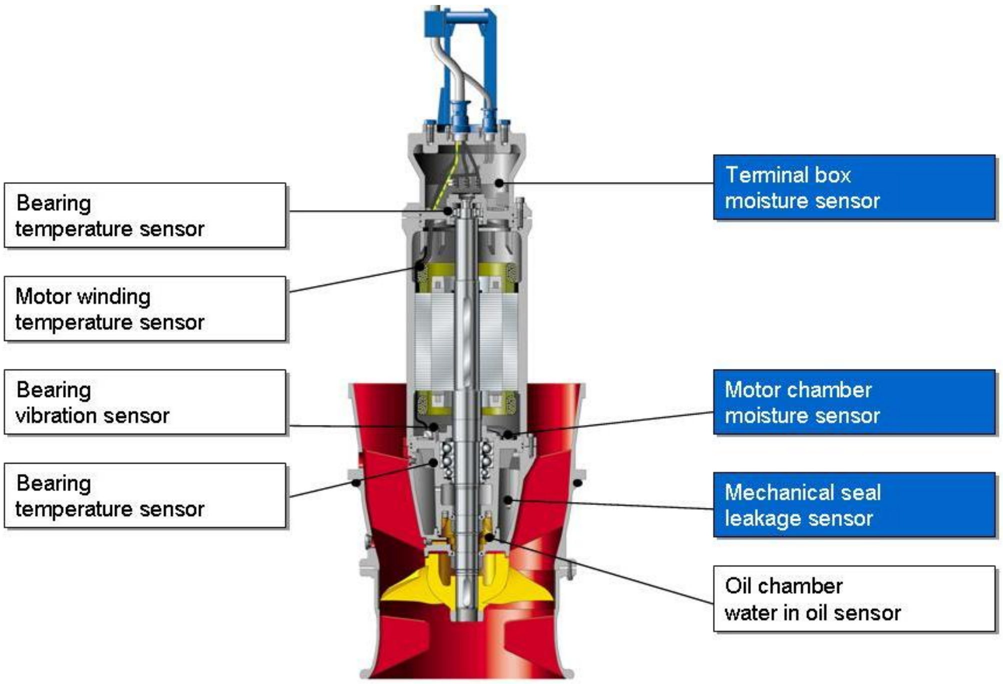

Figure 5-23
Leakage Sensors

5.7.5.1 Moisture Protection Electrode

Conductive sensor electrodes are widespread. They are a simple, effective method for water detection.

- Screwed mostly to the bottom side bearing bracket (sometimes additionally in terminal box).
- Sensor voltage must be an alternating voltage in order to prevent electrochemical passivation of sensor.
- Max. voltage depends on design and local standards
  - (e.g. USA less than 30 Vac mandatory)
- Triggering occurs with resistance to earth of <6 kOhm.

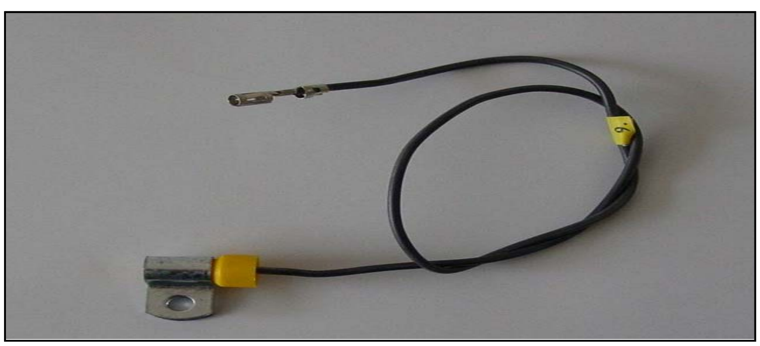

Figure 5-24
Sample Electrode

EMC Sensitivity:

- Conductive electrodes are generally sensitive regarding EMC.
- Screened (shielded) sensor cables and segregation from power cables is essential.
- It is possible to compensate EMC effects by special monitoring relays with special electronic filters on inlet terminals.

5.7.5.2 Mechanical Seal Monitoring by Float Switch

The design of a submersible motor must have a leakage chamber between motor side mechanical seal and motor bearings. In case of failure of all mechanical seals a certain amount of leakage water can be collected in this chamber. The level of leak water can be monitored with a float switch.

- Float switch comprises typically a potential free NC-contact (250 Vac; 1.5 Amp)
  - Closed leakage chamber empty
  - Open leakage present, check mech. seals

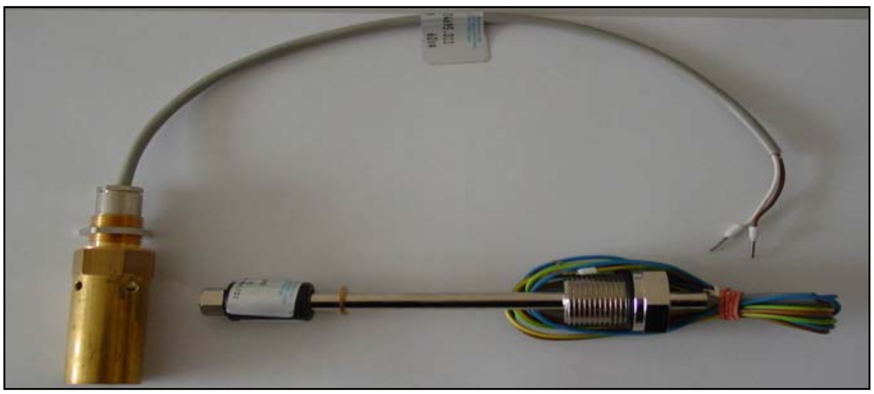

Figure 5-25
Different Types of Float Switches

EMC Sensitivity

- Generally insensitive
- Mechanical contacts are typically so called REED switched. Magnetically operated contact springs are located in an evacuated micro glass tube.
- They are very reliable and absolutely not sensitive regarding EMC.

5.7.5.3 Mechanical Seal Monitoring with Conductive Electrodes

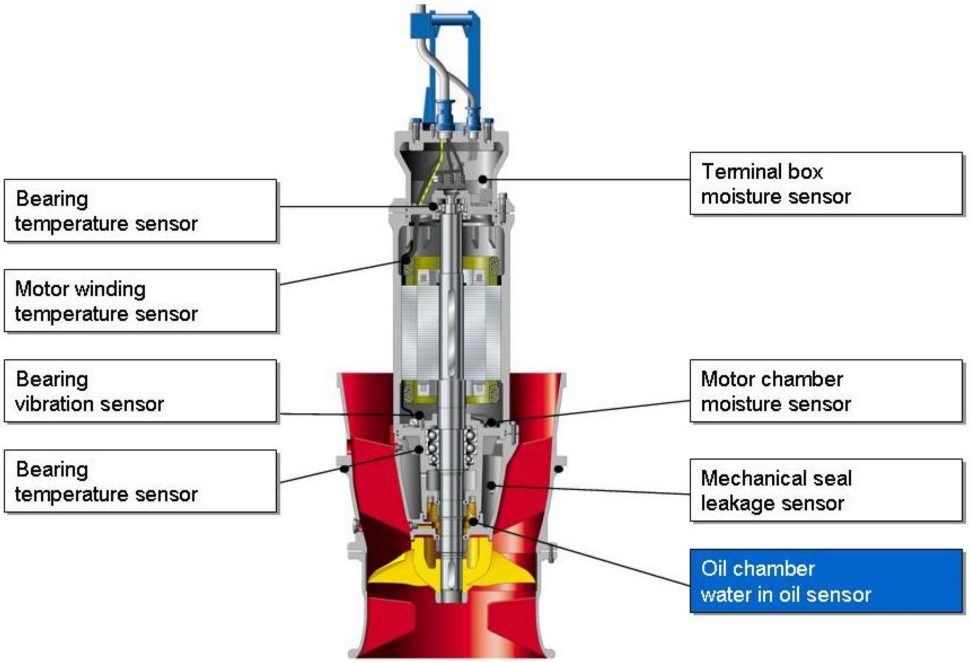

Figure 5-26
Water in Oil Sensor

Many pumps are equipped with two mechanical seals for safety reasons. For cooling and greasing of mechanical seals an oil chamber is usual between them. In order to monitor pump side mechanical seal a mixture of water and oil must be analysed.

This is usually done with a special conductive moisture sensor.

For basic technical sensor data see clause 5.7.5.1. Only the mechanical design is adapted to the oil chamber.

Figure 5-27
Conductive Water in Oil Sensor

EMC Sensitivity:

- Conductive electrodes are generally sensitive regarding EMC.
- Monitoring relay must be adjusted accurately on the resistance of a permitted mixture of water and oil. This is complicated and critical for a VFD driven pump.
- Screened (shielded) sensor cables and segregation from power cables are essential

5.7.6 Vibration Sensors

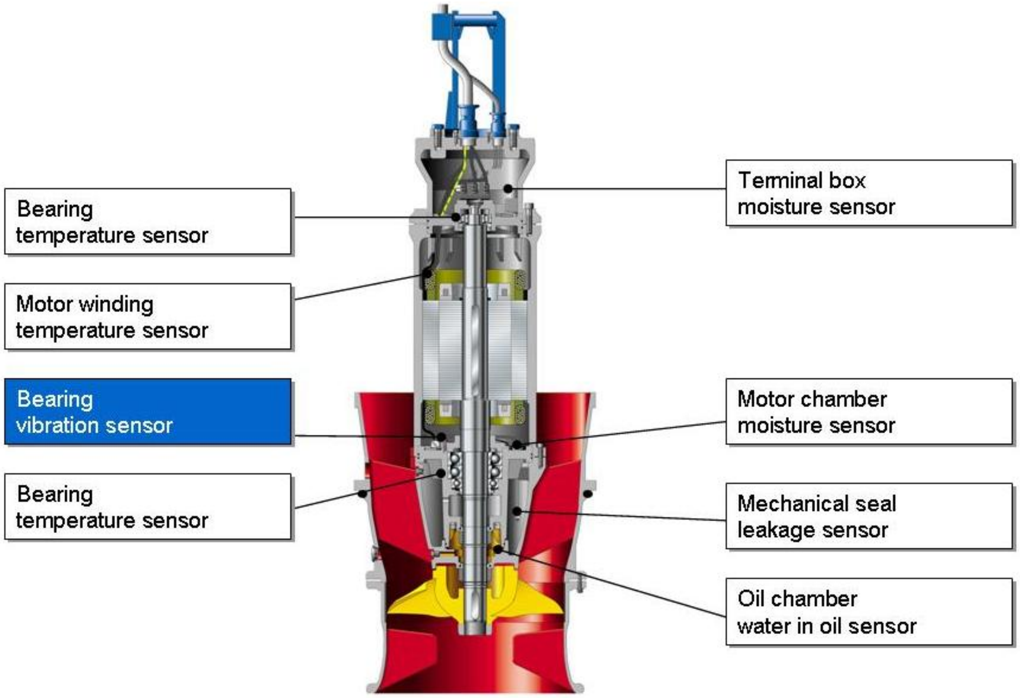

Figure 5-28
Vibration Sensor

There are many different sensors for vibration acceleration and vibration speed in use. They have following common features:

- Analogue high frequency sensor information

EMC Sensitivity

- Very critical with respect to EMC
- Screened cables and special electronic filters are essential.

Figure 5-29
Acceleration Sensor on Locating Bearing

5.8 Summary of Sensors

5.8.1 EMC Robust Sensors

EMC Robust Sensors which do not need special care include:-

- PTC temperature sensors
- Thermal contact temperature sensors (Bi-metal)
- Float switches with mechanical contacts

In general these sensors do not need separate screened sensor cables for connection of pump and control panel.

Even combined power and control cables are possible for small VFD operated submersible motor pumps.

5.8.2 EMC Critical Sensors which need some care are:

- All conductivity electrodes
- Pt 100 RTD thermometers

These sensors always need a separate control cable. If the pump is continuously submerged and cable length outside water is very short (junction box beneath pump sump) screening of pump cable may possibly be neglected since surrounding water has the function of a perfect EMC screen.

If this is not guaranteed a screened sensor cable is strongly recommended. In some cases special monitoring relays with electronic filters will be necessary to suppress nuisance tripping

Combined power and sensor cables are not possible!

5.8.3 EMC Problematic Sensors

EMC very critical sensors which are problematic together with VFD:

- Vibration sensors

These sensors need a separate screened control cable for themselves.

Screened power cables will be mandatory also.

Special digital filters may be needed in order to get rid of high VFD harmonics.

5.9 Other Sensors and Transducers

Within a pumping system it is likely that other sensors and transducers will be installed for satisfactory system operation, these include level, flow and pressure transducers.

In general devices that are connected by co-axial cables are inherently less EMC immune. Devices with signal converters in the head and twisted pair connectors tend to be substantially immune from EM disturbance.

In all cases correct grounding and equipotential bonding of the system is imperative.

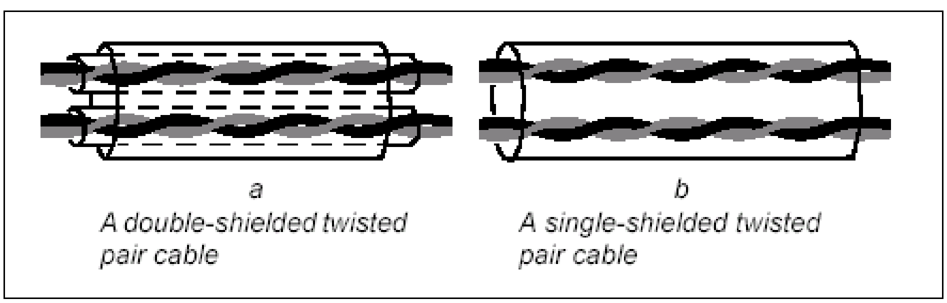

Figure 5-30
Preferred Sensor Cables

Chapter 6 DIMENSIONING

When dimensioning a variable speed submersible pumping system, the hydraulic considerations will determine the type of pump and approximate powers required.

The electrical considerations will start with the availability of a power supply, and the point of common coupling to other users of the public electricity supply.

This in turn will determine the EMC category of the system.

6.1 Determine Voltage /Current

A VFD is a source of current and therefore must always be selected on the basis of the motor name plate current. Where a catalogue gives kW ratings, these are always on the basis of typical values for conventional motors of 4 pole or 6 pole speed, these should be ignored for the purposes of submersible pumps..

The kW rating of a motor is the power that is delivered at the motor shaft and NOT the power that is delivered to the motor terminals.

The current drawn from the supply is related to the kW rating, the supply voltage, the motor efficiency and the motor power factor.

6.2 Motor Derating

The design voltage for the motor is a critical factor. EN 50160 stipulates the public supply voltage characteristics in Europe, and specifies 230/400 V +/- 10%. Industrial networks may also use 690V, 3300V and higher. In North America supplies may be at 460/480 V. or, 575/600 V.

It is also important to note that in North America the no load voltage of the distribution transformer is often specified, while in Europe it is always the full load voltage.

In order to achieve the most “motor friendly” output waveforms, the majority of well designed VFDs do not generate the same voltage at the output terminals as is fed to the input.

Only VFDs fitted with “active rectifiers” will reliably give an output voltage equal to the input network voltage.

Typically a system should be designed to allow for a 10% volt drop, as IEC 60034-1 stipulates a voltage tolerance of 5%. This implies that for (say) a 400 V 50 Hz system the motor will receive the correct voltage only up to 45 Hz.

To give full power beyond this frequency will draw more current and may cause additional heating.

The pump manufacturer must therefore select a suitable motor for the specific application.

In addition, if output devices are used with the VFD, a further volt drop will occur, and either the pump motor should be designed to allow for this, or a transformer used to correct any discrepancy.

6.3 Size of Converter

The first step is selecting a pump end that will meet the duty and a motor that fit the pump.

- How to select a frequency converter for a specific pump:
  - Choose the input voltage range. This should fit the motor voltage, and the mains supply at the installation site. This is the first parameter in selecting a VFD. Take care (seek technical advice) when using a VFD to convert the input voltage to different output voltage range
  - Find the maximum motor current on the motor label or in the datasheet on the selected motor. Combined with the input voltage find the drive that is able to deliver the maximum motor current. Do not oversize the Frequency Converter Choose the first converter in the product family that can satisfy the motor current.

  - o Be aware of that overloading the motor by the pump, will result in a higher motor current, than the one on the motor nameplate.

- ➢ Select the enclosure class.
  - o Choose IP00/20/21 for panel mounting, Choose IP54/55 for wall mounting.
- ➢ Select the accessories required for the application.
  - o Typically this may include input or output inductors or filters, sensors, additional I/O, man machine interface and communication options.
  - o Care must be taken to allow for the volt drop to the motor terminals.
  - o Many deep well applications require sinusoidal output filters, and the filter voltage drop must also be considered.

These are the main steps in selecting a frequency converter, selecting the different accessories might lead to additional steps.

6.4 Additional VFD Components

Additional components may be required to limit the rate of rise of the pulse, reduce the reflection coefficient and thereby reduce the peak voltage level. Some of the devices are also used to compensate for large capacitive cable charging currents. These techniques may be summarised as follows:

- ➢ Output Reactors
- ➢ Output du/dt Filters (sometimes known as d*u*/d*t* filters)
- ➢ Sinusoidal Filters

These solutions should be correctly matched to the application and the basic characteristics are as described below. In each case the effects of volt drop in the device on the final terminal voltage should be established, together with the potential reduction in the motor peak torque. These are not generally available with submersible pump motors, due to the restricted space available.

Figure 6-1
Typical Inverter output Sine Filter

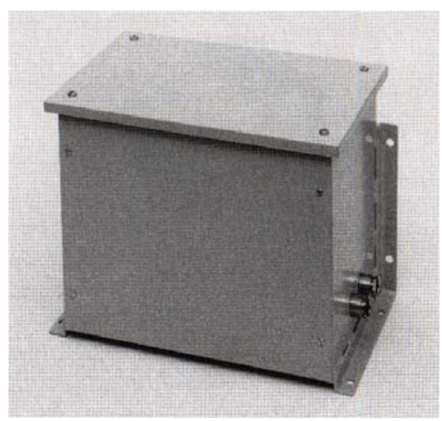

Figure 6-2
Enclosed Sine Filter

Motor Power [kW]	Max. motor cable length [m] No conducted emissions filter		Max. motor cable length [m] EN 55011 Class A, EN 61800-3 Cat C2/C3 integral conducted emissions filter	
	Switching frequency. 4 kHz	Switching frequency. 8 kHz	Switching frequency. 4 kHz	Switching frequency. 8 kHz
5.5	100	100	50	30
45	200	100	30	30
110	300	150	100	Not offered

Table 6-1
Typical Variation of Allowable Motor Cables for Typical Manufacturers of VFDs

shows the typical variation in allowable maximum cable lengths for a typical manufacturers product.

The use of du/dt filters will generally double the listed distances.

A sinusoidal filter does not normally have a restriction. This table is used for illustration only, and the specific figures for a particular VFD should be taken from the manufacturers technical details.

In many cases a range of filters is available with differing performance.

Traditionally VFDs have often been applied to existing and new motor systems as a stand alone component, placed between the power network and the driven motor.

When a stand-alone drive is applied, it is important to ascertain that it is compatible with the motor, the motor cabling and the power network system. Drive motor systems available from system integrators, as well as packaged systems generally assure that the selected components will work well together.

6.4.1 Comparison for Preventative Measures

In considering the relative merits of the various solutions, the issue of additional costs, losses and weight should also be considered.

The tables below give some indications.

Typical relative costs – Drives and preventative measures (Conventional TEFC Motor = 100%)				
Rating	Drive Unit	Preventative Measure		
		Output Inductor	Output du/dt filter	Sinusoidal Filter
2.2kW 400V	125%	50%	100%	150%
75kW 400V	100%	30%	40%	45%
250kW 400V	90%	10%	15%	30%
160kW 690V	100%	10%	20%	35%
250kW 690V	70%	10%	15%	25%

Table 6-2
Additional Preventative Measures and Costs

Typical losses – Drives and preventative measures				
Rating	Drive Unit [kW]	Preventative Measure		
		Output Inductor [kW]	Output du/dt filter kW]	Sinusoidal Filter [kW]
2.2kW 400V	0.53	0.09	0.10	0.63
22 kW 400 V	0.53	0.09	0.10	0.63
75kW 400V	1.4	0.20	0.24	2.2
250kW 400V	7.1	0.22	0.25	9.7
160kW 690V	4.2	0.09	0.12	6.6
250kW 690V	5.8	0.12	0.15	8.0

Figure 6-3
Additional Preventative Measures and Losses

Typical weights – Drives and preventative measures				
Rating	Drive Unit [kg]	Preventative Measure		
		Output Inductor [kg]	Output du/dt filter [kg]	Sinusoidal Filter [kg]
2.2kW 400V	9	2.2	2.4	6
22 kW 400V	26	9.0	9.5	26
75kW 400V	34	19	21	75
250kW 400V	200	82	90	690
160kW 690V	67	60	62	250
250kW 690V	210	82	90	250

Figure 6-4
Additional Preventative Measures and Weights

6.5 Feeder Sizing

Because a significant number of borehole pumps and motors are used in rural areas, or in critical locations, where reliability of the power supply is of paramount importance, the use of generators either instead of new cabling and distribution transformer, or as a backup to the normal network supply must be considered.

- Special care must be taken if generators are used as the power source for submersible motors fed by a VFD.
- Maximum allowable voltage dip at starting and continuous run shall be specified by the VFD manufacturer (Note that a VFD does not impose an initial inrush current)
- Maximum allowable harmonic content, generators might be an additional source of, or be susceptible to harmonics

- Generator frequency may not be of great importance since the input voltage waveform is rectified to obtain an approximately constant DC voltage source.

For conventional drive connections, the presence of net side harmonics must be considered in dimensioning feeder cables. Information on cables sizing should be taken from the VFD manufacturers' documentation or by reference to Gambica/REMA Installation Guidelines for Power Drive Systems (Guide No 3).

6.6 Motor Cables

For dry well installation and cabling to a well head junction box in systems without sine filters screened cables should be used. Typical recommended types are shown in Figure 6-5

For submerged applications the cable is generally supplied integrated with the pump, and may be screened for relatively short lengths, and unscreened with special sheath compounds for other applications. Screened cables should be used where possible, when within the limits published by the VFD manufacturer.

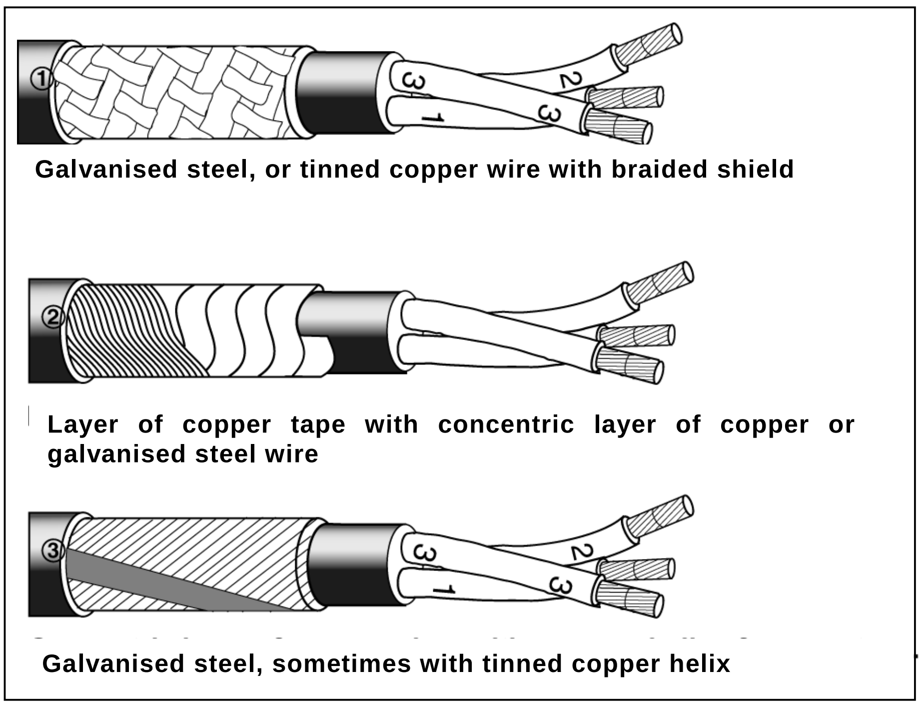

Figure 6-5
Preferred Cable Types for EMC Purposes

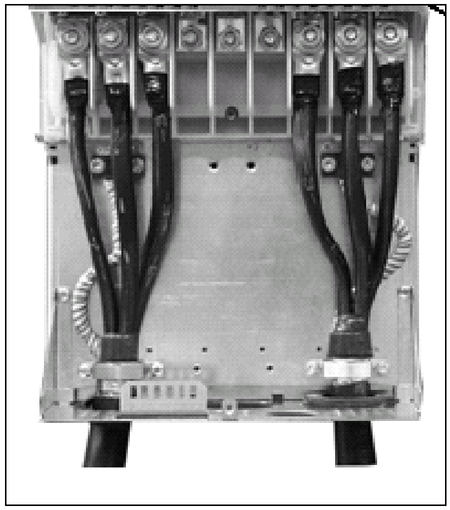

Figure 6-6
Converter Terminals showing cable screen pigtails earthed

Chapter 7 USE IN ATEX ENVIRONMENT[5]

Differing levels of explosion ignition hazard exist in environments where pumps may be installed, and these are shown in Figure 7-1

The installation of equipment in hazardous areas within Europe is regulated by two Directives,

94/9/EC (also known as the ATEX 95 Directive).

This "Product Directive" is required to be implemented by the product manufacturer before a product may be placed on the market for use in a potentially explosive atmosphere

1999/92/EC) (also known as the ATEX 137 Directive)

This "Explosive Atmospheres Directive" covers the minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres.

Among different articles, this Directive specifies:

- Places where explosive atmospheres may occur (Zones);
- Categories of equipment according to the Zone.

The users of all equipment installed in potentially explosive atmospheres (Ex – equipment) are responsible for the application of the Directives.

For the first time, the Directives contain requirements for equipment and for worker protection in locations having atmospheres with potentially combustible dust, which may occur in locations with dry installed pumps.

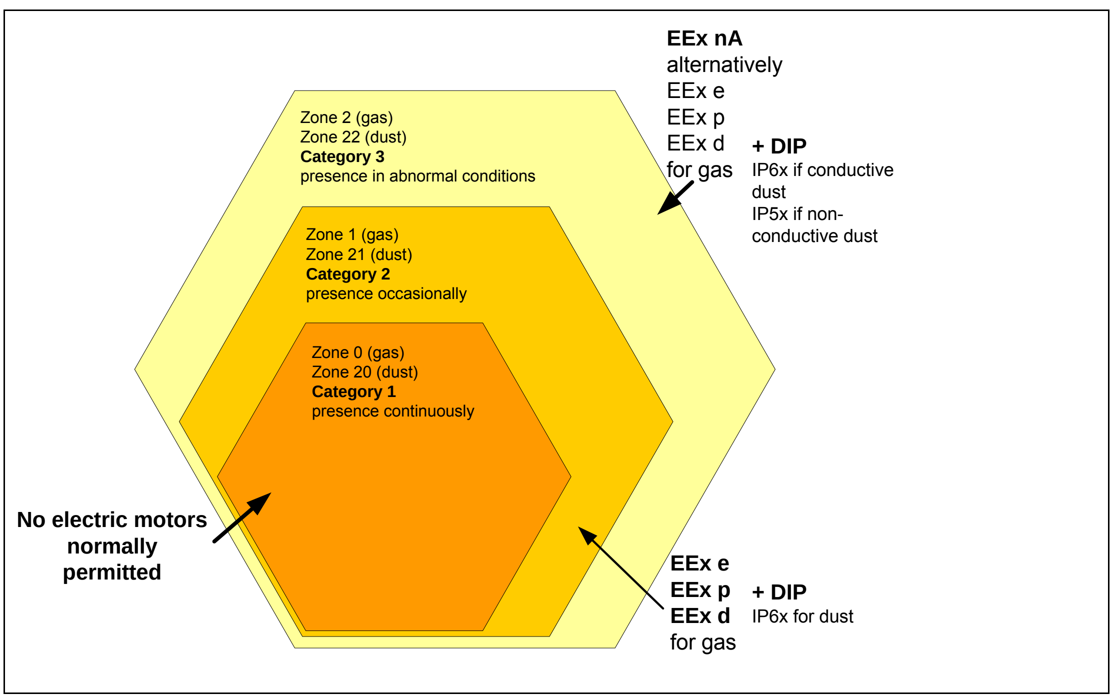

Figure 7-1
Permitted Equipment Categories for different hazard levels

5 Further information regarding installation of VFD powered motors in a location subject to ATEX is given in guides published by CEMEP and GAMBICA/REMA, and available from the appropriate websites.

7.1 Operating Conditions for the System

Usually only the pump and associated motor will be installed in the potentially explosive atmosphere, with the VFD is installed in a safe area.

There are specific documentation requirements for equipment installed in a hazardous area. Under the so called ATEX 95 Directive, the manufacturer has specific responsibilities to prove to an Ex “Notified Body” that the products meet the requirements of the appropriate standards, and that there is a suitable manufacturing quality system in place.

Compared to a motor connected directly to a mains supply, the motor manufacturer must take account of a VFD changing the operating conditions mostly due to:

- Reduced cooling for dry well air cooled motors at reduced speed.
- Increased losses due to non-sinusoidal supply at the motor terminals leading to increased temperature rise, compared to sinusoidal supply.
- Specific additional heat generation, particularly in the rotor cage and supporting structure as a result of harmonic currents.
- Induced voltages in the rotor, which can lead to currents through the bearings (due to PWM technology and high switching frequency);
- Dielectric heating due to high frequency/voltages.

For these reasons the application of the ATEX Directives calls for extra attention to be paid when an Ex-pumpset is used with a VFD and may require them to be tested together for certification.

It is unlikely that a drive can be retrospectively fitted to a hazardous area system.

Note also that equipment not installed in the potentially explosive atmosphere, but having an effect on equipment within it may also be subject to the Low Voltage Directive.

Equipment-groups (Annex I of the EC-Directive 94/9/EC)							
Group I (mines, mine gas and dust)		**Group II** (other explosive atmospheres gas/dust)					
Category M		**Category 1**		**Category 2**		**Category 3**	
1	**2**	**G** (gas) **(Zone 0)**	**D** (dust) **(Zone 20)**	**G** (gas) **(Zone 1)**	**D** (dust) **(Zone 21)**	**G** (gas) **(Zone 2)**	**D** (dust) **(Zone 22)**
for equipment providing a very high level of protection when endangered by an explosive atmosphere	for equipment providing a high level of protection when likely to be endangered by an explosive atmosphere	for equipment providing a very high level of protection when used in areas where an explosive atmosphere is very likely to occur		for equipment providing a high level of protection when used in areas where an explosive atmosphere is likely to occur		for equipment providing a normal level of protection when used in areas where an explosive atmosphere is less likely to occur	

Table 7-1
Permitted Equipment Categories

7.2 Selection of Ex-motor and VFD

7.2.1 General

The type of protection must be selected with reference to the hazard and zone. This is specifically the responsibility of the site owner, and should be the result of a risk analysis. Protection to a higher category is always acceptable, ie Ex d in place of Ex n

The safety aspects include ensuring that:

- No additional risk exists of sparks due to premature insulation failure or to shaft voltages/bearing currents;
- No additional risk exists of exceeding the temperature class, due to extra losses and possibly lower cooling.

These aspects are considered in further detail in the following clauses.

7.2.2 Risk Management of sparks

The motor and VFD manufacturers will ensure that bearing currents are limited and sparks are prevented using techniques described elsewhere.:

7.2.3 Risk Management of excess temperature

The temperature class of the motor shall be checked by calculation or by testing as required by the appropriate standard.
There are two main methods for diminishing the risks of excess surface temperature:

a) To have a physical feedback signal from the motor (thermal sensing element) and use this signal to initiate shut down in the case of excess temperature;
b) To control and limit the heat (⇒ temperature) which can be generated by the motor.

7.2.4 Temperature Sensing

This technique uses thermostats, thermistors or RTD devices embedded in the stator windings, with the appropriate controls to ensure that the temperatures are within the permitted limits.

This does not always control any additional temperature rise within the rotating element, and for high power motors the manufacturer/Notified Body may stipulate the use of additional thermal detectors at the bearings.

It is also mandatory that the protection used in conjunction with the temperature detectors is suitable for the purpose (including any intrinsic safety barriers where appropriate). As the correct functioning of the protection is critical to the safety of the overall system, the functional safety of the protection should be assessed and approved in accordance with the appropriate standards.

This method is applicable to all motor types.

When considered specifically for an Ex d design equipped with suitable integral thermal protection, type testing can demonstrate that for a sample electrical input and motor load, the protection will trip the motor before any surface temperature reaches the limit. This must also include a period after de-energisation. In this case a “blanket certificate” may be issued detailing only the input and load parameters.

7.2.5 Control of Heat Generation

Control of heating is achieved by limiting the current passing through the motor at a specific frequency. As the torque generated is directly related to current, a **loadability curve** may be established, which gives the maximum continuously available torque at a particular speed or frequency, when the motor is fed at the correct voltage and frequency.

The curve is dependent on the motor design, and can be advised by the manufacturer. The loadability curves must take into account the VFD technology**,** the surface temperature class of the motor, and the type of Ex protection.

In many cases a manufacturer will publish the loadability curves for his products to allow users to check that the load characteristics fall within the VFD capability. Figure 7-2 shows an example of a loadability curve for an air cooled cage induction motor, fed by an inverter. This illustrates the reduction in torque capability at low speeds due mainly to the reduction in cooling, and a reduction in torque at base speed to allow a sufficient margin for safety, and a reduction above base speed due to the application of a constant voltage (field weakening).

The manufacturer's confirmation should always be obtained before running a motor above its base speed.

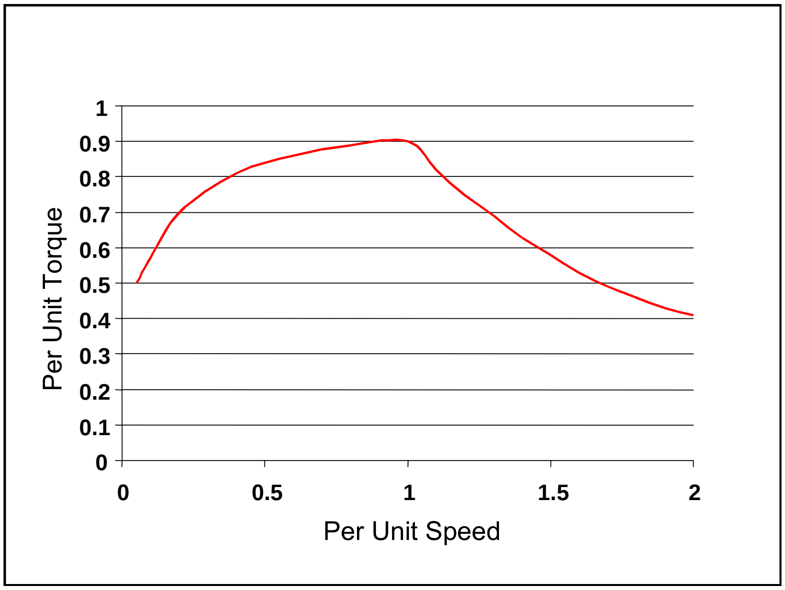

Figure 7-2

Example of Loadability Curve established by test for induction motor for VFD use

7.2.6 Additional Marking

The details of rated power output and other relevant VFD information should be delivered with the motor. This may be done using **additional marking** on the nameplate or in the **operating instructions**, which gives the user the conditions for use of the VFD.

The additional marking includes:

- Relevant electrical characteristics of the converter;
  - These may include inverter type (typically PWM, CSI), switching frequency, d.c. bus voltage and peak rate of voltage change.
- Maximum load torque corresponding to the speed range allowed according to the application
- In a centrifugal pump application; only the torque at maximum speed has normally to be considered;

In many cases motors for variable speed applications are considered to be definite purpose and as such they are specifically designed for a given application. The marking will be in accordance with the specific manufacturer's standard practice.

Documentary evidence of the specific conditions of use should be obtained from the motor manufacturer, and retained.

A VFD driven pump should not be used in a hazardous area without evidence of suitability ie Within the EU – a Manufacturers Declaration of Conformity.

Chapter 8 MAINTENANCE /HOUSE KEEPING

8.1 Maintenance

Maintenance on frequency converters is normally limited to removing dust from fans and keeping the cooling section free of dust and contaminants

However some manufacturers may have additional comments about maintenance, replacement of finite life components such as cooling fans and capacitors etc. Instructions about this issue can be found in manuals and product information.

Local regulations may also require regular electrical safety tests.

8.2 Power Drive Systems

In all types of rotating machinery, the use of a VFD, frees the designer from the traditional constraints of designing machinery for the specific rotational speeds, and even allows operation at higher speed. In many instances, pump designers have to develop products to be sold in markets with both 50 Hz and 60 Hz base frequencies and best efficiency may be achieved at some point between these levels.

Particularly with centrifugal equipment such as fans or pumps, this allows machinery to be operated closer to optimum specific speed for a much wider range of duties.

As the equipment wears a part of the maintenance function should be to ensure that the full range of duties is available from the pump, and if necessary the maximum and minimum frequency settings should be adjusted, and the current checked to ensure that the equipment is not overloaded.

8.3 General

For hazardous area equipment placed on the market prior to the advent of the ATEX Directives (94/9/EC and 99/92/EC) it is highly unlikely that the certification can be applied retrospectively.

In applications where it is not feasible to employ motors which meet the withstand capability achieved with standard or enhanced insulation given in the GAMBICA/REMA Technical Report No 1 Figure 21 curve A or B respectively, some form of alternative solution is required as detailed in this report .

Examples where these alternative solutions may be required include:

- Undefined motor characteristics
- Retrofit application of VFDs to ‘old’ motors
- Motors with inadequate pulse withstand capabilities
- In the above cases, some form of motor terminal voltage modification technique is necessary.

Chapter 9 GLOSSARY OF TERMS

9.1 Basic Terms

Term or abbreviation	Description	Section
a.c.	Alternating current	General
ATEX	“Atmosphères Explosibles” – European Directives using French acronym, covering the essential health and safety requirements for products used in potentially explosive atmospheres	Chapter 7
CE Marking	Indication of compliance with all appropriate EU Directives	General
CEMEP	European Committee of Manufacturers of Electrical Machines and Power Electronics	General
CEN	European Committee for Standardisation, responsible for the preparation of non electro-technical harmonised (EN) standards EN standards may be prefixed by the symbol of the national issuing authority ie: BS	General
CENELEC	European Committee for the Electrotechnical Standardisation – responsible for the preparation of electro-technical harmonised (EN) standards	General
d.c.	Direct Current	General
du/dt or du/dt	Rate of change of voltage	General
EN	EuroNorm – Standard issued by CEN/CENELEC, normally prefixed by the national issuing body e.g. BS EN	General
IEC	International Electrotechnical Commission – International Standardisation Body. Also the prefix for standards prepared by this organisation	General
IGBT	Insulated gate bipolar transistor	General
NEMA	National Electrical Manufacturers Association (USA)	General
PD	Partial discharge	General
PWM	Pulse Width Modulated	General
U or V	Voltage (Generally used with suffixes)	General

9.2 Specific Terms

Accessible part	Part or surface which can be touched by means of the test finger of EN 60529, including any conductive part connected to accessible metal parts.
All-pole disconnection	For single-phase appliances disconnection of both supply conductors by a single initiating action or, for three-phase appliances disconnection of all supply conductors except the earthed (grounded) conductor, by a single initiating action. NOTE - The protective earthing conductor is not considered to be a supply conductor.
Basic Insulation	Insulation applied to **live parts** to provide **basic** protection against electric shock. NOTE - Basic insulation does not necessarily include insulation used exclusively for functional purposes.
Class I appliance	Appliance in which protection against electric shock does not rely on **basic insulation** only but which includes an additional safety precaution in that conductive **accessible parts** are connected to the protective earthing conductor in the fixed wiring of the installation in such a way that conductive **accessible parts** cannot become live in the event of a failure of the **basic Insulation.** NOTE - This provision includes a protective conductor in the **supply cable.**
Control cable	Flexible **cable,** for connecting sensors and control devices, which is **fixed** to the appliance.
Creepage Distance	Shortest path between two conductive parts or between a conductive part and the accessible surface of the appliance, measured along the surface of the insulating material.
Clearance	Shortest distance between two conductive parts or between a conductive part and the accessible surface of the appliance, measured through air
Double insulation	Insulation system comprising both basic Insulation and supplementary insulation.
Electronic circuit	Circuit incorporating at least one electronic component.
Electronic component	Part in which conduction is achieved principally by electrons moving through a vacuum, gas or semiconductor
Electrical stress	All physical electrical effects that degrade insulation

Extra low voltage	Voltage supplied from a source within the appliance which**,** when the appliance is supplied at **rated voltage** does not exceed 50 V between conductors and between conductors and earth.
Fixed appliance	Appliance which is intended to be used while fastened to a support or otherwise secured in a specific situation.
Live part	Any conductor or conductive part intended to be **energised** in normal use, including a neutral conductor but, by convention, not a **PEN conductor.** NOTES 1. Parts, accessible or not, complying with 8.1.4 are not considered to be live parts. 2. A PEN conductor is a protective earthed neutral conductor combining the functions of both protective conductor and neutral conductor.
Non self resetting thermal cut out	**Thermal cut-out** which requires a manual operation for resetting or replacement of a part, in order to restore the current. NOTE - Manual operation includes disconnection of the supply.
Normal operation	see ISO 12223
Off position	Stable position of a switching device in which the circuit controlled by the switch is disconnected from its supply. NOTE - The off position does not imply an all-pole disconnection.
Portable appliance	Either an appliance which is intended to be moved while in operation or an appliance, other than a **fixed appliance.**
Pump	Combination of mechanical, hydraulic and electrical parts of an appliance for moving liquids.
Protective device	Device, the operation of which prevents a hazardous situation under abnormal operation conditions.
Rated current	Current assigned to the appliance by the manufacturer. NOTE - For motor-operated appliances, the current measured when the appliance is supplied at rated voltage and operated under normal operation;
Rated frequency	Frequency assigned to the equipment by the manufacturer
RFI	Radio Frequency Interference

Rated frequency range	Frequency range assigned to the equipment by the manufacturer, expressed by its lower and upper limits.
Rated power Input:	Power input assigned to the equipment by the manufacturer.
Rated voltage	Voltage assigned to the appliance by the manufacturer. NOTE - For three-phase supply it is the voltage between phases.
Rated voltage range	Voltage range assigned to the appliance by the manufacturer, expressed by its lower and upper limits.
Reinforced insulation	Single insulation applied to **live parts,** which provides a degree of protection against electric shock equivalent **to double insulation** under the conditions specified in this standard. NOTE - It is not implied that the insulation is one homogeneous piece. The insulation may comprise several layers which cannot be tested singly as supplementary insulation or basic insulation.
Safety extra low voltage	Voltage not exceeding 42 V between conductors and between conductors and earth, the no-load voltage not exceeding 50 V. When safety extra-low voltage is obtained from the supply mains, it is to be through a safety isolating transformer or a converter with separate windings, the insulation of which complies with double insulation or reinforced Insulation requirements. NOTE - The voltage limits specified are based on the assumption that the safety isolating transformer is supplied at its rated voltage
Safety isolating transformer	Transformer, the input winding of which is electrically separated from the output winding by an insulation at least equivalent to **double Insulation** or **reinforced** Insulation and which is intended to supply an appliance or circuit at **safety extra-low voltage.**
Self-resetting thermal cut-out	**Thermal cut-out** which automatically restores the current after the relevant part of the appliance has **cooled down** sufficiently
Speed of rotation	Rotational speed usually shown as r/min
Submersible motor	Motor which in its normal use is, or may become, completely or partly immersed. Motor windings may be dry, immersed in oil or other isolated liquid or immersed in the liquid to be pumped.
Submersible pump	Pump driven by a submersible motor

Supplementary insulation	Independent insulation applied in addition to the basic Insulation, in order to provide protection against electric shock in the event of a failure of the basic Insulation.
Supply cable	Flexible **cable,** for electrical supply purposes, which is **fixed** to the equipment.
Thermal cut out	Device which during abnormal operation limits the temperature of the controlled part by automatically opening the circuit or by reducing the current and constructed so that its setting cannot be altered by the user.
User maintenance	Any maintenance operation stated in the instructions for use or marked on the appliance which the user is intended to perform
Working voltage	Maximum voltage to which the part under consideration is subjected when the appliance is supplied at its rated voltage and operating under normal operation. NOTE - When deducing the working voltage, the effect of transient voltages is ignored.

Chapter 10 REFERENCES AND FURTHER READING

a) GAMBICA/REMA, Technical Report No 1 "Motor Insulation Voltage Stresses Under PWM Inverter Operation"

b) GAMBICA/REMA, Technical Report No 2 "Motor shaft voltages and bearing currents under PWM inverter operation"

c) GAMBICA/REMA, Technical Report No 3 "Installation Guide for Power Drive Systems"

d) GAMBICA/REMA, Technical Report No 4 "Application of the ATEX Directives to Power Drive Systems"

e) IEC 60034 Series – Product Specific Standards for Rotating Electrical machines

f) IEC 60034-17: "Rotating electrical machines - cage induction motors when fed from converters - application guide"

g) IEC 60034-18-41 "Evaluation and qualification of electrical insulation systems used in rotating electrical machines when fed from voltage converters"

h) IEC 60034-25: "Guide for the design and performance of cage induction motors specifically designed for converter supply"

i) IEC 60034-27 draft new 1st edition. PD measurement.

j) IEC 60076 Series – Product Specific Standards for Transformers

k) IEC 60079 Series – Generic Standards for Hazardous Area equipment

l) IEC 61800 Series – Product Specific Standards for Power Drive Systems (VFDs)

m) IEC 61800-3 "Adjustable speed electrical power drive systems – EMC requirements and specific test methods

n) IEC 62068-1 "Electrical insulation systems – Electrical stresses produced by repetitive impulses – Part 1: General method of evaluation of electrical endurance"

o) NEMA Application Guide for AC Adjustable Speed Drive Systems

p) NEMA MG1-2003: Motors and Generators - part 30 - "Application considerations for constant speed motors used on a sinusoidal bus with harmonic content and general purpose motors used with adjustable-voltage or adjustable-frequency controls or both"

q) NEMA MG1-2003: Motors and Generators-part 31 "Definite purpose inverter fed polyphase motors"

APPENDIX

A.1 FREQUENTLY ASKED QUESTIONS

Q – What limits a motor maximum speed?

A – There is a specific maximum speed for any motor, based on two factors;

The mechanical maximum speed, these are normally limited by the bearings and peripheral velocities, typical values for standard TEFV motors with grease lubricated ball bearings are.

The electrical maximum speed, which is due to the reduction in flux causing the available maximum torque to reduce as the square of the increase in frequency

For large 2-pole motors it is common to design with a “flexible shaft” design, which also precludes running at critical speeds below the nominal speed.

Other Issues to be Discussed regarding over and under Speed Operation

Increased load on thrust pads during over speed operation

Refined balancing for over speeds

Motor up thrust bearing

A.2 THINGS TO AVOID

Some basic errors that can be avoided simply when installing variable speed pumps

Example 1

A wet well pump was installed in a sump under a car park, with the drive unit in a building around 20m away. The pump motor was designed to be suitable for either star-delta or direct on line starting, which results in 6 conductors exiting the motor.

These were connected to a screened cable in a junction box at the well head. These cables were run through ducts to the drive, with the control cables from the associated level transducers.

The installation suffered severe problems with interference on the level transducer system.

When the cable tails were reconnected to give the delta connection at the junction box, the problem was eliminated.

Figure A-1 - Junction Box

Figure A-2 - Junction box connections

Figure A-3 - Cable tails common at Variable frequency converter

Figure A-4 - Power and control cables share ducts