APPLICATION OF AC INDUCTION MOTORS WITH VARIABLE FREQUENCY DRIVES

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ABSTRACT

Variable Frequency drives (VFD's) have been available to the cement industry for a number of years. However, with improvements to VFD's (power quality, reliability, stability, costs), their increased acceptance and with the emphasis to cut production costs, VFD usage has become more widespread. This paper seeks to provide professionals in cement plant design and operation with an introduction to the use of VFD control for AC induction motors and how to more effectively specify AC induction motors for VFD applications.

INTRODUCTION

This paper is intended to serve as an introduction to variable frequency drives (VFD's), how they are applied to AC Induction motors in the Cement Industry and specific design considerations for motors operated with VFD's. The subject matter here is quite complex. The author's intention is only to provide a high level introduction to the cement industry professional, with particular emphasis on VFD motor design. Many VFD topics to be covered should be expanded on and have been by other studies, papers and books. Some topics are even controversial.

For additional motor design information, please refer to "Selection of AC Induction Motors for Cement Plant Applications", presented at the IEEE-IAS/PCA 2008 Conference. It provides a general overview of motors, including temperature rise, service factor, bearings, enclosures and accessories.

VFD BASICS

VFD's are electronic power control devices. In the most fundamental sense VFD's are devices that convert/rectify voltage from a constant frequency alternating current (AC) power system to create a direct current (DC) voltage link, and then electronically invert the DC voltage link to create a variable voltage-variable frequency output as shown in Figure 1.

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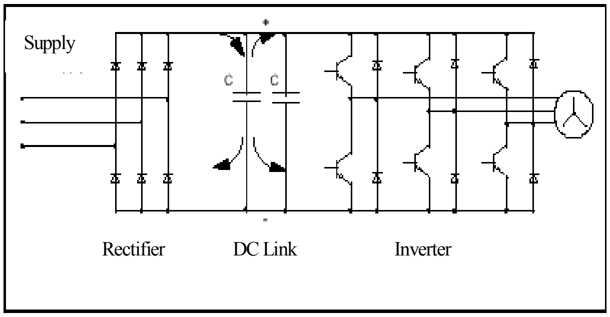

Figure 1 – AC to DC to AC Conversion

At the heart of the VFD are the switching devices. These are the electrical components that convert the power on the DC bus back to an AC signal. The most common devices are Insulated-Gate Bipolar Transistor (IGBT), Integrated Gate Commutated Thyristor (IGCT) and Gate Turn Off Thyristor (GTO).

The majority of VFD's are supplied to operate in constant volts per hertz (V/Hz) mode. In a V/Hz mode, the output volts to hertz ratio is maintained at a user programmable value over the operating frequency range by changing the output voltage in direct proportion to a change in output frequency. Once the output voltage reaches that of the motor rating, the voltage remains constant with any further increase in output frequency.

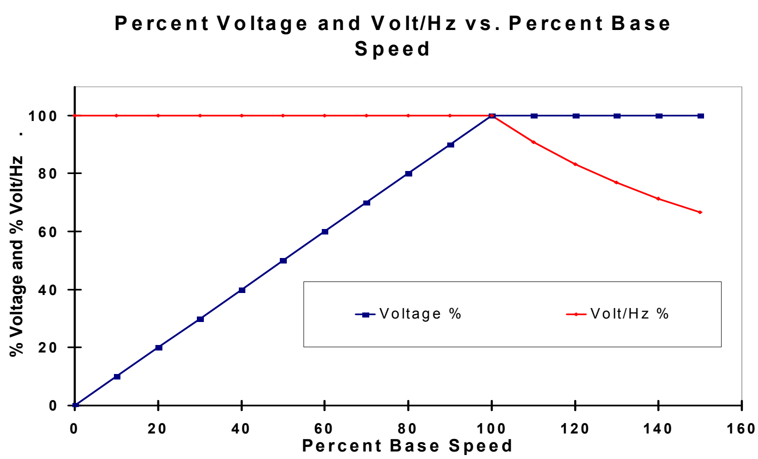

Figure 2 – V/Hz Relationship

VFD's have been available to the cement industry for over 20 years, but with the push toward productivity increase, automation usage, and cost reduction, VFD's are being applied more and more frequently.

Standard AC induction motors are designed to operate at a fixed voltage and frequency. The information that is provided on the motor nameplate is referred to as the motor's base rating point. It defines a reference operating point at a specified speed, voltage, and power. The synchronous (or design) speed is equal to 120 x the line frequency divided by the number of motor poles. Hence 2-pole motors designed for use on 60 Hz frequency systems have a synchronous speed of 3600 RPM, while 8-pole motors have a synchronous speed of 900 RPM. Similarly for motors designed for use on 50 Hz frequency systems, the synchronous speed of a 2-pole motor is 3000 RPM, while an 8-pole motor has a synchronous speed of 750 RPM.

With the exception of motors that are built with multiple windings (2-speed motors), each motor then has just one speed (precise value determined by magnitude of load) that it will operate at. VFD's can be added to the motor control scheme to provide the capability to adjust the frequency applied to its windings, and consequently select its operating speeds.

WHY USE A VFD?

Energy Savings:

By varying the motor's speed, energy savings can be achieved, particularly in fluid flow applications, leading to one of the most common justifications for VFD installation. Formerly, the only way to control pump or fan fluid flow was through the use of valves and dampers.

Figure 3 demonstrates typical power requirements of a 300 kW, 1800 RPM, 95% full load efficient, AC motor operated between 1800 – 450 RPM with a VFD, based upon a typical centrifugal pump load.

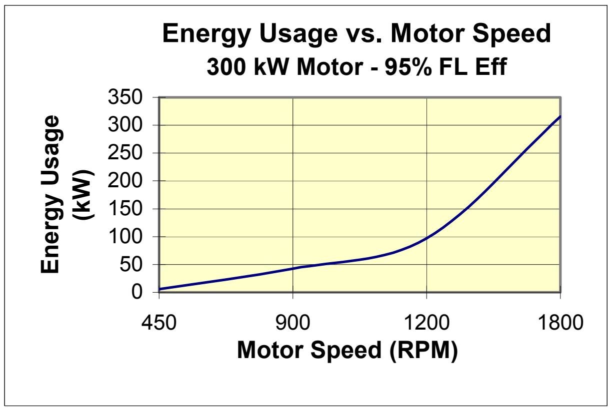

Figure 3 – Centrifugal Pump Energy Usage

Because the pump load decreases by the cube of the difference in speed (speed/base) ^{3}, the energy usage of the motor drops off dramatically at lower speeds. Of course, this is a simplified example that does not take into effect all system losses, but it does demonstrate the substantial energy savings that can be pursued and obtained through the use of VFD's with centrifugal load devices.

Although not as dramatic as in quadratic loads, energy savings can also be made with constant torque loads such as conveyors, varying the speed to better match the loading or volume of material being put through the grinding and crushing circuits. Regardless of the process demand, the motor always ran at full speed. With a VFD, the motor speed can be varied to match the material flow requirements and energy can be saved.

Speed Variation:

Beyond energy usage, applications such as conveyors, crushers and grinding mills can use the motor and VFD packages to provide optimal speed variation. In some cases the operating speed range can be wide, which a motor applied with a constant frequency power source cannot provide. In the case of conveyors and mills, a VFD and motor system can even provide a "crawl" speed for maintenance purposes – eliminating the need for additional mechanical drives.

In any case, by having the ability to alter the feed rates of conveyors and the speed rate of crushing and grinding equipment, new levels of process optimization can be achieved.

Using shaft-mounted tachometers for feedback devices, VFD's can control motor speeds within a fraction of a RPM.

Starting Control:

VFD's can also provide smooth "soft start" and "high torque" motor control functions. Since the motors are no longer started across the line, the high motor inrush current (typically 600% of FLA or higher) that can be detrimental to the power grid is no longer a factor. A VFD will typically limit the amp draw to 100 – 150% of the motor's FLA without need of a reduced voltage starter device.

As previously stated, VFD's also have a unique way of providing a constant Volts/Hz relationship from base speed, all the way down to zero speed. This constant Volts/Hz power characteristic allows the VFD to take advantage of the motor's peak torque, or breakdown torque (BDT). A motor's BDT is typically as high as 180 – 220% of the motors full load torque (FLT). Using the VFD's constant Volts/Hz relationship, the VFD can be operated to provide motor starting torque equal to approximately 80% of the motor's BDT. The combination of a VFD and motor can provide great advantage for starting a high inertia fan load, or to generate the high starting torque required in the starting of a kiln, a crusher or a loaded conveyor.

In the specific case of a kiln application, the motors can also be designed with a VFD to provide 200% - 250% starting torque (or even higher). These motor and drive systems provide smoother starting, with lower amp draw, all with a lower priced motor.

SPECIFYING AC INDUCTION MOTORS

Load Type:

For proper motor selection, the load characteristics of the driven equipment should be known. The driven equipment load type can be divided into (3) main categories; variable torque (VT), constant torque (CT) and constant horsepower (CHP), or combinations thereof, as illustrated in Figure 4.

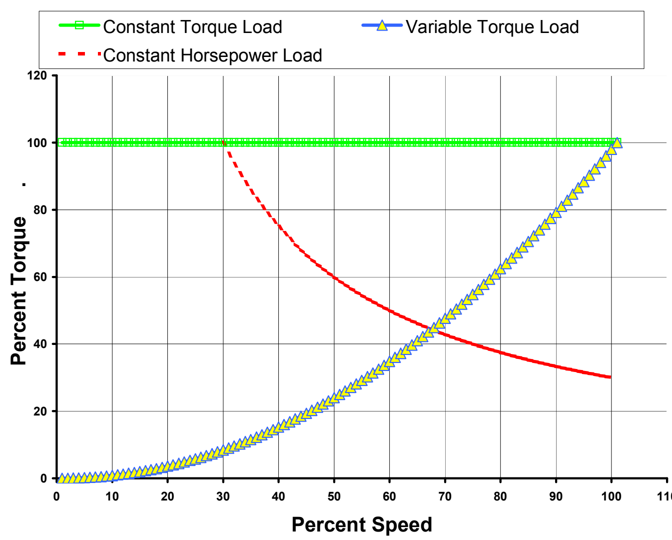

Figure 4 – Load Torque Curves

VT applications include all applications that exhibit a torque characteristic that increase, usually by the square (quadratic loads) as a function of speed. VT applications include: centrifugal pumps, centrifugal compressors and fans.

CT applications maintain a near constant level of torque regardless of speed. CT applications include kilns, conveyors, grinding mills and crushers.

CHP applications include those with a winding requirement, such as a hoist, or constitute a portion of a speed range above base speed in the case of a centrifugal (VT) load or CT load.

Further, some applications are specified by the process equipment supplier to include a combination of CT and CHP loading, applications like kilns and mills. Application note: as speed increases beyond the CT range into the constant power range, the torque output of the motor will decline and will be limited by the VFD as well.

Speed Range:
The next step in properly specifying motors for use on VFD's is the determination of the operating speed range. The speed range required by the load can affect both the electrical (thermal) and mechanical design features of the driving motor.

Typically speed ranges are specified as ratios such as 10:1 or 4:1. This signifies that the normal operating speed range of the motor, when operating through VFD control, will be between the base speed and a speed equal to the base divided by the larger number. For example, an 1800 RPM motor with a 4:1 speed range would operate between 1800 and 450 RPM.

Speed ranges can also be specified on a strictly RPM basis or Hz basis, such as VT 600 – 1800 RPM, or CT 0 – 60 Hz.

Finally, motors can also be specified to have a combination of speed ranges such as a centrifugal pump could be specified as VT 200 – 1800 RPM and CHP 1800 – 1960 RPM, whereas a high pressure grinding mill motor could be specified as 600 – 1200 RPM CT, 1200 – 1320 CHP.

Overload Requirements:
Some applications call for the VFD and motor system to supply torques greater than the motor FLT for short periods of time. This can occur during starting and/or during the normal process. Overloads are typically stated in percents within a time period. A typical overload specification is by the VFD is 150% for 60 seconds, 1 per hour. 150% represents 1.5 times the motor's full load amp (FLA) rating, which equates closely to 150% FLT.

In the case of grinding mills, kiln or crusher applications, the overload requirements can be 180%, 200% or even 250%. The time period will depend on the starting cycle or process.

VFD "Bypass" Requirement:
Often in the system design of a fan or a pump, the VFD will be installed in a circuit that allows for the VFD to be bypassed, and the motor started either across-the-line or with a reduced voltage starter. In that case, the motor manufacturer should be made aware, since the motor now must be evaluated under both starting scenarios.

Of particular concern are high inertia fan applications and applications that require high starting torque, such as mills and conveyors.

Also, VFD's can be used to start the motors and then the motors are synchronized across the line. These are cases where the VFD is primarily used for starting control, and speed variation is not needed. Note, for this scenario, a single VFD can be used to start multiple motors. However, consideration must also be given to safety, to properly isolate the motor from the VFD when running the motor on line voltage.

VFD Type:
As will be discussed later in the Motor Design Considerations section, much of what can make a motor special for use with a VFD is linked to what type of VFD is used. In the production of AC power signals, VFD's can produce both power signals that have voltage spikes and common mode voltages ("fluctuation of the motor neutral voltage with respect to ground"[1]). Voltage spikes can lead to motor stator insulation damage, while common mode voltages can lead to bearing currents and consequently bearing damage.

Many VFD's are offered with output filtering systems as standard or as optional. These systems can effectively eliminate voltage spikes, and some can eliminate common mode voltages. Further, some

VFD's are designed to provide a new sign wave output power signal to the motor, without spikes and common mode voltages.

The best source for VFD output information is from the VFD manufactures, themselves. The VFD manufactures have the best information about their output power quality and can identify minimum stator insulation voltage levels. Or, the control manufacturer can identify the peak voltage levels and then permit the motor manufacturer to determine the need for insulation upgrade. Some VFD vendors market their products on the basis that standard motor insulations can be used with their drives. This is a great selling point where VFD's are retrofitted into existing motor installations.

Please reference IEEE Standard 1566 for additional insight into the specification of the VFD's.

Area Classification:
For safety reasons, with any electrical equipment installation, the existence of a classified or hazardous area must be made known to the motor manufacturer. Hazardous area classifications can prevent the use of certain enclosures and accessories that could be potential for sparking or surface temperatures above ignition levels. Of particular note in the Cement Industry are applications in coal handling. A National Electric Code (NEC) hazardous duty classification of Class II, Group F, Division 2 is common and should be communicated in the specification of the motor if applicable.

Accessories:
Two unique motor accessories for VFD applications are tachometers and shaft grounding brushes.

Tachometers can be installed on the motor shaft, gearbox shaft, or driven equipment shaft. Tachometers through magnetoresistive or photoelectric sensing can provide precise speed measurement feedback to the VFD. Tachometers are available from a worldwide variety of suppliers with multiple "pulse counts", outputs, connector types and mounting configurations. Please note, all tachometers are not created equal, and all tachometers are not up to the task of the extreme conditions of a typically cement application.

When VFD output signals contribute excessive common mode voltage magnitude to the power provided to AC induction motors, steps must be taken to protect the bearings of the motor and the driven equipment. Shaft grounding brushes provide a channel for discharging potentials that can develop on motor and driven equipment shafts. Again, some VFD's are designed to provide an output power signal to the motor, without common mode voltages.

MOTOR DESIGN CONSIDERATIONS

Thermal Consideration:
40C ambient is the most typical maximum in the specification of AC induction motors. However, kiln motor applications are usually rated for 50C, which requires motor thermal de-rating.

In the basic case, motors cool themselves through the use of shaft-mounted fans. When a motor is slowed down from its base speed, the cooling of ability of the motor lessens.

For VT applications, the torque load, and thus thermal heating, is also dropping off as the motor decreases in speed, therefore, the speed ranges does not have an effect on the motor thermal design.

For CT applications, the motor requires a near constant flow of current throughout the constant torque speed range. Constant current equates to near constant heat production; hence the motor can overheat as the speed becomes too low and cooling fans slow down in speed. Typically a TEFC motor can operate in a 2:1 CT speed range without thermal modification. However, some small TEFC motors can handle larger speed ranges (4: 1 or 10:1), while others (open type) cannot even reach a 2:1 range.

Motor thermal designs can be modified in a variety of ways for CT applications. Larger frames can be de-rated. Auxiliary blowers can be added to replace shaft mounted cooling fans. Also open type enclosures "one having ventilating openings which permit passage of external cooling air over and around the (stator) windings of the machine"[2] can be cooled using externally ducted air, much the way DC motors commonly have been designed.

⇨ *Please refer to ADDITIONAL RESOURCES selection item 4, or NEMA MG1 for further explanation of motor temperature rise and enclosures.*

<u>Electrical Design Considerations:</u>
Voltage selection for the motor and drive are the first design consideration. Debate exists over a threshold of when to transition from low (<1000) to medium (2300 – 4000) to high voltage 6 kV+. Strictly left to the motor design, 800 hp is a normal transition from low to medium voltage based on 460V power systems. This can be stretch higher, particularly with slower speed (> 2-pole) designs, and 575V and 690V power supply. One-time cable costs for low voltage can be offset with lower priced drives, switchgear and motors – total system cost having the final say. Common LV DC bus designs can also provide lower system costs, where a single bus can be used for multiple applications for example with dedicated inverters for a kiln and clinker cooler fans.

In addition to voltage selection, within the electrical design realm, two primary factors come into consideration when adapting/designing an AC induction motor for use on a VFD; stator insulation and temperature rise.

Depending on the VFD and whether it has an output filter or not, the power signal from the VFD can subject the motor insulation to much higher voltage stress than the normal sinusoidal AC power system. As depicted by Figure 5, an unfiltered VFD without design features to limit voltage spiking caused by the VFD's switching devices can produce high level of "spiking" at the front end of voltage peak as shown in this low voltage VFD example.

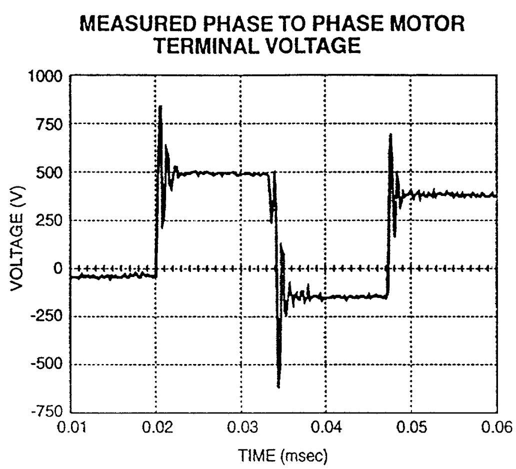

Figure 5 – Unfiltered VFD Power Signal

Depending on the magnitude and rise time of the spikes, the motor's insulation system may need to be upgraded to avoid premature degradation and failure, as shown in Figure 6.

When VFD's were first being applied in the field, many motor failures occurred due to lack of consideration of the voltage spikes produced by VFD's. The VFD and motor industries are now much more aware of this issue. Today, some VFD manufacturers will even promote that drives, either with their inherent design, or with the use of output filters, can produce sine wave power signals that are of superior quality to many utility AC power systems.

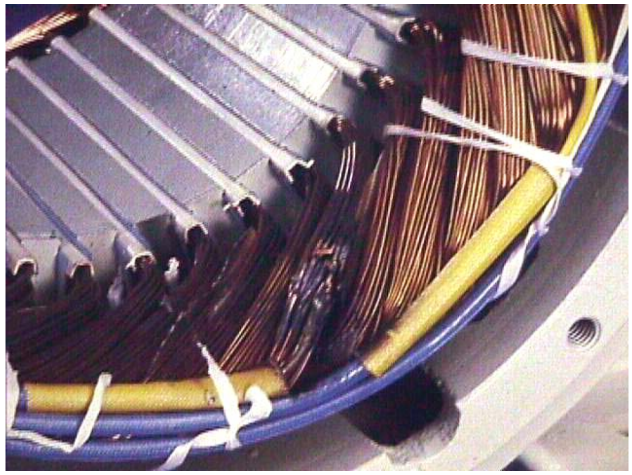

Figure 6 – Motor Stator Winding Failure due to VFD Voltage Spikes

NEMA MG 1-1993, Rev. 3, Part 31, Paragraph 31.40.4.2 provides guidelines for “definite purpose inverter fed motors” in regard to peak voltage withstand and rise time design limitations both for motors 600V and less, and for those greater than 600V.

In some cases standard insulation systems can be used, but in others, the voltage rating of the insulation system must be upgraded and additional “turn” insulation must be added to the stator coils. For example; a motor designed for use with an unfiltered 4000V PWM VFD may need to utilize a stator insulation that includes additional coil turn to turn tape and ground insulation rated at a minimum of 6900V (4000 x 1.732) to provide adequate protection from VFD induced voltage spikes.

Non-sinusoidal power signals also inherently lead to higher heat generation in AC induction motors. Additional heating due to non-sinusoidal VFD power signals are typically less than 5% with today’s new inverter designs. However this should be considered in the motors electrical design in addition to the heating previously discussed in CT speed ranges.

Specifically in regard to the non-sinusoidal heating, many motors will be rated with Class B temperature rise on a sine wave power system, suitable for class F temperature rise on a VFD, or other users may utilize the motors’ extra thermal capacity due to a sine wave-duty rated 1.15 service factor (SF) rating to adapt to VFD duty.

Mechanical Design Considerations:

Bearing Insulation:

VFD induced shaft currents and bearing insulation have been a “hot” topic in recent years in other process industries, including steel and paper. Many theories and solutions have been proposed, but most industry experts will agree that the problem can exist and must be addressed.

When voltage differentials develop in motors, the potential for bearing currents exists. Bearing currents that are allowed to persist will result in microscopic pitting of the bearing surfaces as the amperage produces sparks between the bearing’s moving surfaces. The pitting will then lead to premature bearing failure as the bearings’ rolling (or sliding) surfaces become damaged, as illustrated in Figure 7.

Figure 7 – Bearing Damage due to Shaft Currents

The culprit of voltage potential with VFD controlled motors is the common mode voltage VFD's can produce. Common mode voltage, applied to the motor terminals, can be minimized via the VFD design technique, proper grounding, VFD output filtering or a combination of the three.

When common mode voltages cannot be adequately controlled external to the motor, the motor itself must be modified. The minimum solution is commonly agreed to in the motor industry is to insulate the opposite drive end (ODE) motor bearing. Insulating the ODE bearing breaks (or opens) the circuit loop of stator-to-bearing-to-shaft-to-bearing-to-stator.

In the cases where the VFD is known to (or suspected to) produce voltage potentials across the motor's air gap – that space between the rotor outside diameter and the inside diameter of the stator – additional bearing protection is in order. The voltage potential component across the motor's air gap has been found to act as a capacitor - a capacitor with relatively low impedance to high frequency voltage. Current flow across the air gap can now form a complete circuit if the motor's drive end (DE) bearing is not insulated. Hence the next level of bearing protection from circulating currents is to insulated both the ODE and DE bearing and add a shaft grounding brush. The shaft grounding brush prevents a voltage potential build-up on the isolated shaft, and if placed on the DE, can limit the risk of VFD induced shaft currents in the driven equipment bearings.

Speed limitations:

Because VFD's are operating motors as speeds other than their base design speeds, the mechanical features of the motor must be considered.

For motors with anti-friction bearings, care must be taken not to exceed the speed ratings of the bearings when motors are run at speeds above base speeds. These same bearings will also experience shorter bearing life when run continuously at higher speeds.

Split sleeve bearings, designed to be self-lubricated at base speed may require the addition of flood lubrication at higher speeds or at low speeds. Note, sleeve bearings do have minimum, continuous speed ratings that vary by factors including rotor weight, bearing size, oil type and temperature.
⇨ Please refer to "Sleeve Bearing Design for Slow Speed Applications in Cement Plants" presented at IEEE-IAS/PCA 2008 for additional information.

Mechanically, all rotating elements have safe maximum speeds. Four pole and slower motor rotors are typically suitable for 25% over speed without modification. Two pole motors are typically limited to 10% over speed without more in-depth review and/or modification.

Two pole motors and very large 4 pole motors must also be analyzed in the domain of critical speeds. For example, a 2-pole motor, larger than 2000 hp will typically have a first critical speed below base speed. When applying such a motor on a VFD for use on a pump or fan with a wide speed range, the VFD must be programmed to not run continuously near the critical speed(s), or the motor must be designed in a special manner to provide a “stiff shaft” – one with its first critical speed(s) above base speed.
⇨ Please refer to “Bearing Considerations for Motors in the Cement Industry”, presented at the IEEE-IAS/PCA 2007 event for additional information about motor bearings

Noise Production:
Motors produce (2) types of noise output; magnetic and that due to air flow. Magnetic noise can be adversely affected by non-sinusoidal power signals and by non-base frequencies. Motors are designed to limit noise output at the base speed, however with VFD applications, the motor can be operated at many speeds besides the base speed ones that could lead to magnetic resonance noise. “Magnetic noise is primarily structure-borne, and cannot be reduced by internal sound lining. Structure-borne noise results from vibration of the stator core and teeth.”[3]

CONCLUSION

VFD’s provide unique and beneficial opportunities for AC induction motor control in cement plant applications. VFD’s can offer energy savings, process control through speed variation and starting control for motors. However, the specification and design of AC induction motors does become more complex with VFD usage. For optimum motor and VFD performance, and customer satisfaction, the application parameters must be understood jointly by the plant personnel, the process equipment suppliers, VFD supplier and the motor manufacturer. Communication, education and sharing of information are the key components of successful motor specification and procurement.

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[1] NEMA Application Guide for AC Adjustable Drive Systems, Paragraph 5.2.10.4, Page 34.
[2] NEMA MG 1-1993 Rev. 1 Part 1, Page 8, Paragraph 1.25.
[3] W. R. Finley, “Noise in Induction Motors – Causes and Treatments,” IEEE Transactions Nov/Dec 1991, Volume 27, Number 6, Page 1205.

ADDITIONAL RESOURCES

- Application Guide for AC Adjustable Speed Systems. Copyright 2001 National Electrical Manufacturers Association
- IEEE Standard for Performance of Adjustable Speed AC Drives Rated 375 kW and Larger, 7 June 2006
- Bearing Considerations for Motors in the Cement Industry, Rolf Hoppler and Reinhold Errath (ABB), IEEE-IAS/PCA 2007
- Selection of AC Induction Motors for Cement Plant Applications, Barton Sauer (Siemens), IEEE-IAS/PCA 2008
- Sleeve Bearing Design for Slow Speed Applications in Cement Plants, Sumit Singhal, (Siemens), IEEE-IAS/PCA 2008
- NEMA MG 1, 1993, Rev. 3 Part 31. Definite-Purpose Inverter-Fed Motors