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MOTOR REFERENCE

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This document contains summary information about the following motor topics:

- Motor selection information
- AC induction motors
- Inverter duty motors
- Variable frequency drives
- Motor losses
- Troubleshooting

The information contained in this document was gathered from a variety of online, interview, and print sources, including NEMA specifications, with support from the California Energy Commission (CEC) PIER Program.

MOTOR SELECTION

Terms like "inverter duty", "inverter ready", and "inverter rated" are marketing terms and are useless without any backup data.

In order to select a motor, first identify the load torque characteristic over the speed range intended for operation. This information will identify the motor load torque requirement, which can be translated into motor input current. The input current determines the motor heating over the speed range and the motor manufacturer can identify how far down in speed the motor should be able to go. This point is highly variable and is a function of cooling method (TEFC, ODP, or aux. blower), horsepower (typically, a 250hp TEFC motor is only good for 2/1 where a 5hp TEFC motor is good for 5/1), and general design (extruded aluminum or cast iron, high or premium efficient).



Example of inverter duty motor name plate

Once the continuous current and peak current required for the motor have been determined, select a drive with output current ratings that meet or exceed that level. A variable torque drive has only 10% peak over current capacity and a constant torque drive has 50% peak over current capacity. One is not necessarily more reliable than the other as long as it is sized to cover the motor currents as described above. Drive terms like “variable torque” and “constant torque” are somewhat misleading; both kinds of drives get used on both kinds of loads. The terms simply refer to the amount over current capacity they can produce short-term.

When contacting a dealer, it is good to provide as much information as possible, such as:

Pump Information: Characteristics, dimension, shaft, mounting, etc. How the motor fits with the pump will affect the bearing, efficiency (heat), frame size, etc.

Horsepower: 15-250 HP

RPM Rating: 900-3600

Voltage Rating: 480V

Phase: 3 phases AC

Motor Type: Vertical hollow shaft inverter duty

Frame Size: The frame is important because of the weight, the space available and also price. The frame selection will depend on the motor size, the pump size and motor mounting.

Mounting

Motor Application: For instance, pumping water from a canal

Speed Range: low – max. Specify the highest and lowest RPMs. It is recommended to provide a torque vs. speed curve. Typically, the control operating output frequency range is 2 to 1 for variable torque type loads. The 2 to 1 speed range is not a consideration issue with the control, because all adjustable frequency controls operate over a minimum of 6 to 1 output frequency range.

Operating Speed Range: The desired speed range may be difficult to achieve depending on the type of application. In general, depending on motor size and load type, very wide ranges may require a special motor. **Operation at very low speeds, requiring the motor to run at very low frequency (*below approximately 6 Hz*) or very high speeds requiring the motor to run at very high frequencies (above 90 Hz) may require a special motor.**

Motor synchronous speed varies directly with the control output frequency. Therefore, the frequency required to achieve a desired application speed can be approximated by dividing the desired speed by the motor rated speed and then multiplying by the rated frequency of the motor. If the minimum or maximum frequencies are near or outside the limits mentioned above then the motor manufacturer should be consulted before proceeding. Examples of speed ranges are listed below, expressed as a ratio of the motor base speed to a minimum speed.

Constant and variable torque speed range examples (Base speed = 2500 RPM)

Minimum Speed (RPM)	% Motor Base Speed	Speed Range Ratio
1250	50	2:1
625	25	4:1
250	10	10:1
125	5	20:1
25	1	100:1

Motor Cooling: There are two general methods of motor cooling or ventilation:

- 1) Speed dependent: this method is used in totally-enclosed fan cooled or open drip-proof motors. The cooling depends on the motor speed since the fan rotation is supplied by the motor. A change in motor speed will result in a change in fan speed and this change depends on the speed range. Some motors at low speed may have 20 to 50 percent of their base speed.
- 2) Speed independent: some types of systems that use this method are totally-enclosed non-ventilated, totally-enclosed air-over, blower-cooled, etc. The cooling rate does not change with motor speed. This method is effective with motors operated at low speed.

Space Heater: Electric motors frequently have space heaters installed, at the customer's request, to prevent moisture condensation in the motor when it is not running. In applications where the possibility of condensation is not a factor, or where continuous operation of the motor prevents the formation of condensation, space heaters are not necessary.

Enclosure: This will depend on the application and location. If the motor is located in a hazardous or corrosive environment, it will require a different enclosure than a protected motor inside a room. A Weather-Protected Type I (WPI) machine is a guarded machine with its ventilating passages so constructed as to minimize the entrance of rain, snow and airborne particles to the electric parts. It is the most common type of enclosure for motors used in farms. ***All the motors at the Water Resources Facility have WPI enclosures.***



Other types of protection include:

Totally Enclosed Fan-Cooled (TEFC) machines are frame-surface cooled totally enclosed machine equipped for self-exterior cooling by mean of fans integral with the machine but external to the enclosed parts. They are often used in environments that are hazardous, harsh, or present a high risk of contact with salt or salty water, like close to the sea.

Totally Enclosed, Blower Cooled (TEBC) motors are most commonly used for variable speed motors combined with variable speed drives of some sort. Sometimes these motors are rated as "Inverter duty" or "Vector duty". They are considerably more expensive than similarly rated TEFC motors. The motor is constructed with a dust tight, moderately sealed enclosure which rejects a degree of water. A constant speed blower pulls air over the motor fins to keep the motor cool at all operating speeds.

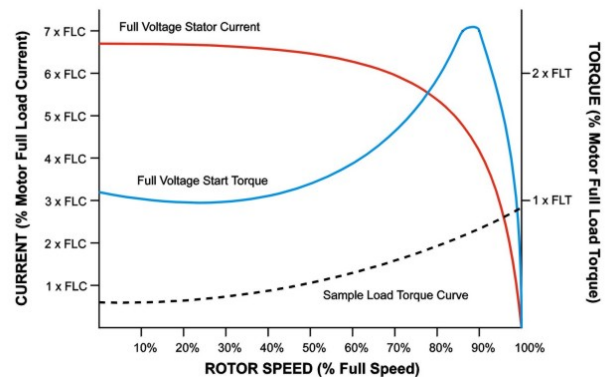
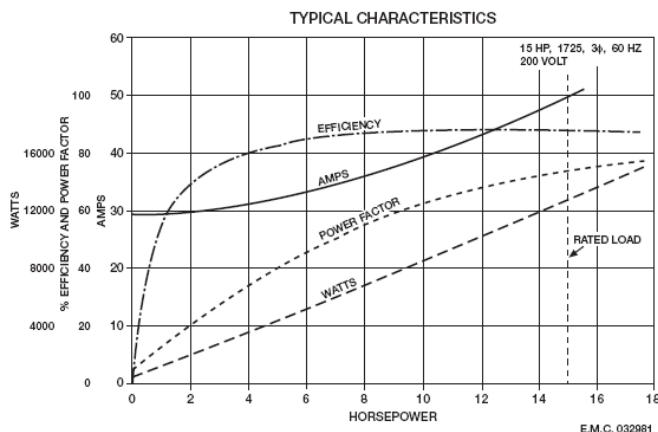
Different Sensors: Could be for motor or bearings, or temperature monitoring. One dealer stated that these could probably be added for no extra charge. Sensors could help monitor and detect some motor problems. Normally, temperature reading and trend could give a good idea about the condition of the motor.

AC INDUCTION MOTORS

How they work:

- The stator has three windings mechanically spaced 120 degrees apart.
- The three stator windings are driven by a three phase symmetrical voltage set (voltages spaced 120 degrees apart). This AC supply voltage creates a rotating magnetic field in the stator.
- The rotor consists of conducting bars along the motor axis. The bars are shorted at both ends of the rotor. The rotating magnetic field cuts through the rotor, inducing a voltage in the rotor bars. Sequentially, the bars create their own magnetic field.
- The rotor magnetic field will attempt to line up with the stator magnetic lines of force. Since the stator magnetic field is rotating the rotor “chases” the stator but stays just slightly behind, creating “slip”.
- Theoretical motor speed = $(120 * \text{frequency}) / (\text{number of poles})$.
- The actual speed of the motor is just slightly less because of “slip”.
- Increase in inrush current will reduce the slip and increases efficiency.

Inside a motor, the magnetic fields try to align, just as two magnets close to one another will try to align their magnetic fields. This perpetual effort at alignment causes the motor's rotor to spin. The strength of the fields and their degree of misalignment make the effort to align, or the torque, more or less strong.

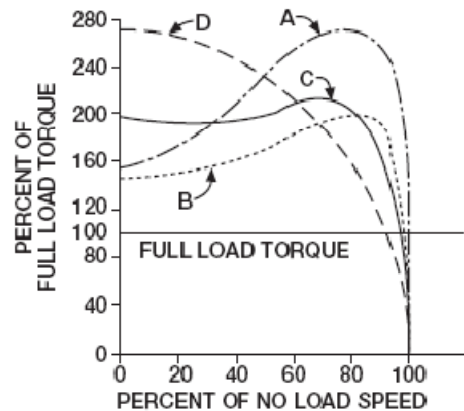


INVERTER DUTY MOTORS

Motor Design

The motors recommended by NEMA MG-1 are Design A and B squirrel-cage motors

The following information is from NEMA MG1-2006 and applies to 60 Hz NEMA Designs A and B squirrel-cage motors. These motor are rated 5000 horsepower or less at 7200 volts or less.



Design A: a squirrel-cage motor designed to withstand full-voltage starting and developing locked-rotor torque, pull-up torque, breakdown torque, with locked-rotor current higher than certain values (see MG1-12.35.1) for 60 Hz and having a slip at rated load of less than 5 percent.

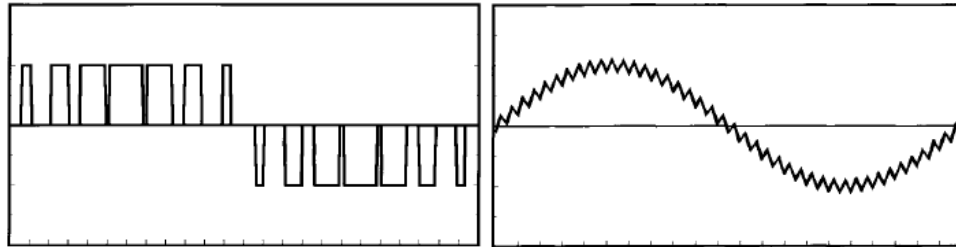
Design A motors are generally of little concern and the motors are well suited for variable speed operation, exhibiting low slip and high efficiency. The potentially higher breakdown torque of a Design A motor will extend its constant horsepower speed range beyond that achievable by a Design B motor. However, caution should be used when applying Design A motors in by-pass operation, as their high locked-rotor current can increase starter, thermal overload, and short circuit protection device sizing. Design A motors may also suffer greater thermal and mechanical stress than other designs when started across-the-line. Design A motors with very low slip may also exhibit instability under lightly loaded conditions.

Design B: a squirrel-cage motor designed to withstand full-voltage starting and developing locked, breakdown, and pull-up torques adequate for several general applications, drawing locked-rotor current not to exceed certain values (see MG1-12.35.1) for 60 Hz and having a slip at rated load of less than 5 percent.

Design B motors are applied in variable torque, constant torque, and constant horsepower applications. Adjustable frequency control algorithms are generally optimized to the speed-torque-current characteristics of Design B motors. They exhibit good efficiency and low slip, and are suitable for across the-line starting in bypass mode. Design B motors with very low slip may also exhibit instability under lightly loaded conditions.

Why are Inverter Duty Motors Recommended?

Pulse Width Modulated (PWM) inverters change the rms value by turning the controlled value ON and OFF at a relatively high frequency while varying the voltage pulse width. Sketches of the voltage applied and resultant current are shown in the figure below.



Voltage (l.) and line current (r.) from a PWM ASD

Source: IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 33, NO. 2, MARCH/APRIL 1997

The spikes in voltage resulting from the PWM stress the motor winding and insulation, resulting in early failure. Standard motor and even premium efficiency motor are not built to withstand this type of electrical stress.

The spikes in voltage cause an electrical stress and an increase in motor temperature. The increase in motor temperature is due to an increase in current and in non-Fundamental current which is an increase in variable losses, core losses and spray losses.

Inverter duty motors are built to withstand the stress caused by the change in frequency. Today the only specifications related to inverter duty motors are NEMA MG1, Parts 30 and 31. They outline motor capabilities when used with VFDs for motors rated 600 volts or less. MG1-30.2.2.8 requires that standard motors utilize an insulation system able to endure repeated voltage peaks of up to 1000 volts with rise times of 2 or more microseconds. MG1-31.4.4.2 defines an inverter duty motor as having an insulation system able to withstand peaks of 3.1 times rated voltage with rise times of 0.1 or more microsecond.

The new inverter duty motors are premium efficiency motors with inverter duty insulation. The inverter duty motors are different from standard motors due to several factors:

1. The premium efficient winding is created using vacuum-impregnated windings to eliminate air pockets in the system that inflate as the temperature increases, causing the wire to collapse.
2. The magnet wire is coated with high dielectric strength film to allow it to resist fast rising time pulses.
3. Maximized wire size reduces the wire resistance and increases efficiency.
4. Some manufacturers add phase and ground protection using stronger dielectric materials or applying sleeving over the first turn at the line end of the motor.
5. The insulating material has a higher temperature rating.
6. Rotor bars are modified to increase surface area and decrease slip.

In other words, an inverter duty motor is as efficient a motor as any premium efficient motor but is built to better withstand electric stress.

VARIABLE FREQUENCY DRIVES

An inverter duty motor is controlled by a Variable Frequency Drive (VFD), also called a Variable Speed Drive (VSD). The VFDs available in the market are not all the same and do not all use the same technology. Computers and processors improve and advance every day, and as a result VFD technology advances as well. Unfortunately, motor technology does not advance at the same speed as these controllers. As a result, there are some problems created by the controller such as voltage spikes. On the other hand, the advances in VFD technology result in better control and better efficiency. Some losses are caused by voltage spikes but the current used to drive the load is reduced because the controller is reacting better to the change in load. Information related to one of the VFDs used by the ITRC is presented below in order to illustrate some of the technologies that are now available. The VFD presented is built for water pumping, so some features have been added to make more suited for pump control.

VLT 8000 Aqua (used by the ITRC in its WDF):

This AFD (Adjustable Frequency Drive) features an inverter control system called VVC^{plus} (Voltage Vector Control). VVC^{plus} controls an induction motor by energizing it with a variable frequency and a voltage that matches it. If the motor load is changed, the magnetization of the motor changes as well, and so does its speed. Consequently, the motor current is measured continuously and the actual voltage required and slip of the motor are calculated from a motor model. Motor frequency and voltage are adjusted to ensure that the motor operating point remains optimal under varying conditions.

AMA (Automatic Motor Adaptation): This feature in the VLT 8000 Aqua measures main motor parameters and standstill; it automatically optimizes operation between the driver and the motor by reading and checking the values without spinning the motor. VVC^{plus} uses AMA to measure static values of stator resistance and inductance. This data is provided to the motor model, which serves to calculate no-load values for the load compensator and the voltage vector generator.

- Optimizes motor performance
- Improves star capabilities
- Compensates for motor cable variances

AEO (Automatic Energy Optimization): This feature ensures that the relationship between voltage and frequency is always optimum for the motor's load. Thus, it doesn't provide a constant voltage/frequency ratio. In order to automatically provide the correct voltage at any operating frequency and load, the driver must continuously monitor the motor's status and respond to any changes. The VVC^{plus} control algorithm is central to this. Current is monitored on all three motor phases so that both the real and reactive components for motor current are known at all times. The combination of the AEO and AMA results in automatically maintaining a peak motor efficiency under all conditions.

- Minimizes energy consumption
- Maximizes motor efficiency by controlling the motor magnetization current
- Reduces motor noise
- Simplifies commissioning
- Improves load shock handling
- Improves handling of fast reference change

Recommendation: There are four different insulation materials. The choice of insulation depends on the maximum expected windings temperature. If the expected temperature is close to one insulation class it is better to select the next higher insulation class for the motor winding. The rule of thumb is that a winding temperature higher than the insulation rating temperature reduces the motor life expectancy. On the other hand, a lower winding temperature than the insulation rating increases the motor life expectancy.

Insulation classification MG1-1.66

Insulation Class	Temperature Rating
A	105°C
B	130°C
F	155°C
H	180°C

NEMA Application Guide for AC Adjustable Speed Drive Systems

Non-Fundamental Currents (NEMA 5.2.1.2): Distortion of the motor currents varies inversely with switching frequency because of the low pass filtering effect of the leakage inductances of the motor windings. The higher the switching frequency the lower the total distortion and the better the current waveform, up to a point. As switching frequency is increased higher and higher, distortion of the motor currents about their zero crossings caused by the switch deadband (intentionally built-in time delay between upper and lower switch conduction) becomes significant. Usually, however, tradeoffs between current distortion and switching loss are such that little is to be gained above approximately 5 kHz.

Motor temperature is a function of both cooling and the magnitude of heat producing losses in the motor. These losses are increased, when compared to operation on line power, because of the current distortion. The non-fundamental currents contribute very little to useful torque, but do increase several components of motor losses. Core losses are increased due to eddy currents and hysteresis. Rotor conductor losses are increased due to high frequency surface losses. The high frequency component also adds to the total rms current and thus the I²R loss in the stator conductors. The magnitude of this increase in losses depends on the switching frequency of the control and the motor design characteristics.

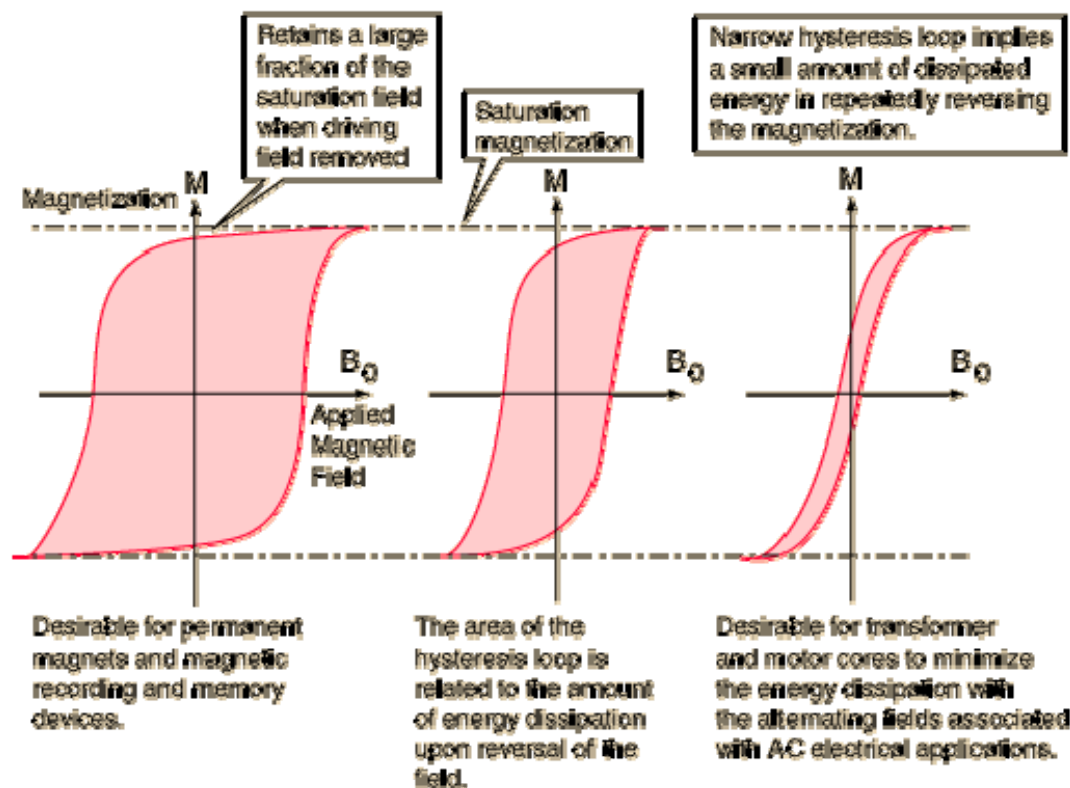
MOTOR LOSSES

Power losses are the fraction of input energy converted to heat instead of being used to drive the load. These losses are divided into two groups: fixed and variable losses.

Fixed Losses

Fixed losses are constant regardless of load, which is why small motors have higher losses as a percentage of input power than large motors. It is not accurate to say that fixed losses are always constant but assumed so, and this assumption will not create a significant error. Fixed losses include mechanical friction losses (brush friction, air friction, bearing friction or windage) and magnetic core losses (hysteresis and eddy current).

Core Losses: Core losses are the combination of hysteresis losses and eddy current losses. These losses vary with the load current on the motor, speed variation, and condition of operation. These losses are considered constant; however, they are considered constant and any variations are accounted for under stray load losses.



Mechanical Losses: Friction of the moving parts (such as fan blades) causes losses of energy. As in core losses, these mechanical losses are considered constant from no load to full load.

Variable Losses

Variable losses include losses that vary with the current drawn by the motor; they are called copper losses or I^2R . They also include stray load losses.

Winding Losses: In a 3 phase induction motor, the voltage is applied directly to the primary winding. An induced current by the primary winding magnetic field flows in the rotor or secondary winding. Generally, the secondary and primary windings are made of copper or aluminum. The winding's wire resistance and the motor drawn current is the cause of the variable losses. The winding's resistance varies with the temperature, load, uneven sharing of current among conductors, nature of the wires and other similar factors.

Stray Losses: All the losses that are not accounted for; this includes any variation in core and mechanical losses.

Significant causes of variation in the performance of different types of component

	transistor	diode	IC	resistor	capacitor	inductor	relay
temperature	X	X	X	X	X	X	X
aging	X			X	X		X
radiation	X	X	X				
vibration/shock				X	X	X	X
humidity				X	X		
life				X	X		
electrical stress	X	X			X		

X: Significantly affected by environment

MOTOR TROUBLESHOOTING

Temperature Related Life-Shortening Factors		
PROBLEMS	SYMPTOMS	CURES
Low Voltage	Overload Tripping High Current Short motor life	Correct power supply or match motor to actual power supply voltage rating.
High Voltage	Overload Tripping High Current Short motor life	Correct power supply or match motor to actual power supply voltage rating.
Unbalanced Voltage	Unbalanced phase currents Overload Tripping	Determine why voltages are unbalanced and correct.
Overload	Overload Tripping High Current Short motor life	Determine reason for overload. Increase motor size or decrease load speed.
High Ambient Temperatures	Short motor life	* Rewind motor to higher class of insulation. Oversize motor to reduce temperature rise. Ventilate area to reduce ambient temperature.
Blocked Ventilation	Short motor life Runs hot Amperage O.K.	Clean lint and debris from air passageways or use proper motor enclosure for application.
Frequent Starts	Short motor life	** Use reduced voltage starting method. Upgrade class of insulation.
High Inertia Loads	Short motor life Overload Tripping during starting	Oversize motor frame. Use higher class of insulation. ** Use reduced voltage starting method.

* Bearing lubrication must also be matched to high operating temperature.

** Reduced voltage starting method and motor characteristics must be matched to the load requirement.

Replacements for Failed Motors

When motors fail, they must be repaired or replaced quickly to avoid lost production. Often—with some advanced planning—it is economically attractive to replace these motors rather than incur the expense of rewinding.

Though common practice is to replace failed motors below 20 horsepower and repair those above 20 horsepower, replacing all failed motors up to 50 hp is almost always economic. Replacing larger failed motors is also often cost-effective, depending on how heavily the motor is used. Because it reduces capital costs, the return from upgrading to a one size smaller energy efficient replacement instead of rewinding is even more attractive than replacement with a same sized energy efficient motor.

Opportunities to specify energy-efficient motors may exist if the customer is:

- Designing new facilities
- Modifying existing installations or processes
- Procuring pre-packaged equipment or systems with electric motor components
- Considering rewinding failed motors
- Replacing oversized (underloaded) motors
- Implementing an energy management or preventative maintenance program
- Able to obtain utility rebates

Bearing Failure

Major causes of bearing failures include misalignment of the motor and load, vibration, incorrect lubrication, excessive radial or axial loading, lubricant contamination or inadequate maintenance. With a motor controlled by a VFD there is a less frequent cause of motor failure, which is electrical current that goes through the bearing. The solutions for these failures may include:

- Good pump and motor installation
- Good motor and pump selection
- Use the lubricant type and amount indicated by the motor company
- Space heater to reduce moisture in the lubricant
- Proper maintenance and data record
- Good electric grounding

It is difficult to say if motors or the pump bearings fail more often. It all depends on the installation. There are different causes of pump bearing failure such as misalignment, resonance, improper greasing, excessive speed or load, or electrical problems from the VFD in case the shaft current is grounded through the pump.

The use of insulating bearing is not widely recommended because the problem will be shifted somewhere else. If the path of the current is blocked the current will try to find an alternative path, which will cause the problem to go from one location to another. One solution is to control the path of the current by installing shaft grounding ring to drain the current (voltage) to the ground. However, the best solution is to control the problem from the source by minimizing the high frequency pulses by installing a filter between the VFD and the motor.

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