EXPERIENCE
WITH SYNCHRONOUS
AND
SLIP RING INDUCTION MOTORS
DRIVING CEMENT MILLS

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1.0 Abstract

The ball mill is the largest single power consumer in a cement plant. In recent applications 11,500 hp and larger drives have been installed.

It is essential that with such large loads all aspects of the application will be subject to evaluations that reflect the best available technology and operating practices.

This paper examines the factors, which influence the selection process: the type of load and its characteristics, the requirements of the motor and power system.

Recent experiences with operating synchronous and slip ring induction motors are discussed.

2.0 Introduction

In the process for selection of a suitable motor, there are several issues to consider that for the purpose of analysis can be grouped into two distinctive categories.

In the first category is the technical analysis, which is based on engineering considerations that evaluate the merits of the installation of either a synchronous or of a slip ring induction motor.

In the second category is the economical analysis that follows closely the results of the technical evaluation with emphasis on the original investment cost and the cost of operating and maintaining the equipment over its useful life span, which is estimated as thirty years.

Among the technical issues the first should be identifying the torque requirements and initial power system limitations. The choice of motor design will largely depend on these requirements.

The other issues relate to electrical energy savings. With the cement mill being the largest single power consumer in the plant, the choice of motor and drive will directly influence these savings, which can be significant.

Several cement mill installations in operation today are discussed. The relative trouble free operation experienced at these installations since start up, is a tribute to the engineers and designers who have contributed to the design of these installations.

3.0 Ball mill and motor

Traditional ball mills exert high starting torque characteristics. This in combination with a material charge whose behavior is difficult to control have resulted with many applications where motors had to be oversized in order to accommodate these characteristics.

More recently however, the application of mill load level control has added a degree of consistency to the charge and also has increased productivity. (Reference 1)

3.1 Ball mill load characteristics
The torque speed characteristic of a typical ball mill is shown in Figure 1.

On this curve there are three distinctive points of interest, which uniquely characterize the ball mill operation.

**a)** The breakaway from rest is identified as the region on the graph requiring 40% to 70% of nominal torque from rest to approximately 20% speed.

**b)** Cascading the charge region is identified when the load is rotated through 50°-60° at 20% to 80% of nominal speed and requires 110% to 140% of full load torque. The higher value torque will be required in the case of a more compacted charge.

**c)** Continuous operating region is when the mill has reached its full speed and torque requirements.

The magnitude of all three points in Figure 1 should be considered typical. Cascading point will vary depending on the mill supplier.

The torque speed characteristic curve for a recent ball mill is shown in Figure 2. Mill suppliers define the starting torque at an angular displacement of the charge. The cascading point of this mill is at angle of 60°. This implies that a motor connected through a 60:1 reduction be capable of transferring 120% of its rated full load torque when it has turned through 10 revolutions.

Practically the value of the cascading torque is influenced by the fluidity of the charge, which is lowest after a prolonged shutdown.

A good operating practice to ensure a lower start up torque would be to have a low level of material in the mill at start up or to inch the mill one or two revolutions to ensure the charge is loosened.
3.2 Motor torque defined

During acceleration to full speed a typical motor develops a torque characteristic that undergoes various changes in magnitude in relation to speed. The transition points along the torque speed curve are illustrated in Figure 3.

![Figure 3 - Typical torque speed curve for an induction motor](image)

- **a)** Starting or locked rotor torque is defined as the minimum torque necessary to free or break away the load and motor. The magnitude of this torque is proportional to the square of the stator terminal voltage.

- **b)** Accelerating or pull-up torque is the torque developed by the motor at any speed during the acceleration period. This torque must be always higher than the torque required by the load at that speed.

- **c)** Rated torque is the design nameplate torque developed by the motor.

In the case of the induction motor it is the rated torque at rated slip. The slip of the typical induction motor is less than 2% at full load.

For a synchronous motor the rated torque is the synchronous torque at zero slip. The torque which the motor develops as an induction motor at the speed (97%-100% at which it can pull the load into synchronism is called the pull-in torque. At this speed DC excitation is applied to lock the rotor into synchronism.

d) Maximum or breakdown torque for an induction motor is the maximum torque developed by the motor just before the critical slip occurs and the motor pulls out of step. This torque must correspond to the maximum torque specified by the mill supplier. For the induction motor the magnitude of this torque is a square function of the stator terminal voltage.

The maximum or pullout torque for the synchronous motor is the maximum steady state torque that the motor develops for one minute before it pulls out of step. For the synchronous motor the pull out torque is a function of the available excitation on the rotor field and the stator terminal voltage.

e) The reluctance torque of synchronous motors is the harmonic torque component developed as a result of the non-uniform magnetic flux density in the air gap of salient pole machines. The magnitude of this torque component varies in strength as the poles of the rotor and stator change relative positions. Although this characteristic is not usually identified on the data sheets,
its contribution influences the values of both pull-in and pullout torque.

The torque speed characteristic of a 4100 hp 900rpm synchronous motor is shown in Figure 4. The curves are plotted for three values of stator terminal voltage.

3.3 Differentiating Characteristics

The stator winding of a synchronous motor is no different than the stator windings of an induction motor. However, because of its operating principle the rotor of the synchronous motor contains an isolated and independent electrical circuit which theoretically cannot self start.

Upon start and until the motor comes up to almost synchronous speed, the motor operates on the same principle as the induction motor.

From stand still the torque is produced by transformer action in the air gap of the machine, through the interaction of the rotating magnetic fields induced by the stator and those induced by the starting winding.

The operating characteristic of the induction motor is such that the internal torque developed by the machine is a function of rotor resistance and slip at which it occurs.

A conventional induction motor with a squirrel cage winding and a predetermined rotor resistance is essentially a constant speed machine with a few percentages drop in speed from no load to full load.

To briefly illustrate this concept it is best to refer to the THEVENIN equivalent electrical circuit of the induction motor shown in Figure 5(a) and 5(b), (Ref.3).

The relationship between internal power and torque for an induction motor is a function given by the equation:

\[
T = \frac{P}{(1-s)\omega_s} \tag{1}
\]

\(P\) = internal power
\(T\) = internal torque
\(\omega_s\) = synchronous angular velocity of the rotor
\((4\Pi f/p)\)
For a three phase electrical circuit with a terminal voltage \( V_{1a} \), the torque and power relationship in equation (1) is rewritten using the electrical circuit components in Figure 5(a) as following:

\[
T = K \left( \frac{r_2}{s} \right) \left[ \left( \frac{R_1 + r_2}{s} \right)^2 + \left( \frac{X_1 + x_2}{s} \right)^2 \right] \tag{2}
\]

\[
K = \left( \frac{3V_{1a}^2}{\omega s} \right)
\]

\( R_1 \) = stator resistance  
\( X_1 \) = stator reactance  
\( r_2 \) = rotor resistance  
\( x_2 \) = rotor reactance  
\( s \) = slip

Normalizing both sides of the equation, the internal torque is at maximum when the power delivered to impedance \( r_2/s \) is at maximum.

\[
r_2/s_{\text{max}} = \left[ \frac{R_1^2 + \left( X_1 + x_2 \right)^2}{s} \right]^{1/2} \tag{3}
\]

This equation illustrates the relationship between the value of the starting torque, rotor resistance and slip. The slip ring motor with a varying external resistance can develop the maximum torque at any speed Figures (8) and (9). For the synchronous motor this is a function of the design of the starting winding and salient pole winding resistance.

### 3.4 Synchronous motor

The difference in operating principles between the synchronous and the induction motor rests with the design of the rotor electrical circuit.

The rotor of the synchronous motor contains a second separate electrical circuit, which operates independently of the starting winding. This circuit is called the field winding and imparts to the synchronous motor two operating characteristics unattainable by an induction motor: good operating power factor and constant, exact speed.

The field circuit of the rotor is made up of copper wound pole pieces mounted on a spider around the shaft (Figure 6). This is the preferred design for motoring action primarily because of the reluctance torque contribution to reduce the power angle at which a given torque is developed. With a smaller power angle the machine is more stable. A consequence of this design is that the air gap between the rotor and stator of a salient pole machine is two to three times as large as the air gap of an induction machine. The design of the air gap is critical for producing uniform magnetic flux densities and reduced torque pulsations during acceleration. Torque pulsations occur due to the difference between the reactances of the direct and quadratic axis of the motor.

![Figure 6 - Cross section of a synchronous motor](image)

### 3.5 Slip ring induction motor

Figure 7 illustrates a cross section of a slip ring induction motor.
The operating performance of the induction motor is largely determined by the rotor resistance, the air gap between the stator and rotor and the shape of the teeth and slots and the rotor and stator. The most important parameter is the rotor resistance. The rotor resistance determines the starting current, the load efficiency, the speed regulation and the starting torque. The shape of the teeth and slots affects the reactance of the rotor circuit, which in turn influences the maximum torque and starting current capabilities of the motor.

In contrast to the synchronous motor, the rotor of the slip ring induction motor is cylindrical in shape and has the winding bars (field) uniformly distributed around the circumference of the rotor.

The slip ring induction motor is essentially an induction motor with the three rotor circuit phases connected to slip rings mounted on the rotor shaft. The internal rotor circuit resistance is kept very low to minimize the copper losses. By connecting an external series resistance into the rotor circuit, the slip at which the maximum torque develops can be accurately controlled. A typical torque speed curve for the slip ring induction motor is shown in Figure 8.

The magnitude of the maximum torque is proportional to $V^2$ and is not affected since it is a function only of the rotor circuit reactance.

The foregoing comments essentially describe the main differentiating characteristics between the two motors.

3.6 Torque, efficiency and power factor.

Torque and efficiency ratings of motors used in the cement industry are listed in this section. These are known as “standard ratings”. However, in reality there is nothing standard about the large horsepower motors used with cement mills and all applications must be uniquely engineered.

3.6.1 Synchronous motors

The torque ratings of synchronous motors designed to drive ball mills may be classified as low to intermediate torque ranges (normal ranges), and high torque.

For ball mills applications NEMA identifies the minimum net torque requirements as following:

a) Locked rotor torque (LRT) = 140% of rated torque
b) Pull in torque (PIT) = 110% of rated torque
c) Pull out torque (POT) = 175% (0.8 pf) = 150% (1.0 pf)

For the applications under considerations, the motors are designed with normal torque (standard) range and are started de-coupled from the drive.
a) LRT = 40%-80%
b) PUT = 30%-50%
c) POT = 175%

The inrush currents for normal ball mill motors are typically between 4.0 to 4.5 per unit of full load current. In contrast, the inrush current for the high torque motor can be 6 to 8 per unit of full load current. In some applications the high inrush can be of great concern, especially when we deal with weak power distribution systems.

A motor exerting a high torque is more expensive to build than a motor with normal exerting torque. Motors rated 1200 rpm can be built also with low inrush currents. In this case a solid pole construction is employed.

Typical efficiencies of ball mill motors are between 96.5% to 96.8% at full load. In general, for the higher rated torque machines these ratings are a few fractions lower.

Synchronous motors can be built with unity or leading power factor, where as a lagging power factor is an inherent characteristic of the induction motor.

The synchronous motor with a 0.8 leading power factor and 175% pull out torque is the preferred choice in the cement industry.

3.6.2 Slip ring induction motor

The slip ring induction motors like the conventional squirrel cage motors are designed with high breakdown torque. For the squirrel cage motor the maximum torque occurs at a fixed slip determined by the rotor resistance. For the slip ring induction motor through control of the external resistance the maximum torque can occur at any speed (Figures 8 and 9).

![Image of torque characteristics](image)

Figure 8 - Slip ring induction motor torque as a function of external rotor resistance

The torque characteristics are as following:

a) Locked rotor torque (LRT) = 200% of full load torque
b) The pull up torque (PUT) is a function of the rotor resistance, which remains resistive throughout the acceleration period.
c) Breakdown torque (BDT) = 250% of full load torque
d) Starting current = 200% of full load current
e) Efficiency = 93.7% to 94.5% at full load
f) Full load speed 98.7% of rated speed. (1.3 to 2 percent slip)
g) Full load power factor 81% to 86%

The main advantages can be identified as the high starting torque and relatively low starting current. These are important advantages when applied to weak power distribution systems. Another advantage is that this motor can be coupled directly to the gearbox without the need of a clutch or a fluid coupling. Although this practice is very common, transient torque protection must be provided during faults to minimize impact on the gearbox.
The main disadvantages are the lower power factor and lower operating efficiency especially at the lower speed range.

3.6 Motor torque pulsations

A detailed analysis of the origins and effects of torque pulsations are found in references (2) and (5).

Both types of motor will experience one form or another of torque pulsations during acceleration. If the electrical torque pulsations are neglected, they can excite mechanical natural frequencies in the drive train. At these frequencies, the combined effect of torque pulsations may build up to cause substantial damage to the drive train. Gearboxes are notorious for having as many critical frequencies as there are gears.

The synchronous motors are more prone to torque pulsations. For these reasons as well as for preventing further damage to the drive train because of torque transients caused by power system disturbances, the best practice would be to install an air clutch or a fluid coupling between the motor and gear box. These devices act to limit the effects of the power system under disturbance conditions.

In conjunction with the installation of these devices, a torsional analysis study for the drive train including the motor must be performed.

All motor manufacturers have an interest at stake in the performance of their motor and therefore, must include a complete analysis of the drive train with their quotations.

3.7 Construction and ventilation requirements

The cement mill motors located outdoors are supplied with weather protected Type 2 enclosures, Figure 10, or are totally enclosed with air tube over frame heat exchanger, Figure 11.

Water-cooled secondary heat exchangers are high maintenance items and should be avoided if possible.

The rotor of the synchronous motor by virtue of its design with larger air gaps and shorter core length can be more effectively ventilated than the rotor of the slip ring motor. This is an important consideration when operating in a dusty environment such as it is often encountered in a cement plant.

The enclosures of ball mill motors are more effectively cooled when the
designers provide ventilation from opposite ends of the shaft. However, not all suppliers make available this feature and this can affect the hot spot temperature of the motor and produce an inferior design.

The frames of the motors used to drive ball mills are designed with bracket or pedestal mounted bearings. The motor construction with pedestal bearings is more robust and usually is designed with a larger footprint. These frames are available for 4500 hp and larger horsepower ratings.

The bearings used with the mill motors are of the split sleeve type, which can be self-lubricated or flood oil lubricated. One important issue with flood lubricated bearings is the oil reservoir must be large enough to contain an adequate amount of oil to ensure lubrication in the event of a failure of the lubrication pump. Oil rings will usually provide sufficient lubrication to allow the motor to coast to rest.

The motor manufacturer must ensure that there is adequate lubrication for the sleeve bearings when an inching motor is employed to spot the mill while the main motor remains coupled to the drive train. This can be achieved with high-pressure lift pumps at the bearings.

Another important issue with sleeve bearings is that by virtue of design, they can accommodate only limited axial thrust loading. This fact is often neglected particularly with shaft mounted couplings. To overcome this limitation, air clutches and mechanical couplings can be supplied with limited axial movement whereas fluid couplings can be specified with thrust bearings.

Thrust collars can also be included with the sleeve bearings.

The exciter of the synchronous motor can be mounted inboard or outboard the bearing housing. For low speed motors (< 450 rpm) the exciter is mounted inboard. For higher speed motors (> 514 rpm) the exciter is mounted outboard.

For the slip ring motors the collector rings are also separately enclosed and ventilated to prevent carbon dust contamination of the motor windings (Figure 7). As a result, the design of the shaft and collectors becomes more complicated and demands a higher cost.

4.0 Starting methods
4.1 Synchronous motor

The synchronous motors used with ball mills are of standard low torque ratings and because torsional considerations, and also depending on the horsepower and speed ratings, are coupled to the load through air clutches or fluid couplings. With this arrangement the motor can be started uncoupled from the load which reduces starting torque design requirements and the cost of the motor.

A typical stator and rotor electrical circuit diagram is shown in Figure 12.

Upon starting, the field discharge resistance is in parallel with the field winding. This is necessary to prevent damage to the insulation of the field windings from the induced voltages, which are generated during acceleration to full speed. With low torque motors the field discharge is very small and is mounted on the rotating exciter.

When alternating current is applied to the stator the motor performs as an induction motor. The field winding is not in the circuit until the rotor has reached 97% of synchronous speed. The synchronizing control senses the correct speed of the rotor and gates the SCR to apply dc power to the field.

The application of DC excitation current produces a polarized north-south magnetic field, which wants to align with the rotating south-north poles of the stator. This action overcomes the slip and pulls the rotor into step with the stator.

![Figure 12 - Synchronous motor electrical circuit.](image)

Excitation power and control

The brush-less exciter Figure 12 is essentially an alternator or rotating rectifier with a stationary field and a rotating armature and rectifier assembly mounted on the shaft of the motor. The alternator field requires only a few amperes of direct current to provide the necessary excitation power and maintain regulation and leading power factor of the loaded machine. The operation is electronically controlled and the equipment is relatively maintenance free.

The synchronizing circuitry provided with the rotary exciter is factory set and does not require any subsequent adjustment. However, if the electronic components are replaced for whatever reasons, then a complete setup procedure must be followed as per manufacturer’s instruction. When spare parts are ordered for a particular machine, it is advisable to request the manufacturer to have all circuit boards pre-tested, set up and name tagged.
4.2 Slip ring induction motor
The rotor circuit windings are connected to three collector rings mounted on the rotor shaft. Carbon brushes ride on these collector rings and transfer the secondary current of the rotor to the external resistance Figures 7,9 and 13.

As indicated earlier, the slip at maximum torque is proportional to the value of the rotor resistance and applied stator terminal voltage. This implies that in order to achieve maximum torque at stand still the motor must be started with maximum resistance inserted into the circuit. With the high secondary rotor resistance in the circuit at start, the inrush current from the power source is also reduced.

There are two types of secondary resistance control.

a) Liquid rheostat
b) Multiple banks of resistors

The liquid rheostat is the preferred method for starting large loads, primarily because it offers step-less transition through the acceleration period. This is an advantage, particularly when torque pulsations are a concern. The starting characteristics of a motor with step-less and discrete control are illustrated in Figure 9.

A liquid rheostat may be used to start or spot more than one motor. Starting and spotting can be designed for manual or automatic operation. A separate shorting contactor must be used with each motor.

The grid resistance secondary circuit controller is normally used with lower horsepower rated motors. The resistor banks are arranged to provide stepping increments in speed by using shorting contactor to cut out the external resistance of rotor circuit incrementally at predetermined time intervals.

5.0 Power system considerations

5.1 Utility power supply

Electric utility companies set limits on current inrush and voltage drop produced when starting large motors. These limits are necessary because they impact not only on other consumers in the plant but also on other utility customers. Before a drive can be selected these limitations must be defined. The foregoing applies to new as well as to existing facilities, which require upgrading.

A power system study must be completed to ensure the correct load flow and that the short circuit duty of existing equipment is not exceeded.
5.2 Motor voltage

The voltage distribution levels for existing cement plants are 4.16 kV and 6.9 kV, typically.

It has become increasingly evident to designers and suppliers that these voltage distribution levels are no longer adequate when drive applications require motors having 5000 hp and larger ratings.

An argument can be made that for new installations, motors over 5000 hp should be supplied from 6.9 kV or 13.8 kV distribution. This practice has been adopted in other heavy-duty industries with great success. The investment cost for equipment and installation are lower. A higher voltage level usually implies a stronger power source that will allow larger motors to start directly across the line without adversely affecting other consumers in the plant.

From the foregoing discussion, the factors affecting the suitability of the motors can be summarized as following:

a) Voltage drop
   Should be limited to 10% or less at other motor terminals. Most motors are designed to tolerate this drop.

b) Starting torque
   A 10% reduction of the nameplate voltage will limit the torque to 81% of full voltage rating.

This is a concern with synchronous motors, which are normally designed to provide 60%–80% of rated torque on starting.

A voltage drop of 10% will reduce their starting torque to 48%–65% of full voltage torque respectively, which in some cases may not be enough to accelerate the load. However, when synchronous motors start de-coupled from the load, the voltage drop at starting is not as much of a concern.

Although an argument can be made that in general all motors will start with a larger voltage drop, the best practice is to start quickly and bring the motor up to full speed in the shortest possible time.

5.3 Power factor

Utilities impose heavy penalties for poor power factor. Cement plant power distributions are designed to ensure that the average power factor of the plant is maintained above the 90% lagging as stipulated in most power utilities contracts.

From power factor and regulation point of view the synchronous motor provides superior dynamic performance at leading power factor, which compensates the remainder of the plant.

The slip ring induction motor, in contrast, can be compensated only to 92% to 95% lagging power factor. Power factor compensation capacitors, switchgear and protection equipment must be installed with the motor. Additional capacitors must be installed to correct the power factor for the remaining loads. The plant load profile must also be evaluated in order to ascertain effects from harmonic sources and switching circuits.
Another concern exists with brushes and capacitor banks. The brush holder must maintain a positive contact with the collector ring in order to prevent the rotor circuit from becoming unbalanced. When the rotor circuit becomes unbalanced negative sequence torque pulsations are generated, which in the presence of power factor capacitors can build up and become destructive.

6.0 Mill arrangement

6.1 Drive train arrangement

The choice for mill drive arrangement depends on the mill size, mill design and supplier. The supplier’s design philosophy is important since it determines the torque requirements of the mill. Some suppliers design their mills with high torque and high speed requirements and can be driven only with slip ring motors.

The following describe the most popular mill drive arrangements (Figures 14 and 15).

a) The center drive is most reliable and requires little maintenance. It is also the most expensive because of the large gearbox with multiple reductions in front of the motor. It has also the largest overall footprint.

b) The dual pinion gear box and girth gear drive uses a smaller gearbox and a girth (ring) gear around the circumference of the mill. Maintaining alignment of the girth gear and pinion is usually the concern with this arrangement.

c) The single pinion gear and girth gear drive requires a low-speed motor and air clutch. This arrangement is universally used in mineral processing with lower capacity mills.

The motors used with these arrangements have speed ranges from 200 to 1200 rpm.

6.1 Drive train efficiency

An argument can be made that all the drive train components should be considered in the evaluation, since they all draw energy from the same source.

The energy dissipated by the drive should include the contribution from the following components:

Synchronous motor

- motor at rated load and speed
- excitation package
- air clutch and air supply source or fluid coupling and cooling
- gear reducer

Slip ring induction motor

- motor at rated load and speed
- brush gear loss
- rheostat and cooling
- gear reducer
7.0 Application experiences

7.1 Ball mill drives with synchronous motors. (Tecoman, Ramos Arizpe)

In three separate installations synchronous motors were used to drive mills with center and girth COMBIFLEX gearbox arrangements. In prior installations only slip ring induction motors were considered because of the starting torque requirements. The operating power factor and voltage drop restrictions imposed by the local utility were the other limitations.

a) Girth gear COMBIFLEX gear drive - 7250 hp, 1200 rpm, 4.0 kV motor. (Figures 14 and 16)

b) Center mill drive - 6032 hp, 514 rpm, 4.0 kV motor. (Fig. 15 and 17)

The engineering feasibility study recommended the use of low torque synchronous motors in combination with an air clutch or a drain-able type fluid coupling. Those were the economical choices for these applications.

Before a decision could be reached several technical issues had to be resolved. There was concern with the rating of the air clutch and the slip loss of the fluid coupling.

For the center mill drive modifications had been made to a standard design air clutch to increase its holding power.
This was necessary because the standard ratings available from the manufacturers were designed to perform reliably only up to 3500 hp, 514 rpm.

For the COMBIFLEX drive a drain-able type fluid coupling was chosen. This type of coupling has been used in similar applications and proved to be reliable. Zero slip or lockable fluid couplings were not considered at the time.

One important issue with some fluid couplings is the axial thrust exerted on the sleeve bearings. Unknown to the supplier, the drain-able fluid coupling exerted an axial thrust on the bearings of approximately 3000lbf on start-up and it maintained approximately 880lbf of thrust during running.

As a result, the bearings were damaged and were replaced with higher torque rated bearings. The bearing housing had to be enlarged to accommodate the new set of bearings and to provide larger end float clearances, Figures 18.

The disadvantage of this coupling is that the slip loss is approximately 2% at full load and as a result, it diminishes the efficiency gained from using a synchronous motor. Another issue is the requirement for a water-cooled heat exchanger to dissipate the slip losses. In colder climates cooling water can become a maintenance headache.

The voltage drop issue was addressed by specifying to the motor manufacturer to design the starting winding of the synchronous motors to limit the voltage drop to less than 10%. This eliminated the requirement for reduced voltage starters.

The steady state results of the power system study for the 6050hp motor are illustrated in Figures 19 and 20. In order to maintain the plant power factor over 90% with the slip ring motor drive, the size of the power factor correction capacitors had to be 6300 kVAR. This rating includes the requirement for correction at the motor to 95% lagging and an equivalent compensation for the plant to provide the same power factor as the contribution from the synchronous motor.

Table 1 illustrates the investment cost alternatives for the 6050 hp, 514 rpm ball mill. The figures shown are $ x 1000.

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<th>Synchronous motor</th>
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</table>

Figure 18 - Bearing saddle of 7250 hp motor machined in the field.
The 6050 hp synchronous motor and clutch combination had approximately 30% investment cost advantage over the installation with the slip ring motor. Another advantage with this combination drive is the 2% higher efficiency of the synchronous motor.

A similar evaluation was completed for the 7250 hp, 1200 rpm COMBIFLEX ball mill drive, but using a synchronous motor with a drain-able fluid coupling. The investment cost was 21% lower for this drive combination. The energy savings was the same because of the approximately 2% slip loss of the fluid coupling.

Although the energy savings appear insignificant, they can add up to considerable amount over the life of the equipment.

The above installations have been in operation for several years and have performed satisfactorily with only minor maintenance issues. One initial problem was the premature wear of the modified air clutch. The solution was to replace the liners with a higher temperature material.

A more serious problem was the requirement for additional ventilation for the 6050 hp motor. The manufacturer designed the motor with a WP2 enclosure with center end ventilation, which was not sufficient, Figure 21. The intake louvers had to be enlarged and additional forced fan-cooled equipment was installed to remedy the problem. This motor has operated without problems since that time.
7.2 Ball mill with slip ring induction motor.

A recent feasibility study for a new cement grinding facility in an existing plant, recommended a 6700 hp, 900 rpm, 6.6 kV motor for the cement mill drive.

The existing power distribution had a low fault level and could not tolerate direct on line start of a synchronous motor. The feasibility study recommended the use a slip ring induction motor.

Table 2 illustrates the investment cost alternatives for the 6700 hp, 900 rpm ball mill drive. Figures are $x1000.

<table>
<thead>
<tr>
<th></th>
<th>Slip ring motor 2.0xFLC</th>
<th>Sync.motor 2.5xFLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor and rheostat Capacitor bank</td>
<td>372</td>
<td>536</td>
</tr>
<tr>
<td>Switchgear motor</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>Switchgear capacitor</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
<td>631</td>
<td>841</td>
</tr>
<tr>
<td>Total</td>
<td>746</td>
<td>871</td>
</tr>
</tbody>
</table>

In this application the use of a 2.5 per unit low inrush current, 900rpm synchronous motor with a lockable fluid coupling was not as economical as using a 2.0 per unit slip ring induction motor. Power system constrains were the determining factors in this application.

8.0 Maintenance and operational issues

8.1 Synchronous motors and exciters

The synchronous motors are the choice of drives in many applications in the Cement Industry. They have proven to perform reliably in many installations over long periods of time. However, some problems occur, from time to time.

One problem encountered with synchronous motors in a recent installation is the inboard mounting of the brush-less exciter.

In two separate applications with synchronous motors supplied by the same manufacturer, the exciter became loose, rotated about the motor shaft and damaged the rectifier and control circuit assemblies.

We attributed these two occurrences to the motor manufacturer’s lack of experience with the mill operation. In this application in order to keep the frame dimensions small, the manufacturer designed the exciter with a large diameter and narrow width and attached it to shaft with rivets, Figure 22.

Subsequent modifications included the installation of additional fastening pins and Allen screws as well as a keyway. These modifications did not help as it can be seen from figures 23 and 24.
We learned from this experience that the inertia of the exciter and fastening to the motor shaft must be carefully considered for each application. Another option would be outboard mounted exciter.

Recently an existing ball mill installation experienced problems with the original liquid rheostats. The mill arrangement is a dual pinion girth gear drive and uses 2×3000 hp, 900 rpm, 4 kV slip ring induction motors. Improper timing sequence and a high electrolyte concentration were causing considerable slip losses, which had to be dissipated internally in the tank. As a result, the solution evaporated over time. To compound the problems, the original supplier no longer supported the equipment.

Two smaller rated rheostats had to be purchased to replace the original larger rated single unit.

One important design consideration when starting both motors at the same time is the value of the slip compensation resistor. The purpose of this resistor is to compensate for small variations in the internal resistance of the rotor to ensure that torque is developed at the same slip.

8.2 Slip ring motors and liquid rheostat

Slip ring induction motors have performed reliably in many applications, which remain in operation today. Some of the frequent problems encountered with their operation relate to liquid rheostat and secondary controls.
8.2.2 Slip ring motor protection

In an older installation with two 5000 hp slip ring motors, the carbon from the brushes built-up and contaminated the collector wire leads which flashed to ground. The rotor did not contain a ground-fault circuit protection relay, device 64, Figure 25, and kept running. A passerby noticed the sparks and the smoke coming out of the motor, and alarmed the control room to stop the motor. Without his intervention, probably the motor would have kept on running to destruction. A separately ventilated enclosure for the slip rings would have prevented the accumulation of carbon dust.

Following the ground fault incident described above, the protection of the rheostat was enhanced with the addition of a ground fault protection relay (Device 64).

Another problem, which often happens with liquid rheostats is that the acceleration timing gets out of tune and the motor can run below base speed. Depending on the type of controller, the motor and liquid rheostat can overheat or the shorting contactor can be applied prematurely.

In order to avoid these types of occurrences, a motor speed reference signal may be used to interlock with the protection circuit.

8.3 Air clutch

The air is normally supplied through the hallow shaft of the rotor, opposite the drive end, Figure 14. This feature must be specified to the motor manufacturer at bid time because it requires a special manufacturing process. The rotary seal used to connect the air supply must be of the highest quality to ensure reliable operation.

The air clutch can become a high cost maintenance item if the quality of the air supply is not adequate or improper timing sequence is applied to the clutch. Either one will prematurely wear the drum and pads.

In sub zero temperatures, the air must be dried and the air pipes must also be heat-traced to prevent freezing.

8.4 Fluid coupling

The fluid couplings used with ball mill drives are the drain-able types. A secondary water-cooled heat exchanger is normally employed to remove the heat from the oil.
There are numerous lengths of pipes, which interconnect the hydraulics and the coupling with the heat exchanger. In order not to give rise to standing vibrations and noise, long lengths of unsupported pipe must be avoided. Vibrations impact negatively on the housing and bearings of the fluid couplings.

The fluid couplings connected to motors with sleeve bearings must be supplied with thrust bearings.

9.0 Conclusions

In the foregoing sections we discussed some of the important characteristics of the mill drives and the requirements for establishing a criteria for selecting the motor for the application. Both types of motor design will perform adequately under varying load conditions.

The problems described are not generic in nature and therefore, can be avoided through well-defined engineering specifications, manufacturing quality assurance, inspection and test programs.

In applications with low inrush current restrictions, such as when upgrading an existing plant, or in applications requiring a high torque and a high speed, the slip ring motor generally will prove to be the technical and economical choice.

In all other applications the synchronous motor will provide the best values.

Recently, fluid couplings with zero slip features have become available at competitive prices in the larger horsepower ratings. The improvement in efficiency will give an added economic advantage to the synchronous motor drive application.

Air clutch designs are available at competitive prices for large power ratings and low speed ranges. Their application with low speed synchronous motors drives provides another economic advantage.

In a recent application for a ball mill, an 8000hp synchronous-induction motor is being considered. This type of motor has been in use for many years in applications where high torque, high inrush currents and power factor in combination, are of concern. The windings and brush-gear of this motor are of a special design and construction. The high manufacturing cost, reliability in few limited applications and maintenance issues have rendered this design unpopular in North America. In fact there is only one remaining manufacturer in the World to offer this design.

In another recent development with ball mill drives and synchronous motors, a Load COMMUTATED Inverter (LCI) drive is used to start the mill. After synchronization the motor runs like a normal synchronous motor. The main advantage of this design is to provide higher per unit torque with lower inrush current at zero speed, much like the DC motor.

The investment cost of the LCI drive is relatively high however, it becomes economical in applications when more than one motor is accelerated from the same inverter. This new application is being evaluated at the present time.
The author would like to thank Cementos Apasco for their cooperation for providing the information and photographs included in this paper.

References


