BALL MILL DRIVE MOTOR CHOICES

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By:

Jack H. Green
Maintenance Supervisor, Electrical Engineer
Monarch Cement Company

John J. Stroker
Manager, Electrical Engineering
Penta Engineering Corp.

ABSTRACT

The time has come to re-think our approach to mill drive motors because of the growth in size of newer ball mills, the starting torque restrictions of some of the newer mill drive configurations, and the softness of some utility services. This paper looks at the serviceability and economics of five different mill motor options to meet these restraints. Some approaches are new, some are old standards, and some, like the phoenix, have risen from the ashes to return again.

BASIS for COMPARISON

Since most capital cost decisions usually invoke cost comparisons, this paper will attempt to assess the costs and operating characteristics for each factor of comparison. The factors that will be examined are:

- Initial cost
- Starting characteristics
- Operating cost and maintenance.

I. INTRODUCTION

There have been quite a number of mill drives over the years. In North America, the most common drive in the past has been the low speed synchronous motor driving through an open pinion and bull gear. When utility softness was a concern, the super-synchronous motor was used. In other parts of the world, the wound rotor motor was preferred. In the late 1950s, when mills approached 2500 HP, the center drive mill arrangement with the enclosed geared drive using a high-speed synchronous motor became quite popular. In more recent times the wound rotor motor with the liquid rheostat has come into use in North America when a soft-start was required to overcome torque restrictions or voltage drop problems. Appearing in the 60's were the center gear drives with twin synchronous motors. Problems with torque oscillation and high cost lead to limited use of this drive configuration. In an attempt for a better drive solution, it was reasoned in the early 70's that less was better, and the gearless drive was born. This can be accomplished using the wrap-around principle or the external principle, where the motor rotor is directly connected to the mill torque tube. Since the speed of these motors is extremely slow (15 RPM), the cost is high, the size tends to be rather large, and the problems with harmonics have been significant. This type of drive motor has come into limited use mostly outside of North America and with mills above 6000HP.

This study began with a decision by The Monarch Cement Company to add a new cement finish mill to their plant in Humboldt, Kansas. The new mill would have a drive that was about four times larger than any of their present mills. In meeting with their local electrical utility, it soon became apparent that additional power to the plant site would be required, and that inrush current and voltage drop would have to be handled very carefully. The utility also insisted that the power factor be better than 85%. In addition to these restrictions, one of the proposed mills included a gear box that was not suitable for the shock load of an air clutch. This paper limits its scope to investigating the serviceability and economics of five mill motor options that are currently able to meet these limitations.

II. SYSTEMS TO BE CONSIDERED

The following five drives systems are to be studied:

- Drive 1 - A 5000 HP, 1200 rpm wound rotor motor with liquid rheostat and power factor correction capacitors to a dual pinion gear driven mill;
- Drive 2 - A 5000 HP, 514 rpm synchronous motor with an air clutch and gear box to a center drive mill;
- Drive 3 - A 5000 HP, 514 rpm synchronous motor with soft-start and an air clutch and gear box to a center drive mill;
- Drive 4 - A 5000 HP, 1200 rpm induction motor with a VFD controller as a soft-start to a dual pinion gear driven mill;
- Drive 5 - A 5000 HP, 1200 rpm synchronous - induction motor with liquid rheostat and dc field excitation to a dual pinion gear driven mill.

For the power supply in this study, four different scenarios will be considered as a power system in order to evaluate the different drive systems. It is assumed that there is an additional 1300 kW on line at the time of the mill motor starting.

- System 1 - A 69kV to 4160V 10 MVA transformer with 8% Z, and a utility source with a short circuit capacity of 25 kA
- System 2 - A 69kV to 4160V 10 MVA transformer with 5.5% Z, and a utility source with a short circuit capacity of 25 kA
- System 3 - A 69kV to 4160V 10 MVA transformer with 8% Z, and a utility source with a short circuit capacity of 2 kA
- System 4 - A 69kV to 4160V 10 MVA transformer with 5.5% Z, and a utility source with a short circuit capacity of 2 kA

III. INITIAL COST

The mechanical drive, as well as the motor used with the mill, can greatly affect the cost of the mill. The chart below shows the cost effect of the type of mechanical/electrical drive used for the mill.

MILL DRIVE COSTS		
SYSTEM		RELATIVE COST
1	Dual pinion drive with wound rotor motor & capacitors	100%
2	Center Drive w/ synch. motor & clutch	156%
3	Center Drive w/ synch. motor, clutch & soft-start	206%
4	Dual pinion drive with VFD-induction motor	175%
5	Dual pinion drive with synch.-induction motor	106%

Table 1

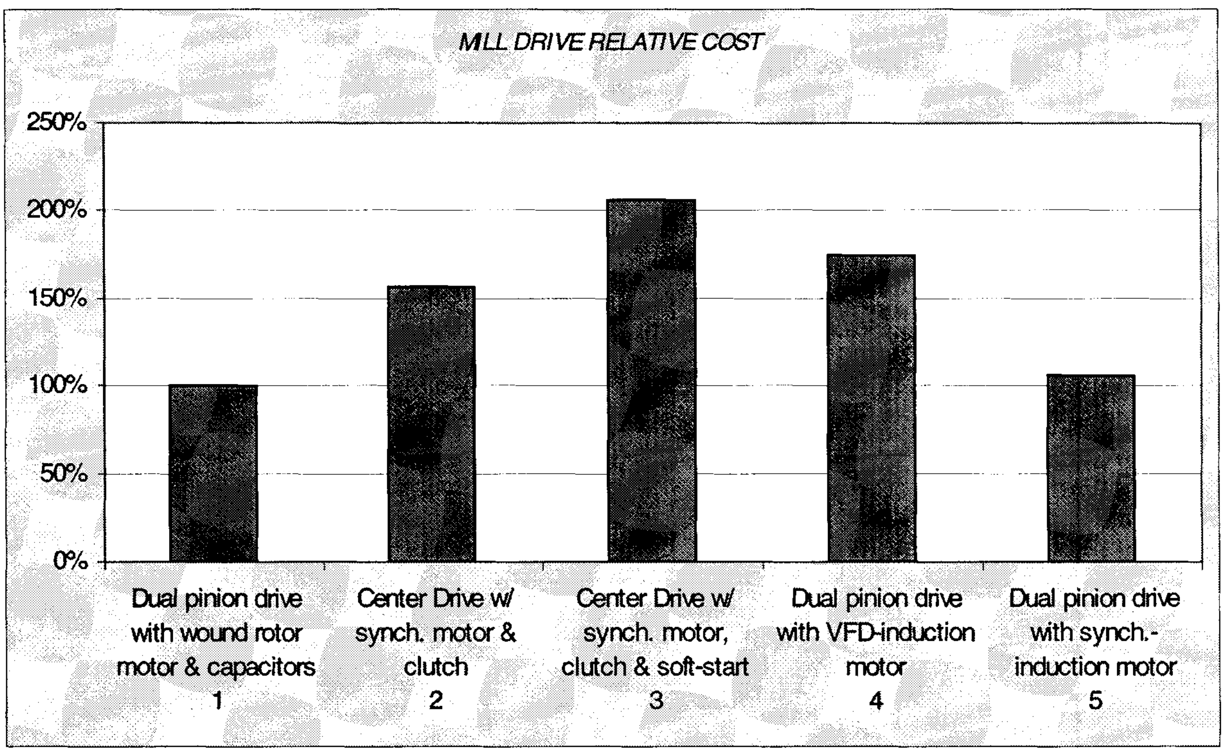


Figure 1

IV. STARTING TORQUE AND TIME CONSIDERATIONS

The mill used for this comparison is a 4.4-meter diameter by 13.6 meter long ball mill with a 5000 HP drive motor. It is designed for approximately 90 s.ton per hour. This type two-compartment mill is a state-of-the-art shell supported cement finish mill. The torque and time requirements of the mill with the ball charge will set the magnitude and time of the inrush current during mill starting. The inertia for this mill reflected to the motor shaft is calculated to be 24,300 ft-lbs^2. The time to accelerate the mill to the design speed is given by the following calculation:

$$\text{Time} = \frac{WK^2 \text{x Speed Change}}{308 \text{ x Avg. Acc. Torque}}$$

where:

time = seconds
WK^2 = inertia of load plus rotor

$$\text{Avg. Acc. Torque} = \frac{\frac{(FLT + BDT)}{2} + BDT + LRT}{3}$$

where:

FLT = Full Load Torque
BDT = Breakdown Torque
LRT = Locked Rotor Torque

The starting torque characteristic of this type of ball mill is not linear. Figure 2 shows the graph of mill speed versus torque requirement:

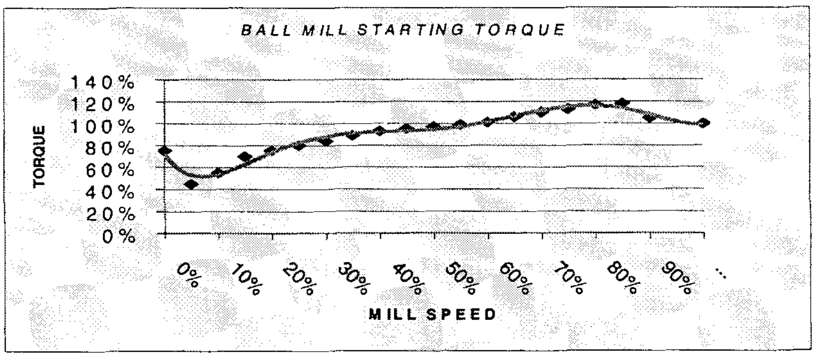


Figure 2

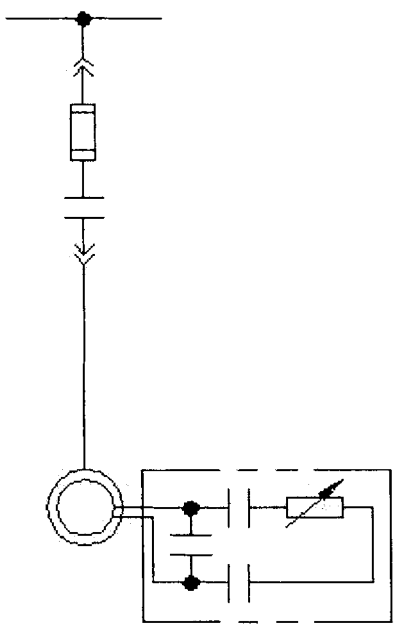
The graph clearly shows that the torque requirement exceeds 120% at 80% speed. This is why the starting torque of the drive motor should be at least 130% of full load torque.

V. CONSIDERATION OF DRIVE STARTING SOLUTIONS

This section will examine the starting torque and voltage drop characteristics of each of the five drive motor options with the four different power sources.

A. WOUND ROTOR MOTOR WITH POWER FACTOR CORRECTION CAPACITORS

This is the most economical choice on a first cost basis. This solution meets the requirements of all gear trains on the market for ball mills.. With this type of drive arrangement, the acceleration time will be controlled by the ramp control used in the liquid rheostat. If we set the acceleration time at 20 seconds, the average torque required is reduced to 47.35 ft.lbs, allowing less than 175% starting current.



DRIVE #1

The choice of a wound rotor motor requires the use of power factor correction capacitors to meet the power factor requirements of the electrical utility. The cost of these capacitors needs to be included in the analysis of mill motor drive systems. These drives typically have an inrush of 150% – 200% during starting. The starting conditions with each of the four power systems are presented in Table 3, and it should be noted that the stiffness of the utility line and the size and impedance of the incoming substation play a part in the voltage drop during starting.

Wound Rotor Motor With Capacitors

Motor Ratings								
VOLTS	**PHASE**	**HZ**	**HP**	**RPM**	**AMPS**	**S.F.**	**ENCLOSURE**	**Acc. Time**
4000	3	60	5000	1200	797	1.15	WP II	20 sec.
TEMP. RISE	**EFF.-75%**	**EFF.-100%**	**P.F.-75%**	**P.F.-100%**	**SEC AMPS**	**BKDN TORQUE**	**START CUR.**	
80°C	96.7%	96.7%	73%-lag	78%-lag	1761 A	280%	175%	

Table 2 Typical Motor Nameplate Data For Wound Rotor Motor

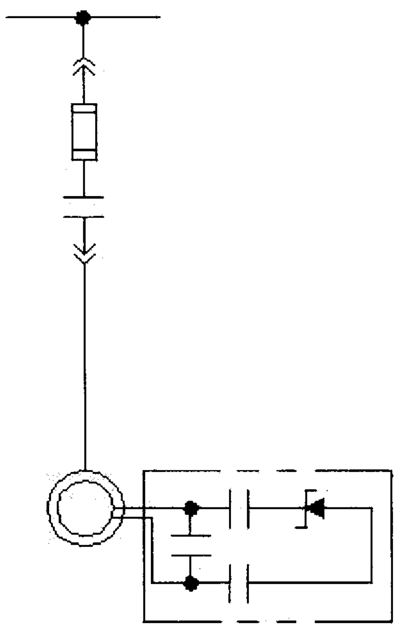
Power System #1	5.7% at motor 5.5% at motor starter 0.1% at Utility entrance
Power System #2	4.1% at motor 4.0% at motor starter 0.1% at Utility entrance
Power System #3	7.5% at motor 7.4% at motor starter 1.8% at Utility entrance
Power System #4	5.9% at motor 5.8% at motor starter 1.8% at Utility entrance

Table 3 Voltage Drops from Nominal

The mill can be started easily with any of the four power systems. Since the starting time is controlled by the steps of the liquid rheostat, the voltage drop at starting can be controlled. It can also be seen that this drive should not cause any torque shock problems to the gear train.

B. SYNCHRONOUS MOTOR WITH AIR CLUTCH

The high starting torque design synchronous motors directly connected to the mills have been used for years. This type of drive would be able to accelerate the mill in about eight seconds, but would require about 600% current inrush. The low starting torque design synchronous motors with an air clutch used when starting torque and voltage drop are a problem. In this case, we have chosen to look only at this second case, because motor size and utility softness make a direct connected motor unacceptable.



DRIVE #2

The inrush on such motors is usually between 400% and 450%. However, the acceleration time is rather short since the motor needs only to accelerate the inertia of its own rotor and half of the clutch. The efficiency of such motors is generally very good, and the power factor can be set at unity or up to 80% leading to easily correct for lagging power factor from the rest of the plant. A thorough study is required to check voltage drop while starting, both inside the plant facilities and out on the utility side of the plant substation. Table 5 shows the voltage drop at starting with four different power sources. As with a wound rotor drive, the stiffness of the utility line and the size and impedance of the incoming substation all play a significant part in the effect during starting. This solution, although satisfactory for some power systems, does not have as low an inrush current as a wound rotor motor and may not be acceptable for some gear trains used with ball mills because of the torque shock when the clutch is energized.

Synchronous Motor With Clutch								
Motor Ratings								
VOLTS	**PHASE**	**HZ**	**HP**	**RPM**	**AMPS**	**S.F.**	**ENCLOSURE**	**Acc. Time**
4000	3	60	5000	514	698	1.15	ODP	4 sec.
TEMP. RISE	**EFF.-75%**	**EFF.-100%**	**P.F.-75%**	**P.F.-100%**	**FLD AMPS**	**FLD VOLTS**	**START CUR.**	**P-O TORQUE**
80C	97.3%	97.8%	77% -lead	80% -lead	6.2 A	72.8 Vdc	435%	200%

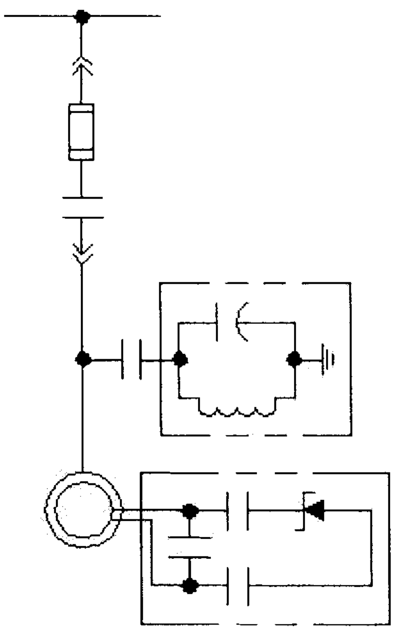
Table 4

Power System #1	12% at motor 11.7% at motor starter 0.6% at Utility entrance
Power System #2	8.9% at motor 8.5% at motor starter 0.6% at Utility entrance
Power System #3	19% at motor 18.6% at motor starter 7% at Utility entrance
Power System #4	15.7% at motor 15.3% at motor starter 7% at Utility entrance

Table 5 Voltage Drops from Nominal

The figures from Table 5 show that the stiffness of the service and the impedance of the incoming transformer greatly affect the voltage drop at starting. It would be acceptable conditions for starting drive power systems 1 and 2 (the stiffer utility service), and not acceptable or marginal with systems 3 and 4 (the softer utility service). It can also be seen by these figures that the most desirable power system is the stiffer utility line and the lower impedance transformer.

C. SYNCHRONOUS WITH SOFT-START AND AN AIR CLUTCH



DRIVE #3

If the 435% inrush of a conventional synchronous motor is too great, and the utility or power system requirements call for even less voltage drop on motor starting, a soft-start can been used to start the synchronous motor. The type of soft-start considered here is the reactor type, although other types (including solid-state) could be considered. No matter what type is considered, this is only possible if the motor is clutched and started in the unloaded state, since the torque available is proportional to the square of the voltage and the clutch will be required to accelerate the mill. With this type of drive arrangement, the acceleration time will be controlled by the ramp control used in the soft-start. Since this drive depends on the clutch to accelerate the mill, it also may not be acceptable for some of the gear trains used on ball mills. The efficiency of such motors is generally very good, and the power factor can be set at unity or up to 80% leading to correct for lagging power factors from the rest of the plant.

Synchronous Motor With Soft-Start

Motor Ratings								
VOLTS	**PHASE**	**HZ**	**HP**	**RPM**	**AMPS**	**S.F.**	**ENCLOSURE**	**Acc. Time**
4000	3	60	5000	514	698	1.15	ODP	6 sec.
TEMP. RISE	**EFF.-75%**	**EFF.-100%**	**P.F.-75%**	**P.F.-100%**	**FLD AMPS**	**FLD VOLTS**	**START CUR.**	**P-O TORQUE**
80C	97.3%	97.8%	77% -lead	80% -lead	6.2 A	72.8 Vdc	300%	200%

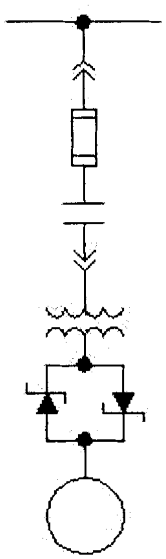
Table 6

Power System #1	6.6% at motor 6.4% at motor starter 0.3% at Utility entrance
Power System #2	4.9% at motor 4.7% at motor starter 0.3% at Utility entrance
Power System #3	11.4% at motor 11.1% at motor starter 4.2% at Utility entrance
Power System #4	9.4% at motor 9.2% at motor starter 4.2% at Utility entrance

Table 7 Voltage Drops from Nominal

The reactor shifts the power factor of the starting current such that voltage drop is lessened at starting. In comparison with a synchronous motor with the clutch, it can be seen that this drive arrangement will start with acceptable voltage drops with all four power systems where the motor clutch combination alone will not.

D. INDUCTION MOTOR WITH VFD



DRIVE #4

If a VFD type of technology (where the frequency and voltage are varied together) were applied for the soft-start, the torque necessary to start the mill would be available. The clutch and its added expense would not be required, and it should be acceptable for all of the gear trains on ball mills. This arrangement offers good starting characteristics, good efficiency, and good power factor correction. A less expensive motor can be used depending on the amount of power factor correction required by the power system and utility. An induction motor could be used since a VFD has a fairly steady 95% lagging power factor over the top half of its speed range. I know of no application of this type of mill drive, although the power and control technology for this drive is very closely related to that of the gearless drive. If this technology could advance and its price were to drop to a more competitive level; it might make an attractive choice for some applications.

INDUCTION MOTOR WITH VFD SOFT-START								
MOTOR RATINGS								
VOLTS	**PHASE**	**HZ**	**HP**	**RPM**	**AMPS**	**S.F.**	**ENCLOSURE**	**Acc. Time**
4000	3	60	5000	1200	635	1.15	WP-II	30 sec.
TEMP. RISE	**EFF.-75%**	**EFF.-100%**	**P.F.-75%**	**P.F.-100%**		**BKDN TORQUE**	**START CUR.**	
80C	95.5%	96%	95% -lead	95% -lead		225%	150%	

Table 8

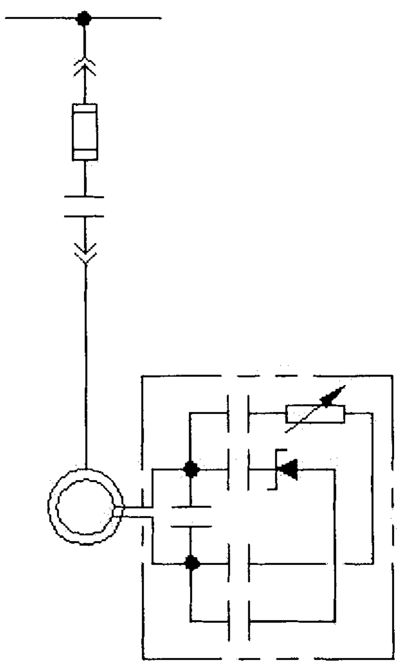
Power System #1	3.6% at motor 3.5% at motor starter 0.1% at Utility entrance
Power System #2	2.7% at motor 2.5% at motor starter 0.1% at Utility entrance
Power System #3	5.1% at motor 4.7% at motor starter 1.1% at Utility entrance
Power System #4	4.0% at motor 3.9% at motor starter 1.1% at Utility entrance

Table 9 Voltage Drops from Nominal

As seen by these figures, the starting ramp of the VFD rather than the stiffness of the service and the impedance of the incoming transformer affect the voltage drop at starting. This drive has an acceptable voltage drop on starting for all of the four power systems.

E. SYNCHRONOUS/INDUCTION MOTOR

This approach that had been used in the past returns to the forefront thanks to technological advancements. This drive system was common in North America and throughout the world in the twenties and thirties in a number of industrial applications. However, as noted in the 1947 edition of the "Electrical Engineer's Handbook," it was no longer considered a good cement mill drive because of its high maintenance and poor efficiency. Now like the phoenix of old, it has returned to meet the problems faced by today's mill drives. No recent installations of this drive are operating in North America, although there are a handful of older drives running. An 8000 HP drive is scheduled to come on-line in Midlothian, TX, later this year.



DRIVE #5

While this drive has the low inrush and soft-start characteristics of the wound rotor motor, it also has the power factor correction ability of a synchronous motor. This is possible since the motor is started as a wound rotor machine with a liquid rheostat. After coming up to speed, the rheostat is shorted, and it has a DC excitation applied to the field, which allows the motor to operate as a synchronous machine. Depending on the amount of power factor correction required by the power system and utility, the synchronous motor can be operate as a unity machine or as an 80% leading machine. This arrangement offers good starting characteristics, good efficiency, and good power factor correction.

SYNCHRONOUS/INDUCTION MOTOR

MOTOR RATINGS								
VOLTS	**PHASE**	**HZ**	**HP**	**RPM**	**AMPS**	**S.F.**	**ENCLOSURE**	**Acc. Time**
4000	3	60	5000	1200	533	1.15	WP II	20 sec.
TEMP. RISE	**EFF.-75%**	**EFF.-100%**	**P.F.-75%**	**P.F.-100%**	**FLD AMPS**	**FLD VOLTS**	**START CUR.**	**P-O TORQUE**
80C	96.5%	97%	>1.0	1.0	1710A	20 V dc	175%	140%

Table 10

Power System #1	5.7% at motor 5.5% at motor starter 0.1% at Utility entrance
Power System #2	4.1% at motor 4.0% at motor starter 0.1% at Utility entrance
Power System #3	7.5% at motor 7.4% at motor starter 1.8% at Utility entrance
Power System #4	5.9% at motor 5.8% at motor starter 1.8% at Utility entrance

Table 11 Voltage Drops from Nominal

The starting characteristic of the synchronous-induction motor is identical to that of a wound rotor motor. It can also be seen that this drive is not a problem to start with any of the selected power systems. When the initial cost of the wound rotor motor is added to the price of the power factor correction capacitors, there is not much of a price difference between the wound rotor motor and the synchronous-induction motor – about 6% more.

VI. MAINTENANCE AND OPERATING COSTS

This section will examine some of the operating and maintenance considerations of the five different drive systems. The cost of energy is assumed to be $.03 per kWH. No consideration was made for demand charges or power factor charges.

A. WOUND ROTOR MOTOR WITH POWER FACTOR CORRECTION CAPACITORS

Wound rotor motors are similar in maintenance patterns to induction motors with the addition of the rheostat equipment and the motor slip rings. The power factor correction capacitors also need consideration.

When first used, these drives used wound resistor for starting in a stepped format. When stepping, this type of secondary control produced torque transients that were some times detrimental to the gear drive. The introduction of the liquid rheostat has allowed for a smooth continuous acceleration. The liquid rheostats of 20 years ago used solenoid controlled valves to control the level of the liquid and the starting ramp for the drive. They functioned reliably as long as the valves were serviced on a regular basis. The more recent introduction of control of the liquid level by pumping instead of the earlier method of solenoid controlled valves has improved reliability and reduced maintenance.
Maintenance of capacitors has been a problem for some plants in that they seem to fatigue with time and fail after they have been in service over a number of years. Under conditions with harmonic distortion on the power system often caused by VFD drives and SCR-DC drives, they some times fail almost instantly after installation.

Based on 8000 hours of operation per year, the annual energy cost for this drive is about $925,750.

B. SYNCHRONOUS MOTOR WITH AN AIR CLUTCH

Synchronous motors are similar in maintenance patterns to induction motors with the addition of the field application equipment and the motor slip rings. If the motor is supplied with a brushless exciter, this can reduce some of this maintenance, especially the maintenance of the slip rings and brushes.

As the mills grew in size, the clutches often became a big problem themselves. The newer clutches used for mill drives use a larger diameter than those used 15 years ago, and thus have a lower torque density than the smaller diameter ones formerly used. Good reliability calls for maintenance of the clutch drive. The clutch should be blown out weekly. The flexible coupling where the air enters the motor shaft deserves special attention. The necessary controls for protecting the clutch need to include:

- A pressure switch on the air supply to assure that sufficient air pressure is present before attempting to engage the clutch,
- A pressure switch on the clutch air to assure that no air pressure is present in the clutch before attempting to start the motor,
- A second pressure switch on the clutch air to assure that sufficient air pressure is present after the clutch is energized,
- A slip detector to assure that there is no slippage once the clutch has been energized.

These newer clutches with the proper safeties have proven to be much more reliable than the earlier models.

Based on 8000 hours of operation per year, the annual energy cost for this drive is about $915,340.

C. SYNCHRONOUS WITH SOFT-START AND AN AIR CLUTCH

The maintenance of this drive is similar to the synchronous motor with the air clutch with the additional maintenance of the reactor circuit. Care should be taken with harmonics on the plant power system to avoid excessive maintenance with the reactor.

Based on 8000 hrs of operation per year, the annual energy cost for this drive is about $915,340.

D. INDUCTION MOTOR WITH VFD INDUCTION MOTOR WITH VFD

The induction motor has the simplest maintenance of the five drives. However, the VFD soft-start may be the most complicated, and drives in this power range almost always require water cooling.

Based on 8000 hours of operation per year, the annual energy cost for this drive is about $1,297,350.

E. SYNCHRONOUS/INDUCTION MOTOR

This drive has the maintenance items of both synchronous drive and the wound rotor minus the problems of capacitors.

This drive has much in common with the current wound rotor design, and could be operated as a wound rotor drive if there were some fault that prevented it from operating as a synchronous machine. It is however different in some respects from the normal synchronous machine. The poles are wound similar to the normal squirrel-cage induction motor as opposed to the salient pole design of most synchronous machines. Since the rotor of a wound rotor motor requires a low impedance to obtain the high starting torque required of a mill drive, the DC voltage impressed on the field needs to be around 20 to 30 volts DC instead of the normal 125 volts DC used with salient pole machines. Since the current to the field needs to increase inversely as the voltage applied drops, it is important to place the secondary controller close to the motor, the field current is rather high.

Based on 8000 hours of operation per year, the annual energy cost for this drive is about $922,890.

VII. SUMMARY

As shown previously in this paper, mill motor choice is greatly dependent on the type of mill gearing system chosen, the power system, primarily the incoming transformer size and its impedance, and the other loads in the plant and the stiffness of the utility's line. A review of the torque shock that the gear train can withstand needs to be made at this time. There could well be a balance between capital invested in the gear train and capital invested in the drive. Once it has been verified that the motor can start the mill and perform the grinding task, it becomes an economic decision as to choice of drive motor. This choice is a balance between initial costs and operating and maintenance costs. Using the specific plant's economic criteria, a present worth evaluation calculation can be made to determine the best economic choice. However one must not discount the enormous value of unscheduled down-time in evaluating true costs.

For the new mill system at Monarch Cement, the power system is not completely defined at this time but it is closest to system 4. Since the power system was not stiff enough to withstand the across-the -line starting and the double pinion drive was the mill selected, a synchronous-induction motor has been selected for the mill motor.

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