KILN DRIVE APPLICATION CONSIDERATIONS

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Abstract - The paper presents available drive train configurations and alternative methods for driving a cement plant kiln. Driving equipment options using hydraulic motors, DC drives or variable frequency drives employing both current and voltage source technologies are evaluated in terms of performance, reliability, maintenance, operating efficiency and total cost of ownership. Drive and motor performance requirements are reviewed in relation to torque/current speed characteristics of the kiln load. Torque pulsations and induced vibrations and their effect on the mechanical drive train components are reviewed.

Index Terms — Kiln application, drive control, torque

INTRODUCTION

Selection and application consideration for drives and motors powering the kiln is a continuously evolving process. The latest variable speed control technologies have proven to be efficient and reliable in several installations in operation today.

In the cement manufacturing process the kiln is at the heart of the operation and its design and application requirements are unique to the cement industry. Its main use is in the chemical transformation of raw mix into clinker. Speed variation is required to control material residency time and clinker output.

Inside the kiln under intense heat (1300ºC-1550ºC) a chemical transformation takes place (PYRO process) changing raw mix into what is known as "clinker".

Control of the rotational speed is a requirement of the process to ensure that the raw materials blend continuously during the chemical transformation cycle with adequate residency time to optimize the PYRO process.

The cold clinker is then ground into powder and blended further with other materials to produce the type and quality of cement powder we use in various applications in the construction industry.

The clinker process together with the design of the kiln, preheater tower and variable speed technologies have evolved over time and some of the older processes and the drive technologies reliably remain in operation today.

The most modern and more efficient cement processes built today would incorporate the preheater tower and a shorter kiln design but with an increasingly higher throughput clinker capacity, which in turn would require a larger powered drive and motor. This process is available for new installations as well as retrofit applications of the PYRO process.

Weather we deal with a new installation or we perform a drive retrofit due to obsolescence, the selection process must rely on close collaboration among the kiln designer, gear, drive and motor manufacturers to ensure that that the end user will receive adequately rated equipment powered by well proven drive technologies, which offer long term reliable performance.

Figure 1- 6000 MTPD -3 support kiln powered by 1100hp AC drive

This paper addresses the available kiln drive technologies, their characteristics and performance. Several high capacity short kilns which were commissioned recently will be featured.

TYPES OF KILNS IN THE CEMENT INDUSTRY

There are two basic horizontal kiln processes in operation today in the industry: wet and dry process. Whereas there are also a variety of small vertical clinker kiln batteries in operation or being built around the world today for the limited product range or capacity plants (600TPD), these will not be discussed.

A few handfuls of the older plants still use the long wet process kilns. These plants use high density slurry as raw mix, which is converted into clinker by burning almost any available type of fuel.

These wet processes have higher specific energy requirements to begin with. In addition the wet slurry forms mud rings at the point of entry into the kiln and this in itself requires higher starting torques to offset the weight imbalance. To prevent build up and to break the mud rings some of the wet kilns are also equipped with chains, which could weigh a few hundred tons and which further increase the starting torque requirements.

The wet kilns are no longer being built primarily because of the high operating and energy costs. For example one of the largest wet kilns in operation today at 3700 MTD has a diameter of 25 ft and overall length of 760 ft. This kiln is powered by 2x1250 Hp DC drives. As we will see below a short kiln of almost 65% more clinker capacity will be powered by a drive rated less than half of this rating.

Figure 2 - 2200MTPD kiln powered by a 350hp single drive

A second variation of the clinker process is the long dry kiln. There are many of these around, typically a technology of the mid sixties and seventies. The main difference is that the raw mix is dry to begin with, the kiln is somewhat shorter and the diameter of the kiln is usually smaller. Internal chains are used to break up the rings built up in the burning zone similarly to the wet process, the additional weight resulting in increased requirement for starting torque. Energy consumption is higher compared with the newer processes but lower than for the wet process.

A typical long dry kiln with a capacity of 1400 MTD clinker would have an overall length of 520 ft and a diameter of 15 ft and it would be powered by one 600 hp DC motor or 2x 300 hp DC motors.

Figure 3 – 2 x 300 hp DC motor and drive train

The long kilns support system would consist of at least five or more concrete pier supports on which the steel tires and bearings would be installed. Alignment run out, shell deformation due to settlement, material build up inside the kiln, refractory erosion and warping all contribute to impose additional starting requirements on the drive and motor.

The modern clinker process incorporates the preheater tower and the shorter kiln design. Depending on the number of stages on the preheater and manufacturer, the shorter kilns would typically be designed with three support stations or piers and be driven by a single or dual drive arrangement and girth gear. The three station kiln would typically have a length to diameter ratio of 15:1.

In comparison with the wet kiln process mentioned above, a modern plant installation for a 6000 MTD clinker production uses a 3 station kiln design having a diameter of 17 ft and a length of 256 ft and is powered by a single 1,100 hp AC drive. The reduction in driving power is self evident for the increased clinker capacity.

The newest of the kiln designs offer even shorter kilns which have length to diameter rations of 11:1. These kilns are supported by two piers and may be driven with the traditional girth gear with single or dual drive arrangements.

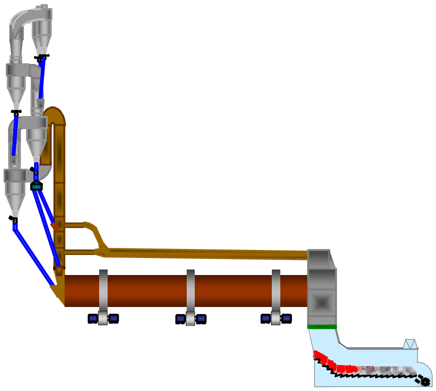

Figure 4 - Preheater and three station kiln arrangement

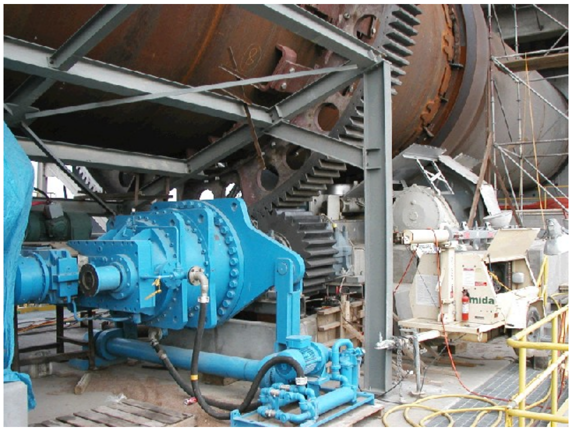

Figure 5 - Traditional Girth, pinion planetary gearbox kiln drive

A recent installation for a 2500 MTD clinker plant uses a 2 pier support design kiln having a diameter of 13.6 ft and a length of 157 ft and is powered by a conventional girth gear and 2 x 335 hp DC drives.

Not to be dismissed is the friction drive which for two kiln stations offers the latest advantages in operating efficiency for the drive train, eliminating the girth gear entirely. With this drive system, the support bearings under the tire are powered directly with smaller motors, which may be electric or hydraulic. This provides an added advantage in limited real estate applications.

A recent installation for a 3300 MTD clinker plant uses a 2 pier support design kiln with a friction drive. The kiln diameter is 15 ft, length of 183 ft and the inlet support bearings are driven directly by 2x 350 hp AC drives.

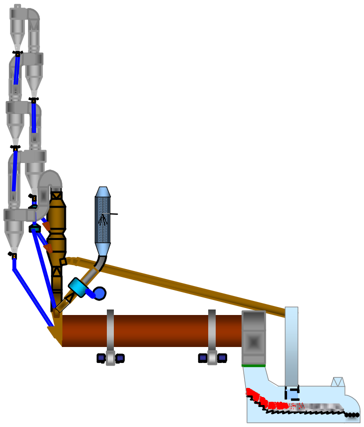

Figure 6 - Preheater and two station kiln arrangement

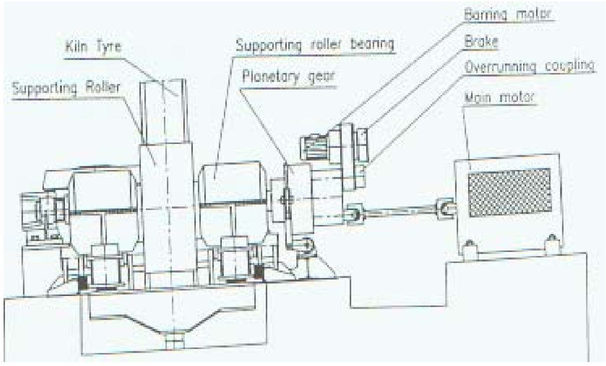

Figure 7 - Electro-mechanical friction drive arrangement

With the short kiln design, shell deformation, ovality, warping and sagging of the shell, ring built up inside the kiln would remain a factor for consideration in defining the starting torque requirements of the kiln.

Apart from the advantages in energy savings offered by each of the PYRO processes and kiln shell design, considerations must also be given to the angle of inclination of the kiln, the total absorbed power of the kiln including losses, operating speed range, reserve capacity, altitude and ambient temperature conditions, which could affect future performance of the driving equipment.

Although friction drives are slightly more efficient than geared drives, slippage considerations may limit the maximum torque transmitted at the tire. Slippage usually won’t come into play under normal operating conditions but can affect starting, particularly with a bowed kiln or with material build up on the refractory brick.

Long kilns or wet kilns typically utilize more expensive geared drives that are capable of transmitting higher torque. Possible disadvantages include gear noise, vibration and the lubrication requirements.

KILN DRIVE CONFIGURATIONS AND TOPOLOGIES

The traditional geared kiln drive train would consist of a motor, coupled through a Cardan shaft to a gearbox, which in turn would be coupled through a pinion to a Girth gear.

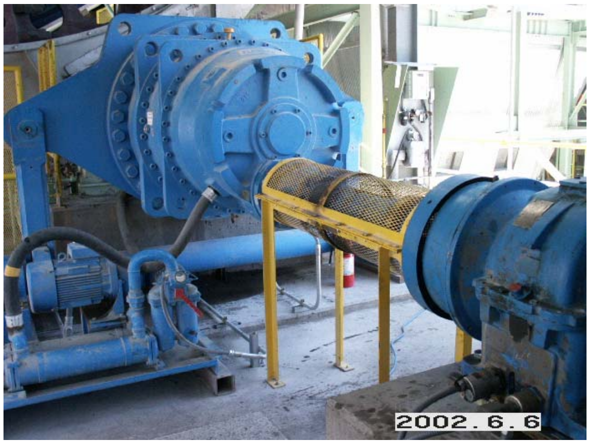

Figure 8 - Planetary gear and Cardan shaft

Depending on the manufacturer and design limitation for power transfer per pinion, single or dual drive arrangements were very common.

In the sixties and seventies, the DC shunt motor and the servo controlled hydrostatic motors were the workhorses of the industry.

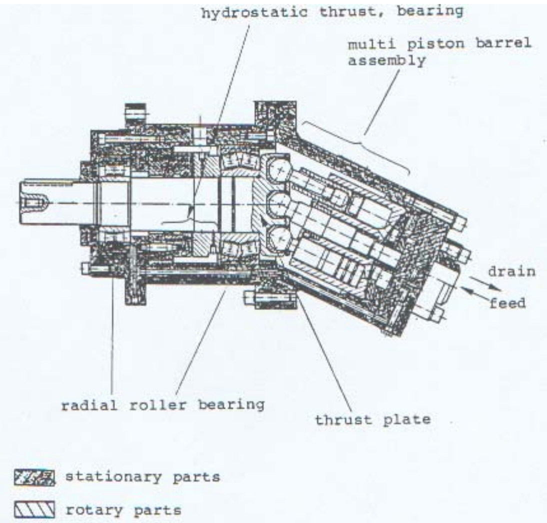

Figure 9 Multi Piston Hydrostatic motor

An important criterion of the drive train design would be that in the event of electrical power or drive loss the kiln's inertia must be prevented from accelerating freely, particularly rollover in reverse direction.

The worst case scenarios are with speeds (2000-3000 rpm), which could be attained due to free fall acceleration to the bottom or six o'clock position, followed by a series of pendulum swings. At these speeds the rotors, gear boxes and seals could break and fly apart causing irreparable damage to equipment and potentially injuring innocent bystanders.

Figure 10 – Multi Piston Hydraulic drive

A proven technique has been employed successfully over the years. An anti-roll back device consisting of a mechanical or hydraulic clutch and drum or disk brake have been employed to slow down the speed of the shell and control its de-acceleration to rest or six o'clock position.

Upon restoring power the kiln would re-start and accelerate normally. However, in the event of prolonged power loss or drive damage the kiln rotation must be maintained turning at low speeds to prevent damage to the refractory and warping of the shell. Typically an internal combustion engine or an emergency power generator and motor coupled though an auxiliary gearbox need to be provided to maintain a low rotational speed of the shell.

A. The hydrostatic drive

A newer (Figure 11) more robust compact version of these drives is used today with friction drives. These drives are of radial piston type design, have an improved seal material, which can resist pressures well above the 600 bar mark, a weak link of the past and have been proven to be comparatively very efficient and reliable.

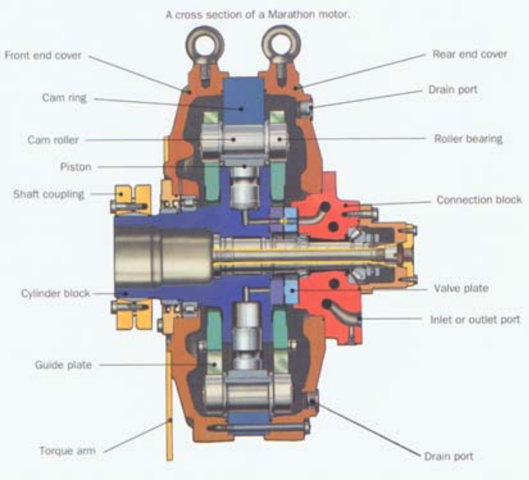

Figure 11 – Radial Piston hydrostatic motor

Briefly, the operating principle of the hydrostatic drives is based on the radial movement imparted by a set of evenly numbered radially spaced pistons inside a round cylinder head block, which is machined as an output shaft. Each piston is attached to a cam roller, which pushes the oil against a cam ring rigidly connected to the motor housing. The push against the cam ring creates torque, which open and closes a set of plate valves which control the flow of oil and converts this torque into a rotary motion.

The decision to employ single or dual drive topology is dictated by the kiln manufacturer's design and is based on mechanical and economic considerations, especially the torque transfer capability of each pinion. At the point where slippage is predicted on a friction drive it is possible to avoid a more costly geared design by adding a second friction drive.

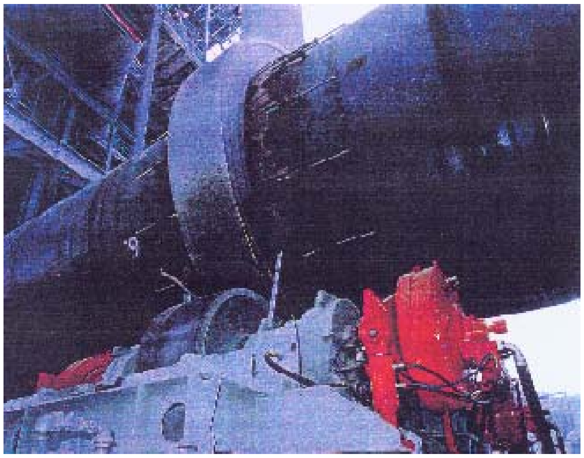

Figure 12 - Hydraulic friction drive

B. DC drives

The traditional workhorse powering the kilns in a cement plant has been the DC motor with shunt connected field and SCR drive. In many respects this holds true today as the majority of kiln drives remain DC.

However, it can be said, that in new installations and many recent retrofit applications the proliferation of the DC drive has subsided together with the fear of relying on the newer AC drive technologies.

The torque speed characteristics of the drive/motor are shown in figure 15. It applies equally to AC and DC drive principle.

Dual drive applications rely on two smaller motors tucked away on either side of the girth gear. Economically this was a good idea since it limited the size of the drive and motor.

Earlier DC dual drives had one power bridge driving two motors. Load sharing was a problem as the push motor was doing most of the work. To balance the torque, load balancing resistors were inserted in series with the armatures.

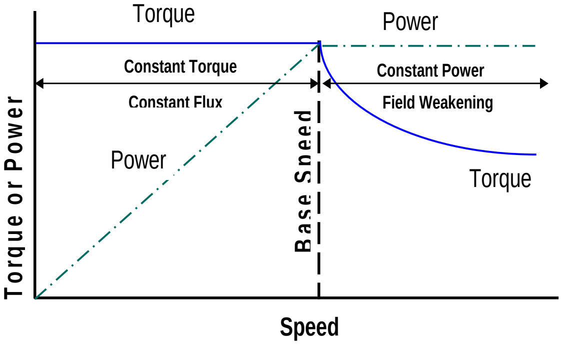

Figure 13 – Drive & Motor Torque / Speed characteristic

DC drives were the first wide range variable speed control used that provided the higher torques required for a Kiln. A single converter bridge, DC drives used a 6 or 12 pulse format based on SCR thyristor technology. Although affective at lower power levels, with higher power the harmonic output back to the line could start to affect other equipment in the distribution system, especially when used without filtering.

Modern digitally controlled DC drives however, will be configured with dual power bridges and separately controlled excitation on the field. Each motor is controlled individually in a Master/Follower relationship to ensure load sharing.

In the absence of slip, encoder feedback is being used to control speed only with respect to one of the motors, while the other motor follows and limits the torque pulsations on the gear face.

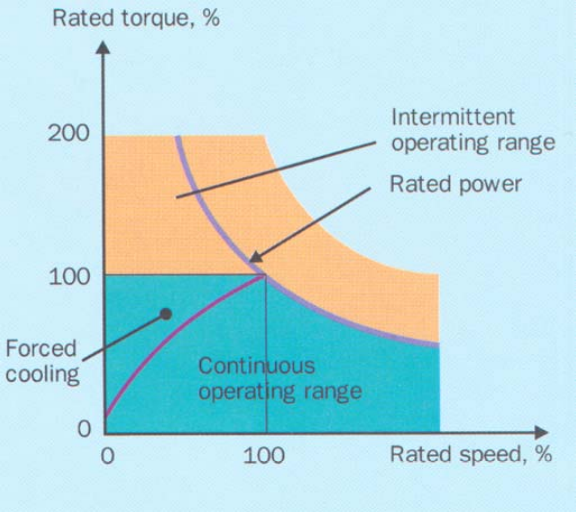

Figure 14 – DC Drive Characteristics

The design of the DC drive package has undergone major transformations in terms of increased ratings of the power switching devices and lower number of components in the power bridge together with the introduction of the microprocessor based algorithms, further reducing losses, while offering self diagnostics for ease of troubleshooting the drive.

C. AC Drives

AC speed control has evolved almost exponentially over the last few years primarily due to advances into the design and packaging of the modern power transistors, thyristors and large power diodes and microprocessor based switching algorithms.

AC Induction motors can operate in a “Constant Flux” and “Field Weakened” modes. The Constant flux mode is often referred to as the Constant Torque range and the Field Weakened mode as the Constant Power range.

Normally, it is possible to maintain a condition of constant flux below base speed. To achieve constant flux above base speed the motor voltage would need to rise above base voltage. In order to stay within the motor voltage limit, a field weakening mode reduces flux and torque, keeping current and horsepower constant. Care must be taken at speeds higher than 125% as BDT levels reduce with the square of the voltage (ratio) and will eventually reduce rated torque levels.

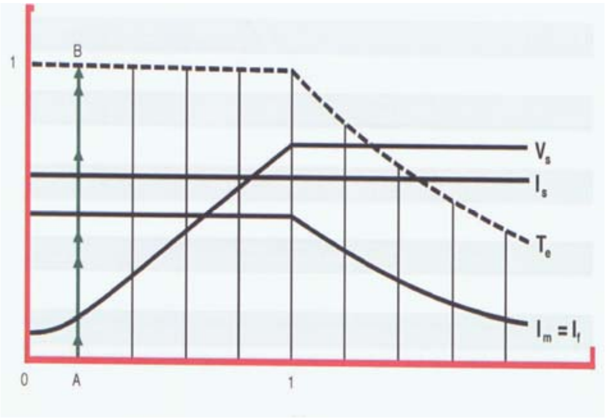

Figure 15 - Torque, load Current, Voltage and excitation current relationship for frequency controlled AC motor:

T= torque, I= current, I_m=magnetizing current, B= Flux density

Other available methods for controlling the speed of AC motors such as slip ring induction motor (WR) and rheostat, squirrel cage with stator with liquid rheostat or electronic rheostat, slip energy recovery and cascade drives, synchronous motor with LCI and recently with PWM drives, although technically all may be designed to drive the kilns of the cement industry, each method has limitations of the operational speed control range as well as torque handling capabilities and have not been proven to be more efficient nor more economical to warrant further development and therefore will not be discussed in this paper.

A drive controller incorporates one or more of the currently available solid state power electronic devices, such as diodes, silicon control rectifiers (SCRs), insulated gate bipolar transistors (IGBTs), gate turn-off thyristors (GTOs) and integrated gate commutated thyristors (IGCTs) and a close cousin the symmetric gate commutated thyristor (SGCT’s). The diodes and SCRs are common elements of either an AC or a DC controller. The other devices are used exclusively with variable frequency drives.

One major difference between the AC and DC controllers is that the later has only one power bridge whereas the AC drive has two, called the rectifier on the input and the inverter at the output. An electrical circuit topology for a VFD is shown below. The drive has three major identifiable component sections:

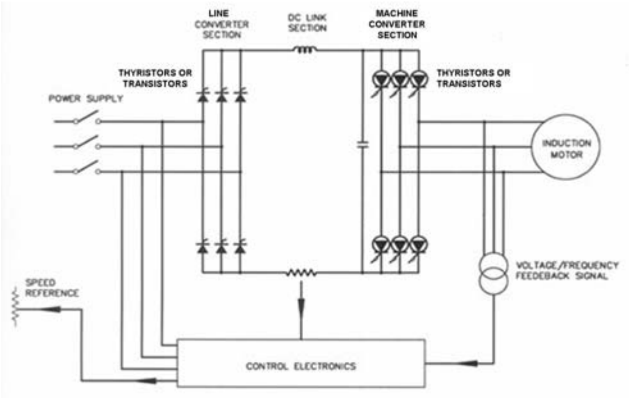

Figure 16 -AC Drive topology diagram

The first section is called the rectifier or line side converter section. Its main purpose is to rectify naturally (diode rectifier) or in a controlled fashion (SCR, IGCT, SGCT or IGBT), the input supply voltage and frequency into a fixed DC voltage.

The second section is called the DC link bus, which may include a reactor or a capacitor bank or both. The primary function of this section is to maintain a base voltage to be switched by the inverter section.

The third section is called the inverter or load side converter section and is designed to switch in a controlled fashion the fixed DC link bus voltage into a variable frequency output. Depending on the current ratings this section may contain GTOs, SCR's IGBTs, or more recently IGCTs and SGCT's.
Regeneration reverses inverter and rectifier operation.

The type of converter switching device and DC link voltage defines the operating principle of the inverter: voltage source or current source. The switching of these devices is controlled by state of the art digital controllers, which contain the algorithms for firing and protecting the solid state devices and the motor. The digital controller also maintains and displays an accurate log of drive faults, which are essential in troubleshooting drive problems. The type of algorithm employed by the digital controller determines the accuracy of the speed and torque output of the drive. It also determines if there is a requirement for a speed encoder or not. Most of the modern digital controllers will include algorithms referred to as constant volts per Hertz, (V/Hz) or Flux Vector control. The Flux Vector is a sophisticated algorithm providing 100:1 speed control range with 0.01 percent accuracy often without the requirement of a speed encoder. However, for a kiln drive, which normally requires 250% torque at zero speed, for up to 60 seconds, a speed encoder is always recommended with forced ventilation to prevent motor overheating at standstill.

A single AC drive can be employed with two SCI motors, which naturally possess a drooping speed vs load characteristic when operated at low slips (i.e. slip < the value at which breakdown torque occurs). In this case, at any given operating frequency the synchronous speed should be common to both. Each motor will tend to equally slow down when loaded and speed up when unloaded, reaching a semi-stable equilibrium. Each motor should be equipped with current transformers and a motor protection relay.

With two drives and two motors an active load sharing regulator (master / follower) is possible. This more expensive arrangement has the advantage of partial redundancy, and independent protection and control for each motor. In this case, motor protection functions may be built into the drive control.

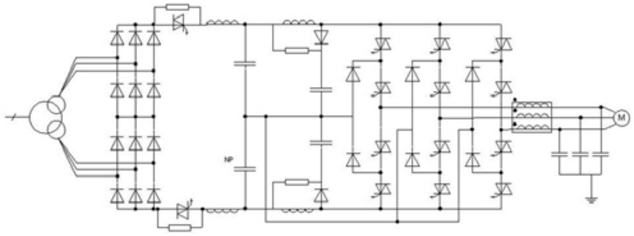

Figure 17 – Three levels IGCT VSI drive design

Dual motor designs are generally in a smaller frame diameter and shaft height which may provide additional flexibility in mounting arrangements. A dual drive arrangement can be implemented with one drive and two motors in which case the motors will share load provided the motors have a drooping speed vs. load characteristic that is identical.

With the advances in AC drives, standard induction motors could be used, eliminating the maintenance requirements associated with DC motors. AC drives can be low voltage or medium voltage, voltage source or current source. Voltage source drives are common in three configurations, namely a 2 level IGBT (transistor technology) with diode rectifier and 3 levels IGCT (thyristor technology) with 12 pulse diode rectifier as well as a 3 level IGBT, also with a 12 pulse rectifier. The later is a combination of the two figures shown above (17 & 18).

The VSI drive is characterized by a large capacitor in the DC Link section of the drive between the rectifier which converts AC to DC and the inverter which converts the DC back to variable frequency AC. This capacitor determines the drives behavior in that it acts like a stable source of voltage while allowing current to change quickly. The simpler diode rectifier can be arranged in a multi-pulse format to reduce harmonics but will not allow power to be regenerated back to the line. This is not an issue for most Kiln applications.

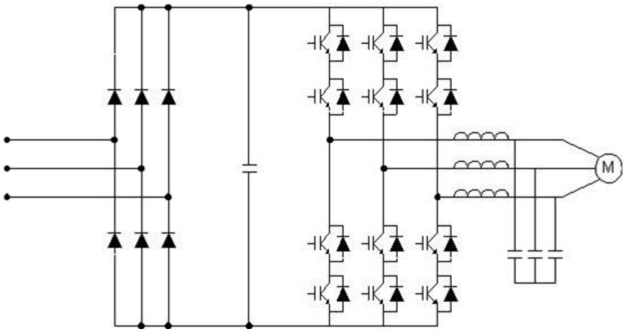

Figure 18 - Two levels IGBT VSI drive design

Other rectifier configurations include an active rectifier which can control harmonics and power factor, two important power quality considerations. An input transformer and output filter rounds out the VSI configuration. The input transformer handles a neutral offset voltage while the output filter prevents voltage transients being applied to the motor. Without this controlled application of the offset neutral the AC drive could not be used on existing motors without jeopardizing their insulation.

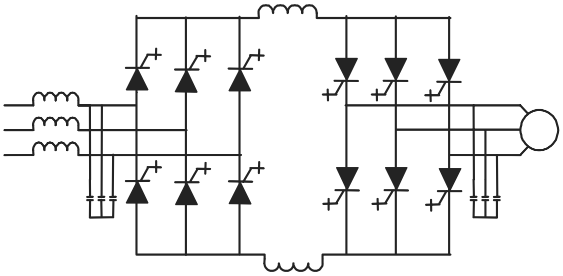

Figure 19 – Active Front End CSI design (SGCT devices)

The CSI drive has a large DC reactor in place of the capacitor in the VSI configuration and this component determines the primary characteristics of the CSI drive. The same rectifier and inverter arrangement exist however in this case the current is the stable quantity and the voltage can change quickly. The voltage of the DC Link varies with motor speed in this design and current drawn is proportional to torque required. The CSI drive can also be provided in different rectifier configurations including an active rectifier to improve harmonics and power factor.

Configuration of the CSI drive is very simple, with low component count (SGCT thyristor technology) and symmetrical rectifier and inverter. Capacitors are used on both sides of the converters to aid in power factor and reduce harmonics both to the line and motor sides.

D. DC motor considerations

DC motors have been used in many drive applications requiring high output torque and smooth speed control. To ensure good commutation and uniform current density distribution among the brushes, an inverse relationship between power and speed has been developed and accepted as a rule of practice for selecting a trouble free operation for a particular load application.

In the case of DC motors a stabilized shunt design is used to compensate for the MMF due to armature reaction, which weakens the field and can cause a rising characteristic. Load sharing resistors in series with the armatures are typically used for balancing the load on the motors.

DC motors have the highest torque to weight ratio but also use a maintenance prone commutator and require a separate field control. Cooling is more efficient with the salient pole design of the DC motor although separate cooling is still required for lower speed operation. Armature voltage feedback provides sufficient speed control although encoders can also be fitted.

E. AC Motor design considerations

The motors employed with AC variable frequency drives are exclusively squirrel cage (SC) induction motors, which are more reliable and less expensive motors to build and maintain than the DC motors. A variable frequency drive with a squirrel cage motor requires little maintenance, which is typically limited to the cooling blowers and motor lubrication.

The squirrel cage motor can be designed to develop a high breakdown torque required by a specific load application. A high torque requirement in the past would have been an incentive for applying only DC motors. Today this requirement can be satisfied by a SC motor designed with a larger frame to produce the equivalent torque.

This is an important consideration in applications such as kiln drives. The power developed at the shaft of the motor is important for achieving production rates, but the torque capability is what determines the selection of the motor frame.

Kilns are driven through high ratio reduction gearing to reduce the torque referred to the motor shaft, allowing use of AC motors with synchronous speeds in the 600-1200 rpm range. There are economic tradeoffs between the motor and the gearbox. In general the size, weight and cost per horsepower of an AC motor rises with declining speed, whereas the size weight and cost of a gearbox rises with the gear ratio.

Figure 20 - 1100 hp TEBV AC VFD motor

Cooling is also a very important issue when motors are used in applications requiring wide speed control ranges. In applications requiring constant load torque over a speed range of no more than four to one, most manufacturers design a motor with sufficient thermal capacity to dissipate the heat generated by the motor's current. For wider speed turn down ratios, separate blowers must be provided to satisfy the cooling requirements. Due to the harsh environment adjacent to the kiln motors totally enclosed motors are usually specified, including rib type TEFC, totally enclosed air-to-air cooled (TEAAC) and totally enclosed water to air cooled (TEWAC) which requires a source of process water for cooling.

If the kiln drive motor is to be operated below 50% speed at constant torque, separately driven ventilation fans are usually required. Shaft driven fan (TEAAC or TEFC) or rotor mounted blowers are inadequate at low speeds in this application since the airflow falls off sooner than the motor losses decrease.

Modern drive controllers turn on and off the power devices at very high frequencies. The switching gives rise to very fast rates of change of the voltage, which cannot be absorbed by standard motor insulation. In the past there have been numerous dielectric failures attributed to build up of voltages in the supply conductors and in the motor insulation. Consequently when an AC motor is used with a VFD using high switching rates, the insulation level must usually be upgraded, and the motor manufacturer must be made aware of the application.

SIZING THE DRIVE AND MOTOR, POWER AND COOLING CONSIDERATIONS

The process of determining the proper sizing of motor and drive begins with an accurate assessment of load torque. It is important to consider not only running torque but worst case circumstances for all operating conditions. Load torque has several components, namely forces required for overcoming friction, inertia and work done by the kiln. Inertia comes into play only during speed changes and is of importance for loads with mass and or higher speeds.

With the charge starting at the bottom center of the kiln, a defining operating condition occurs after starting to rotate but just before the charge reaches its critical angle and starts to tumble. This point usually defines the highest torque requirement during normal operation. As this normally occurs during acceleration, the inertia of the system and resulting accelerating torque should also be considered. There are various additional operating conditions that may change the maximum torque required, namely if the charge becomes more solidified, uneven loading or complete circling of the charge. Starting torque under normal conditions is related to the friction of the gearbox and kiln and the moment of the off center load until tumbling of the material begins.

To accelerate the kiln’s inertia it is necessary to provide enough torque to drive the kiln throughout the speed range and plus to provide a margin for accelerating torque at the minimum applied voltage. An emergency condition has to be considered when re-starting a kiln that has been allowed to stop at temperature and has taken on a bow, thereby increasing starting torque in a periodic fashion for several revolutions.

The worst case combination of kiln bow, material buildup and voltage drop determines the desired motor design characteristics for torque. An electrical overload is imposed on the motor, the drive and the upstream system during the start. The starting time is for a proportional to the product of system inertia and the maximum speed divided by the net accelerating torque.

$$\text{Acceleration Time} = \frac{(\text{wk2load} + \text{wk2 motor}) \times \text{FLRPM}}{308 \times \text{Net Accelerating Torque}}$$

Along with these requirements, equipment inefficiencies must be considered before arriving at the motor torque and drive current required. Once this is established a corresponding motor and drive design can be determined. Often an overload requirement will dictate the motor and drive sizing.

A typical level of 200 to 250% overload torque requirement means the motor speed torque design levels must be able to handle these high overload torque conditions. Motor current levels corresponding to these torque levels are not always linearly related and should be examined for torques approaching the Breakdown Torque of the motor. As can be seen in the figure, this means for instance that 210% current is needed for 200% torque, and 270% for 250% torque, the higher the torque the more the current strays from the linear relationship. The non-linearity is caused by a rather slow drop-off in efficiency (typically 1%) and a more rapid drop-off in Power factor as the motor operates closer to its' Breakdown Torque.

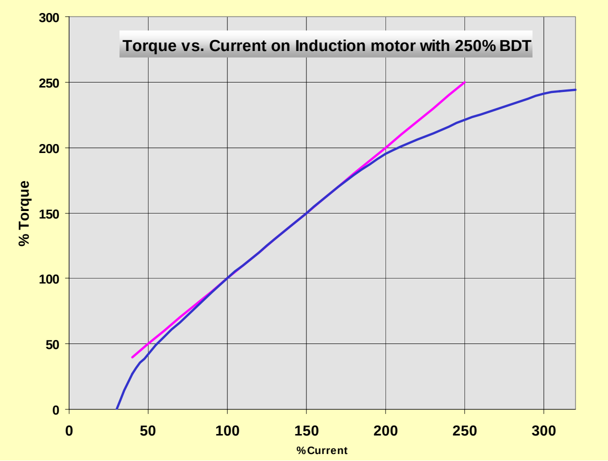

Figure 21 – Motor torque vs. current relationship

The motor should have some margin between the BDT and the maximum torque required by the application. This allows for stable operation with the drive and some margin should higher torques be required.

Drives are usually sized for variable or constant torque loading with torque limits of 110% and 150% respectively. With a 200 to 250% overload condition, the drive current capability is often 70 to 80% higher than normal for constant torque loads. The normal time considered for drive overload ratings is 60 seconds. Drives may be capable of higher currents for a shorter time period. Depending on the current required and the time duration, a drive designed for a 150% overload may be suitable for 200% or 250% overloads. In most cases however, consulting the manufacturer with the overloading information will ensure proper selection. DC drives were well known for their torque capability at low speeds. Both VSI and CSI drives are capable of higher torques throughout the speed range, the primary consideration is providing enough current. More complex torque control and regeneration is not required for most kiln applications unless the drives are used (instead of brakes) to move the charge back to bottom center.

Enclosure considerations are also important to proper drive operation. Ambient conditions will dictate if the type of enclosure required allows the air exchange required for cooling of electronics. Most drives come with enclosures that expel hot air and draw cool air in substantial amounts from their surrounding area. For dusty environments this means filtering and monitoring the incoming air or providing a controlled environment in the form of an electrical room or control house.

In the case of an AC drive and motor system the VFD modifies the inrush of the motor, shifting it to a more forgiving area of the thermal limit curve. In this application the typical current-limit setting is about 200% of FLA. Since the NEMA standard AC Motor design is allowed to have 650% LRA, and the safe stall time is proportional to I^2t, the effective safe stall time on VFD operation is increased by a factor of about 10, allowing ramped acceleration under current limit, the duration of which is typically limited by the 1 minute overload rating of the VFD rather than by the safe stall time of the motor.

Power Semiconductors have much lower thermal inertia and lower permissible operating temperatures than motors. Thermal time constants measured in minutes and permissible junction total temperatures of say 55 Deg C are typical. The impact is that for a torque limited VFD the power bridge must be oversized.

The VFD driven AC motor operates at a low value of slip throughout the speed range, and with speed or rotor position feedback can operate intermittently at up to about 85% of its' design breakdown torque (BDT).

The Drive/Motor ability to provide higher torques for longer time periods allows this configuration to satisfy kiln torque requirements without running into thermal limitations.

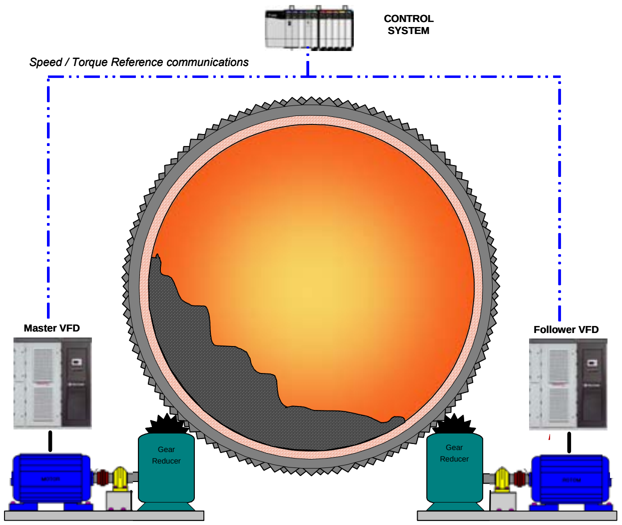

Figure 22 – Dual drive configuration

The drive’s magnetic circuit including DC Links, AC Line Reactors or Isolation Transformers must also be sized to accommodate the starting time and current. DC Link Reactors are specified with inductance linearity to 200% current to avoid saturation.

The time vs. current characteristics of Power Fuses must be selected to coordinate with the calculated starting current / time profile. Programmable motor protection relays with the ability to custom program the Time vs Current characteristics for tripping are an asset on this application.

Controlled stopping of the kiln under normal stop conditions can be provided by a regenerative VFD with adequate momentary overload rating.

A. Continuous Power Rating

The continuous power rating of the VFD is usually satisfied by the time the starting criteria are met, however it is important to specify a one minute overload rating of at least 150%. There are breakpoints in selection of semiconductors, fans, heat-sinks and in the choice of air vs. liquid cooling that may be affected by the running overload. Close co-ordination between the VFD and motor design is required to optimize the system cost. The motor’s power factor at 200% of FLA is an important design consideration for kiln drives, particularly in designs near breakpoints in motor frame size or near breakpoints in VFD device sizes and cooling methods.

The motor Service Factor is usually specified as 1.0 or 1.15. For applications where 1.15 SF is used for prolonged periods of time the VFD must be oversized by 15% to compensate. Motor service factor can be used for prolonged periods, the downside is more rapid deterioration of motor insulation (arrhenius relationship), each 10 deg C of additional temperature rise cuts insulation thermal life by half

B. Cooling Requirements

The Power Electronics are usually located in a clean environment (electrical control room). Usual practice is to provide a 40 Deg C ambient, however the VFD may be capable of a higher ampacity when provided with a lower ambient temperature through application of an air conditioning system.

An important advantage of liquid cooled drives is to remove 90% of the heat rejection out of the control room, reducing the HVAC requirement. Another important consideration in HVAC sizing is the possibility of eliminating the drive isolation transformer, or at least remote mounting it outside the control room.

When applying liquid cooled drives in a cement environment Air to liquid heat exchangers are usually selected since process water is seldom available. If a sufficient quantity of process water is available, then a liquid to liquid heat exchanger mounted within the VFD enclosure can be supplied, simplifying the piping arrangement and conserving real estate.

Air cooled drives may be arranged with ducting to direct hot air out of the control room. In this case it is necessary to provide a clean (filtered) source of makeup air.

METHODS FOR KILN SPEED CONTROL

With the hydrostatic motor drive design torque is controlled as a function of the pressure whereas speed is controlled by the flow of oils.

The torque and speed range shown on the shaded area of figure 24 defines the unique characteristic of the hydrostatic drive. It can develop 200% torque at very low speeds for a relatively very compact design. A typical control loop is shown in figure 25 below.

The main components include a fixed speed electric motor acting as prime mover, oil reservoir, hydraulic pump, a servo controller, an electronic regulator for controlling speed using encoder feedback and set point reference input, which may be set locally or remotely. For kiln drives these would be backed up using redundant controllers and prime movers.

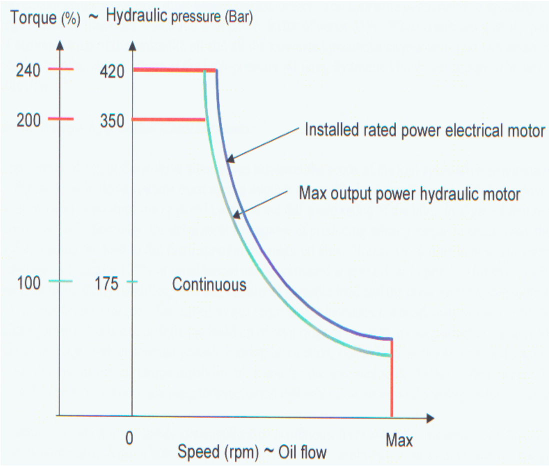

Figure 23 -T-S & oil pressure relation for Hydrostatic drives

Modern hydrostatic drives offer high starting torque at low speed and continuously variable speed control bellow 160 rpm without the requirement of an intermediate gearbox. Operating efficiency is a function of torque and speed.

Depending on power limitations and speed, the hydrostatic drives could be used as single or dual drives with pinion gear coupling and girth gear.

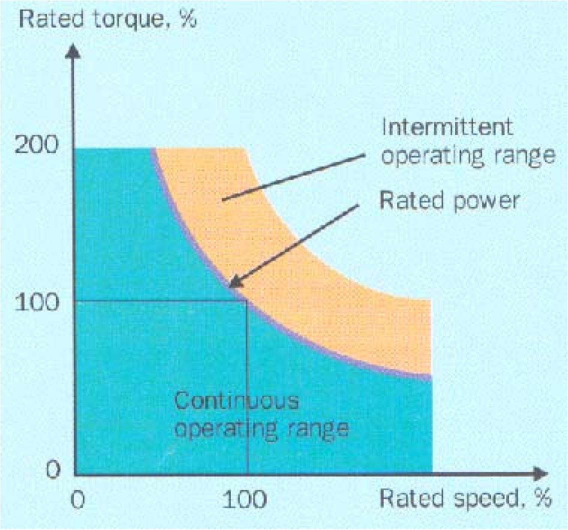

Figure 24 - Hydrostatic drive T-S curve

With friction drives the hydrostatic drives may be used as dual or quad drives coupled directly on each side of the inlet support roller bearings of the kiln. One added advantage is that these hydrostatic drives naturally tend to share the load.

From the kiln design point of view the main advantages for using the friction drives are the lower initial cost, eliminate gears whose teeth passing frequencies can excite torsional natural frequencies. On the other hand shell design and support rollers are much more expensive than conventional planetary gear drives girth gear design and applies only to two station kiln support.

Depending on the capacity of the kiln, two or four hydraulic motors may be required with a friction drive. Therefore each application must be evaluated in terms of available technology, space and torque limitation at the coupling point of the driven shaft, installed cost.

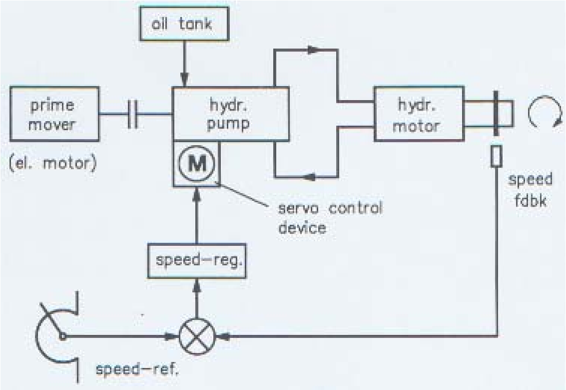

Figure 25- Hydrostatic closed loop speed control with one motor

An argument could be also made that under extreme warping conditions, the friction drive regardless of the output torque capabilities may not be able to move the shell because of slip. So far this has not been the case.

Hydrostatic drive efficiency is a function of the operating point but in general terms comparable in efficiency with electro-mechanical drives. For comparison of relative efficiency, cost and application requirements please refer to the comparison table at the end of this paper.

Accurate speed control is essential to manage kiln production levels and can be used to adapt to changing process and material conditions. Speed control is the primary function of drive used on kilns and it is important that this be accomplished as simple as possible. Easy integration into control systems, access to speed and torque control loops and a torque load sharing control algorithm are other important aspects of the drive control.

Closed loop speed feedback is normally provided to improve starting torque performance for the VFD.

Speed feedback for a DC Drive may consist of a DC Tacho-generator, whereas for an AC Drive it is usually implemented using a pulse tachometer or encoder. A side benefit of providing speed feedback is an increase in speed regulator accuracy. The Pulse Tachometer's cable distance is limited by degradation of the waveform due to cable capacitance.

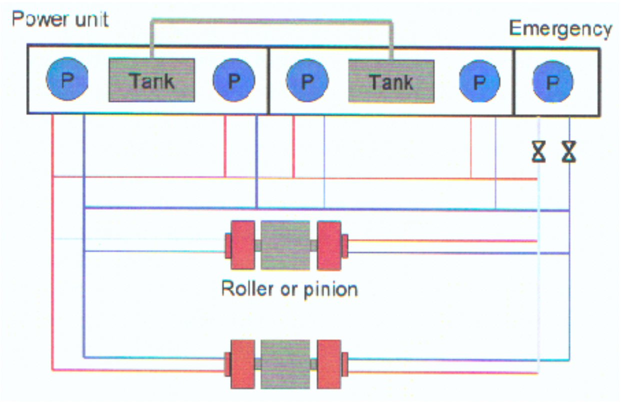

Figure 26 - Dual hydrostatic drive circuit

Speed regulator configurations for DC Drives and VSI drives are usually outer loop speed, inner loop voltage whereas for CSI Drives an outer loop speed, inner loop torque configuration is used, providing DC machine performance using the simpler, more rugged and less expensive AC machine construction.

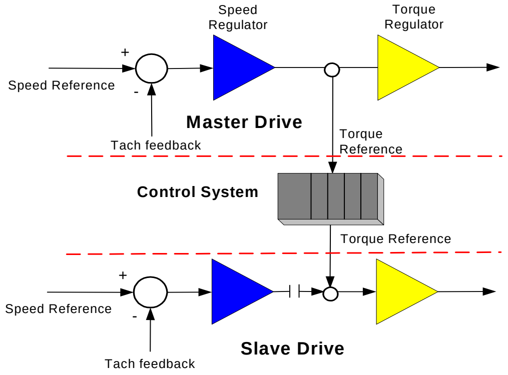

Figure 27 – Master/Follower load sharing control

For project management purposes it is necessary to coordinate between motor and drive supplier to ensure that both the electrical characteristics required by the VFD and the mechanical packaging requirements of the motor are met.

Hermetically sealed magneto-resistive pulse tachometers are available to withstand the harsh environment adjacent to the kiln.

For DC and AC drive systems speed control is accomplished through an analog or digital speed reference provided to the drive. When two drives are used the second must follow the first in speed and torque to ensure equal load sharing. A master speed controller is established and the second drive (follower) either follows the same speed reference with more droop or acts as a torque controller only, receiving a torque reference from the first drive. With torque control, an overriding speed limit is implemented by slightly saturating the speed regulator.

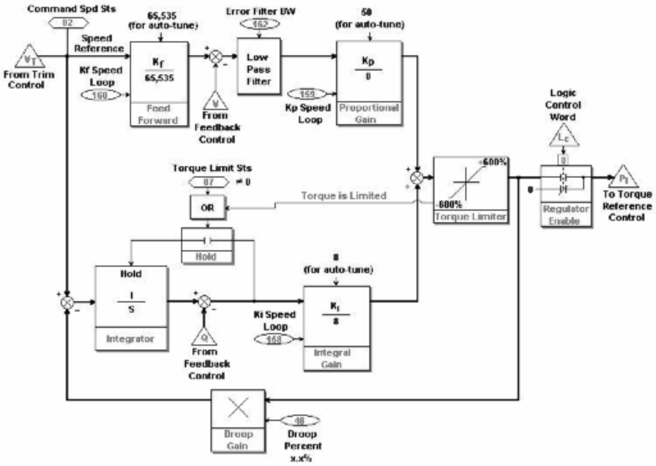

Figure 28 - Speed droop and torque control methods.

A tachometer is required in most cases to meet high starting torque requirements. Communication capabilities and access to speed and torque control loops vary widely between DC and AC control and among different vendors and should be examined to ensure integration and control is compatible with intended process requirements. For high starting torques the drives should be tested before final installation with settings determined for field implementation. 200% and higher torque requirements often mean special settings for drives that may be software limited to 150% constant torque loads.

EVALUATING KILN DRIVE ALTERNATIVES

Although the earlier hydrostatic drives were very reliable and easy to maintain, there are only a few of these drives in operation today, primarily because of equipment obsolescence and increased maintenance cost of the hydraulics and seals with increase operating pressure. Most of these earlier designs have been replaced by DC drives.

The acceptance of the new power electronics technology using variable frequency drives and squirrel cage induction motors has been a bumpy road as the earlier generations of AC drives were expensive and switching devices had limited ratings and were prone to failure.

Modern AC power electronics devices have increased ratings in terms of current and voltage switching capabilities and offer lower switching losses, which makes them today the choice rather than the exception.

The main disadvantage of the DC motor remains with the commutator and brush design which are maintenance intensive and prone to failure.

One of the main advantages of the DC motor is that by virtue of its operating principle with armature voltage and field excitation control it can deliver be highest torque to weight ratio among the electrically powered motors and second only to the hydrostatic motor. The other advantage is no slip and possibility of over-excitation to speed up the motor under constant horsepower output.

In addition to the benefits of an AC VFD for improving the ability of the motor to accelerate the load, the increased torque per ampere reduces the system voltage drop and flicker associated with direct on line motor staring. Compared to other Cement Plant applications such as Vertical Roller mills, SAG or Ball Mills and ID and FD Fans the kiln drive is a relatively small load. The Kiln drive's power factor throughout the speed range is less important in the big picture than it would be for larger drives.

Most motors are designed today with higher ground wall insulation to account for the proliferation of the variable frequency drives. However, not all of the motor manufacturers or cable suppliers are aware of the higher insulation requirements for VFD applications. Therefore, some drive manufacturers also recommend motor lead filters to be installed at the motor terminations in the field. This is an added degree of safety and must be included by the drive supplier.

Other drive manufacturers will install voltage filters in the output of their drives as a standard feature and will claim that their drives do not impose restrictions on the motor feeder length. This is a more desirable option, which is usually available only for the larger drives.

More recent MV drive designs do not require any additional ground wall or turn to turn motor insulation. Each design, however, must be considered on its own merits to determine the most effective solution for the particular drive application.

A. Drive Train Efficiency

The overall efficiency of the kiln drive train is the product of the efficiencies of each component:

$$N = \eta xfmr \times \eta vfd \times \eta\ motor \times \eta\ gearbox$$

It is necessary to Include control power, fan power for drive & separate ventilation for motor, heat exchanger pumps & fans in the efficiency calculations.

DC Drives have an inherent efficiency advantage over most AC drives since they have only a rectifier bridge whereas an AC drives also have inverter bridges, with their associated energy losses. Transformer-less AC drives recoup most of those losses through elimination of the transformer.

Another consideration is the economics of high efficiency motors. Through selection of materials (i.e. grade of electrical steel, copper vs. aluminum rotors bars), minimization of friction and windage and good basic design practices it is possible to realize relatively short payback periods on premium efficiency motors.

B. Power quality issues

All drives generate harmonics to line and load. In addition to the fundamental current, the harmonic currents from the drive also circulate in the windings and iron of the motor and transformer and give rise to additional heating.

The amount of harmonic current generated is a function of the design topology of the drive and switching method of the inverter. A drive designed for six pulse operation will deliver a higher (RMS) harmonic current than a twelve or higher pulse drive. Characteristic harmonic amplitudes are inversely proportional to the harmonic number.

DC Drives are usually available in 6 or 12 pulse systems. The 12 pulse system mitigates line side harmonics by phase shifting the secondary windings in a star / delta configuration to eliminate the 5th and 7th harmonics. AC VFDs are available in several rectifier styles including the following:

6 Pulse (27% THD can be accommodated on large system)
12 Pulse (12% THD), major harmonics are 12h ± 1
18 Pulse (6% THD), major harmonics are 18h ± 1
24, 30, or 36 Pulse (< 5% THD)
Active Front End (< 5% THD)

The active front end configuration uses a PWM switching pattern to electronically eliminate the harmonics, cleaning up distortion at the source of the problem. Tuned filters can also be used to reduce harmonics.

The usual specification requirement for kiln drive harmonics is to comply with the current and voltage harmonic distortion limits detailed in IEEE 519-1992. This standard provides a sliding scale depending on the ratio of short circuit current to load current (Isc/Iload) allowing a higher level of harmonic distortion when the system is large compared to the VFD. Harmonic performance is predicted using harmonic analysis software, and the actual in service result can be measured directly. In order to perform the analysis a completely dimensioned system single line diagram is required, showing all sources of harmonic distortion, linear loads and system impedances. The analysis must take into account the possibility of resonances, especially where power factor correction capacitors are applied, either lumped on the power system or applied directly to the terminals of individual constant speed motors.

Control power quality is important on critical applications in the kiln area. Usual practice is to provide low voltage control power for the drive through a system UPS or a dedicated UPS mounted in the VFD control compartment. This provides noise immunity for the control power and also enables control power dip ride through.

As with all electronics it is necessary to adhere to the manufacturer’s recommended grounding practices to ensure that transients are not coupled into the control through ground loops or stray capacitance.

C. Torque Pulsations

Careful consideration should be paid to the mechanical configuration in order to avoid vibration. The implementation of variable speed control with a complex mechanical drive train increases the risk of mechanical vibrations. With kilns there is a long drive train for the electrical solutions and these should be modeled in torsional and lateral models for the rotating components. Evaluating natural frequencies and sources of pulsations or possible affects of imbalance will determine the speed points where critical will exist. These can be modified with a change in component stiffness, inertia or damping (couplings being the usual point of change) to move these critical out of the operating speed range. If not possible, skip speeds can be implemented in the control to avoid these critical.

Lateral vibrations are readily observed by direct measurement on the shafts and bearing housings using displacement, velocity or acceleration probes. Minimizing lateral vibration can prolong equipment life, and is accomplished by balancing, alignment and ensuring the tightness of all fasteners. Predictive maintenance can indicate when bearings need to be replaced in order to prevent unplanned outages.

Torsional vibrations are extremely difficult to detect unless special instrumentation is applied (e.g. tele-metered strain gauges), usually when a torsional resonance is suspected after a failure. If a situation arises wherein the strain in a shaft or gear tooth exceeds 2-4% of the material’s yield strength on a repetitive basis a sudden and catastrophic failure may occur due to metal fatigue. For this reason a torsional analysis of the complete drive train should be performed at the design stage.

When risks are increased by a wide speed range, it is good practice to perform a torsional analysis for all constant torque and geared adjustable speed applications. This consists of a mathematical analysis of mass elastic data of the rotating system.

A wide speed range increases the likelihood of running on a resonance for prolonged time. Fatigue failures can result from exposure to 10xe8 cycles exceeding 4% of the Ultimate Tensile Strength (UTS) of the material used for any component. Usual practice is to analyze shafts, gears, and couplings. Tachometer couplings can be especially vulnerable since they are typically small diameters.

To minimize or avoid exciting resonances of non fundamental frequencies it is helpful to select a VFD with low Current THD on the motor output waveform. Lateral vibrations can be mitigated by balance, alignment, and natural frequency analysis should be carried out at the design stage.

Modern AC drive control can include tools to dampen any control system interaction with mechanical vibrations, sometimes adding damping to reduce mechanically induced vibrations. Hydraulic drives lack the sources for excitation of vibrations and provide damping, generally representing a lower vibration risk. For AC induction motors, higher slip machines will help with control and damping of any torsional vibrations. Good balancing and alignment specifications will help with torsional and lateral vibration issues.

D. Maintenance

Proper maintenance of the kiln drive system components is necessary to achieve predicted availability and equipment life. A preventative or maintenance program will include periodic cleaning & dust control, lubrication and connection checks as well as proper balancing & alignment.

A predictive maintenance program can include vibration analysis and thermal scanning. The advantage of predictive maintenance lies in minimizing maintenance costs while still avoiding outages by performing maintenance when its necessity is indicated by a physical change.

Diagnostic and troubleshooting aids are a necessity in a successful kiln drive installation. Modern drive systems are equipped with configurable alarm and fault points, and often feature programmable trend buffers with the ability to store a record of multiple operating variables both pre and post trigger.

As a precaution against prolonged outages a stock of recommended spare parts and consumables should be maintained. Equipment should be selected keeping in mind the ease of use, especially mean time to repair.

E. Investment Cost.

The total life cycle cost of a kiln drive system includes the costs of acquisition, installation, maintenance, repair, and power. Considering a 20 to 30 year design life, paying a premium for high efficiency is usually a wise investment. The Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) are key metrics for equipment selection. MTTF can be maximized by minimizing the component count, and by selecting components with high FIT rates (Failure in Time). MTTR is affected mostly by equipment design and ease of troubleshooting.

CURRENT TRENDS

Clinker production capacities from single rotary kiln and preheater / calciner have increased over the years and the trend will continue into the future. Most recently commissioned kilns boast clinker production capacities of 12,000MTD each. The drive train is powered by equivalent 2 x 2500hp twin drives and girth gear arrangement. Other installations are currently at the design stages.

From the mechanical design point of view the challenge with the larger diameter kiln is to ensure that the refractory stays securely in place. For the drive designers the challenges come in terms of reduced harmonics, increased power factor over the speed range, controlled torque, reduced torsional vibrations and increased reliability. The new generation of active front end and multi-pulse medium voltage drives seem to be well adapted to meet the new requirements at this power range.

Other possible configurations allow a single rectifier to be used to supply a common DC bus for dual or quadruple inverters powering two or four motors, for dual pinion or friction drives, thus reducing the number of electrical components.

A more recent design of the CSI drive allows smaller motors to be used with the drive without an input isolation transformer, by eliminating the neutral offset normally handled by the transformer.

CONCLUSIONS

Differences exist in each category for the kiln drive solutions covered in this paper and each must be considered on individual merits. Performance and efficiencies have increased in the transition from hydraulic to DC to AC with each having unique characteristics suitable to particular process conditions. Drive pricing has decreased with advances in manufacturing, economies of scale and has increased with complexity and performance enhancements. Today's processes demand better control over product quality and production and kiln drive solutions have a significant impact on both.

	Hydraulic	DC Drive	AC VSI Drive	AC CSI Drive
Performance	+	-	+	+
Flexibility, ease of integration	-	-	+	+
Reliability	-	+	+	+
Maintenance	-	-	+	+
Complexity	+	+	-	+
Efficiency, operating costs	-	+	+	+
Power Quality	+	-	+	+
Life Cycle Costs	-	-	+	+

Figure 29 Kiln drive comparison table

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