Mill drive selection for semiautogenous grinding mills

Dan B. Kivari and John Chapman

A key operation of any milling circuit is grinding. Over the last two decades, large diameter semiautogenous grinding (SAG) mills have become the preferred primary grinding mills. The drive systems became more complex as the size of the mills became larger, during which time operating and design experience for SAG mill accumulated. Considerable reliance is now placed in power electronics to provide flexibility in SAG mill operation to meet the demands of lower operating costs.

Most earlier SAG mills were designed to operate at fixed speeds. Present day SAG mills can operate at a fixed speed or variable speed through the use of an ac synchronous motor or dc motor. This flexibility, however, comes with an increase in capital and operating costs. Since the capital and operating costs of a project directly affect the project's rate of return, the selection of a SAG mill and its drive system should depend, in part, on the impact that the extra cost makes on the project. This impact can be measured by performing an economic analysis based on net present cost (NPC) calculations.

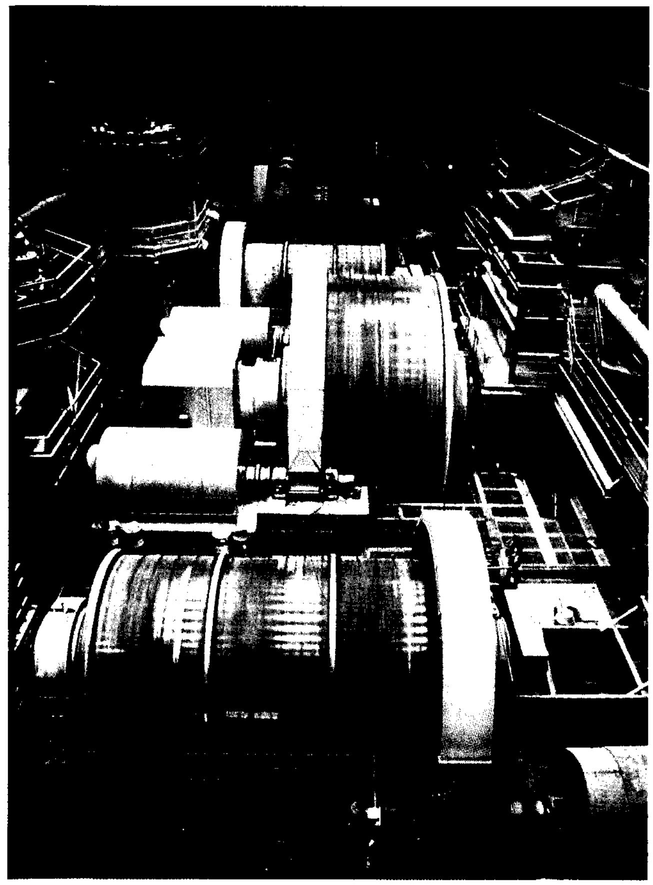
Although the NPC calculation is an important factor in the grinding mill selection, other factors, such as reliability of mill drives and power source, are important elements in the decision making process. This article examines how the NPC calculation, plus reliability and power source, influence SAG mill selection.

SAG mill drives

There are two types of SAG mill drives. Power is transmitted to the grinding mill either through a pinion and ring gear assembly or a gearless ringmotor. Typical gear driven mill and gearless mill with a ringmotor are shown in Figs. 1 and 2.

Early SAG mill designs using gear drives were limited in the amount of power that could be applied to the pinions, 3.7 MPa (5000 hp). The exception to this design was the Hibbing taconite operation. It used two 4.47 MPa (6000 hp) motors to drive a 11-m-diam x 4.5-m long (36-ft-diam x 15 ft) autogenous mill.

However, recent SAG mill designs now include a single pinion drive that is used to transmit 5.6 MPa (7500 hp) to a mill. Consequently, it is now possible, with a twin pinion drive, to have power transmission delivering 11.8 MPa (15,000 hp) to a mill.



To assist in selecting a drive system for a SAG mill, an economic analysis should be performed. The one here involved the determination of the NPC based on the calculations of the capital and operating costs of the grinding systems.

This power level is now approaching that available through the gearless drive system. Consequently, the dividing line that separates gear driven grinding mills from gearless type mills is becoming less clear.

Ringmotors were originally applied in the cement industry where relatively small diameter but long tube mills were used. This experience provided the basis for similar drives for the mineral processing industry.

One of the earliest ringmotors was supplied by Siemens to the cement industry in 1971. The first base metal mill to use a ringmotor was installed in Norway 10 years later. Subsequent to that installation, there have been ringmotors installed for projects in Papua New Guinea, Chile and the US.

Economic analysis

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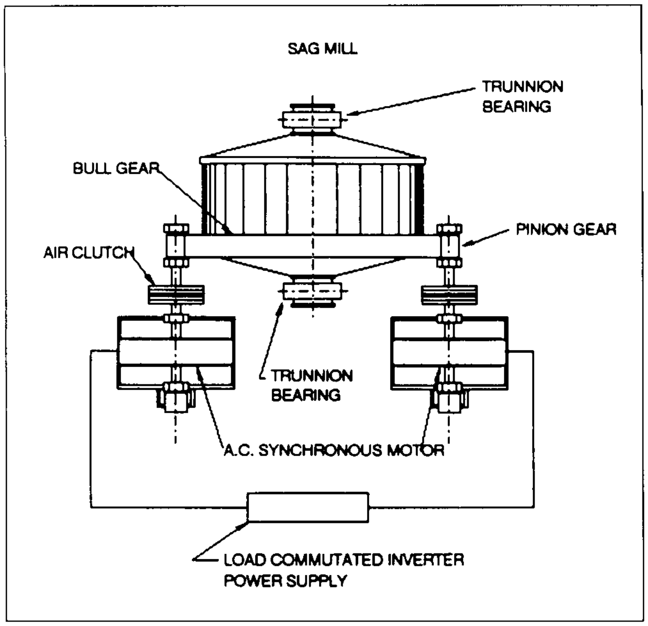


Fig. 1 — Twin-pinion drive gear driven motor.

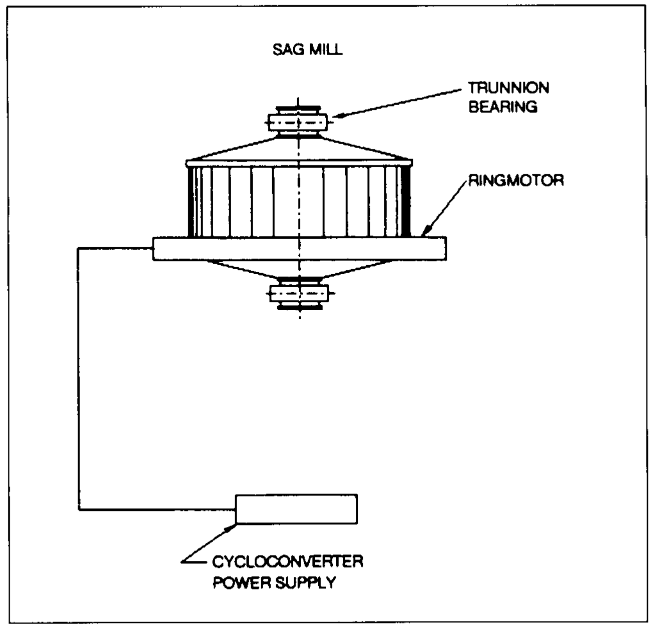


Fig.2 — Gearless mill with a ringmotor.

of the grinding systems. NPCs were determined on grinding systems that used the same size and quantity of equipment so that an economic comparison could be performed (Projects C to F in Table 1).

Capital cost

In calculating the NPC, the capital cost in US dollars for each SAG mill system was determined. Although the capital costs in Table 1 are based on operations with three different production rates (the highest at 20.4 kt/d or 22,500 stpd), the capital cost calculations were performed for four different SAG mill drive systems used on the same size grinding mill:

- fixed speed ac synchronous drive complete with ring and pinion gears;
- variable speed dc drive complete with ring and pinion gears;
- variable speed ac drive complete with ring and pinion gears; and
- variable speed ac synchronous ringmotor gearless drive.

By determining the capital costs for these systems, the NPC for each can be compared directly.

For the variable speed DC drive system, the following electrical components were included in the capital cost:

- 4.5 MPa (6050 hp), 180 rpm, dc

Table 1 — Mill comparison capital cost

Project	Mill size DXL (ft)	Drive system	Capital cost	Horsepower	Production rate
A	Primary SAG, 26x11	Variable speed ac synchronized motor coupled to a gear drive.	mill, $1.3 million motor, $1.3 million	4025	11,000
	Secondary ball mill, 18x27	ac synchronized motor coupled to a gear drive with an air clutch.	mill, $1.6 million motor, $602,000	6050	
B	Primary SAG, 30x11	Fixed speed ac synchronized motor coupled to a gear drive with an air clutch.	mill, $2.9 million motor, $568,000 inching drive,$289,500	6500	17,000
	Secondary ball mill, 18x27	ac synchronized motor coupled to a gear drive with an air clutch.	mill, $2.5 million motor, $602,000	6050	
C	Primary SAG, 34x16	Two fixed speed ac synchronized motors coupled to gear drives with air clutches.	mill, $4 million motor, $700,000 each inching drive, $289,500	6000	22,500
	Two secondary ball mills, 18x27	ac synchronized motor coupled to a gear drive with an air clutch.	mill, $2.5 million motor, $602,000	6050	
D	Primary SAG, 34x16	Two variable speed dc motors coupled to a gear drive with air clutches.	mill, $4 million motor, $1.28 million each	6000	22,500
	Two secondary ball mills, 18x27	ac synchronized motors coupled to a gear drive with an air clutch.	mill, $2.5 million motor, $602,000	6050	
E	Primary SAG, 34x16	Two variable speed ac motors coupled to a gear drive with air clutches.	mill, $4 million motor, $1.75 million each	6000	22,500
	Two secondary ball mills, 18x27	ac synchronized motor coupled to a gear drive with an air clutch.	mill, $2.5 million motor, $602,000	6050	
F	Primary SAG, 34x16	Ringmotor system.	mill, $3.1 million motor, $7 million	12,050	22,500
	Two secondary ball mills, 18x27	ac synchronized motor coupled to a gear drive with an air clutch.	mill, $2.5 million motor, $602,000	6050	

Table 2 — Net present cost comparison — Project year ($millions)											
Description/year	1	2	3	4	5	6	7	8	9	10	11
Project C											
Capital cost	$12.2										
Operating cost		19.1	19.1	19.1	19.1	19.3	19.1	19.1	19.1	19.1	19.1
NPC	$117.94										
Project D											
Capital cost	$12.8										
Operating cost		$19.18	19.18	19.95	19.18	19.42	19.95	19.18	19.95	19.18	$19.18
NPC	$120.16										
Project E											
Capital cost	$12.6										
Operating cost		$19.13	19.13	19.90	19.13	19.37	19.90	19.13	19.13	19.90	19.13
NPC	$119.69										
Project F											
Capital cost	$16.31										
Operating cost		$18.27	18.27	19.04	18.27	18.39	19.04	18.27	18.27	19.04	18.27
NPC	$118.17										

motors;

- closed loop speed and thyristor gate controls;
- dc power conversion equipment;
- PLC;
- signal cable marshalling cubicle;
- measuring and protection cubicle;
- low voltage MCC;
- automatic battery charger;
- maintenance and emergency shutdown indication panels; and
- dc converter power transformers.

The capital cost of the variable speed ac synchronous drive included the cost of the following electrical components:

- ac synchronous motors or single ringmotor;
- load commutated inverter (LCI) for ac synchronous motors or cycloconverter for ringmotor;
- excitation equipment;
- closed loop speed and thyristor gate controls;
- PLC;
- signal cable marshalling cubicle;
- measuring and protection cubicles;
- low voltage MCC;
- automatic battery charger;
- maintenance and emergency shutdown indication panels;
- power transformers; and
- excitation transformer.

Since the fixed speed ac synchronous motor cannot be used to inch the mill, the cost for a separate inching drive was included in this system's capital cost.

Operating cost

As part of the NPC calculation, the operating costs in US dollars were determined for Projects C to F (Table 1) and included the following items: steel grinding media, liners, power and motor efficiency, gear lubrication, pinion replacement, gear inspection and motor system maintenance and inspection.

For SAG mills with gear drives, the cost for one set of pinions was included in the operating cost in the fifth year of operation. For a hypothetical gold mining operation with the following production criteria, the cost of one day of downtime was calculated to be $769,500.

Production criteria:

Rate:	20.4 kt/d (22,500 stpd)
Head grade:	3.4 g/t (0.1 oz per st)
Operating %:	93
Recovery %:	90
Gold price:	$12.22/g ($380 per oz)

Based on operating plant experience, the time required to perform a gear inspection is about one operating day. Similarly, the inspection and maintenance of a dc drive system is about one day. Thus, the cost of one production day was included in the operating cost for each third year of production for the gear-driven grinding systems. Since the dc drive can be scheduled for maintenance during the gear inspection (every third year), only one day of downtime was included in the operating cost for the SAG mill with the dc drive.

The ac synchronous motors used in the gear and gearless drives have a higher efficiency than the dc drive. Thus, for large motor horsepowers, the efficiency would affect the operating cost of the operation. Typically, the overall drive efficiency when using an ac synchronous motor is 92%, whereas the equivalent efficiency for a dc motor is 90.5%. These factors were used in determining the power cost.

Analysis

The NPC has demonstrated that the lowest cost alternative is the fixed speed SAG mill powered with ac synchronous motors. However, the SAG mill with a variable speed ringmotor is only slightly more expensive and has the added feature of being variable speed(Table 2).

The most expensive alternative is the dc drive system. The extra cost occurs partly in the capital cost for the electrical components but mainly in the extra maintenance cost.

If one set of spare parts is included in the capital cost for the dc drive, another $1 million would be added to the capital cost. In comparison, the cost of spare parts for an ac synchronous motor is about $250,000 and for a ringmotor, about $375,000.

Mill drive advantages and disadvantages

Although an economic analysis such as the NPC calculation is necessary in the decision-making process for mill drives, the advantages and disadvantages for each drive system must be examined. A low-cost unreliable, mill-drive system can be the demise of a mining project.

Variable speed mill drives

Developments in semiconductor technology have strongly influenced the application of variable speed drives over the entire spectrum of voltage and motor output power levels. For many years, the dc motor provided the widest range of speed and torque variation by adjusting the voltage applied to the armature and by field weakening. This system required power conversion to obtain a variable dc voltage from the ac mains supply.

Originally, Ward-Leonard generator sets (ac drive motor coupled to a dc generator) provided the required variable dc voltage. Later, mercury-arc rectifiers were used to convert the ac mains supply to dc power. The advent of the thyristor — effectively a more efficient replacement for the single anode mercury arc rectifier with grid control — foreshadowed the development of a wide range of variable speed drives.

Semiconductor device current and voltage ratings have been extended over the last decade. So has the range of applications. Inverter and converter circuits have been designed that enable the ac squirrel-cage induction motor — for many years considered a fixed speed drive — to compete with and, in many situations, exceed the performance of the dc motor.

A similar approach has been used in developing thyristor-based variable speed drives for synchronous motors. Low-speed synchronous motors have frequently been used for ore mill drives in the past. As a single speed machine, the more expensive synchronous motor can often be justified in comparison with an induction motor on the basis of:

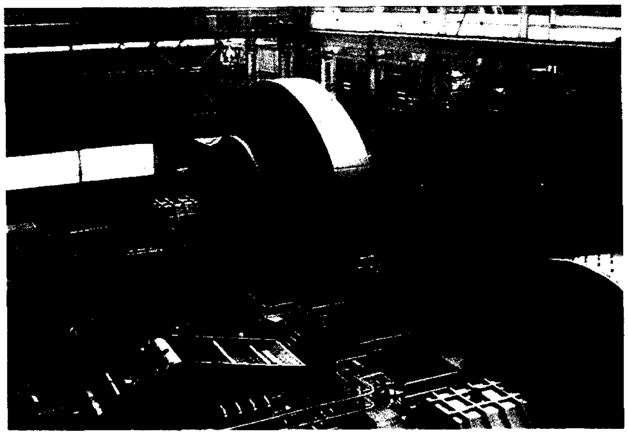
- its higher overall drive efficiency;
- its ability to supply reactive power to the electrical system; and
- its potential for increased mechanical output with reduced excitation, if reactive power capability can be replaced by other means, such as static capacitors.

In comparison, an induction motor, whether of the squirrel-cage or wound-rotor type, requires a gear reducer since motor efficiency is much reduced below four pole speed (1800 rpm at 60 Hz). The gear reducer introduces further losses into the drive-line. The induction motor draws reactive power from the system to provide its magnetizing current and thus increases the requirement for power factor correction.

The SAG mill ringmotor is a special case of the variable speed synchronous motor drive. Economics limit the application of ringmotors to horsepowers generally in excess of 8.9 MPa (12,000 hp) since cost-effective twin pinion gear drives are readily available below this level. The gearless motor speed corresponds to the mill speed, usually in the range of 10 to 15 rpm.

The economies brought about by using a single, large, primary mill must be balanced by some disadvantages for the operator and the electrical engineer. The most significant disadvantage to the operator is the question of reliability. If the single, large, SAG mill is out of service due to mechanical or electrical problems, then the entire throughput of the concentrator is lost with significant effects on the financial bottom line.

On the other hand, the loss of one primary mill of a multi-mill process will, in the worst case, result in a 50% reduction in throughput. For the electrical engineer, the single, large, drive creates several problems of compatibility with the power source.



The NPC calculations and the discussion on advantages and disadvantages of the mill drives demonstrate that a SAG mill with a ringmotor drive is the best system when comparing drives presented here.

Fixed speed ac synchronous system

Advantages of the fixed speed ac synchronous system are that it is presently the industry standard, with a wide range of applications. It also has the highest motor efficiency, low maintenance costs and a relatively low capital cost. It has proven technology and supplies reactive power to the electrical system.

There are some disadvantages with the fixed speed ac synchronous system. These include mill speed changes that are costly and require pinion gear replacement. The system requires a separate inching drive, and its speed cannot be readily changed to accommodate changes in ore characteristics.

Variable speed dc drive system

There are several advantages to the variable speed dc system. It is the first variable speed drive used. It has smooth mill acceleration and mill speed can be optimized to suit ore conditions. The drive can be used for an inching mill and dc power conversions equipment is a proven technology.

Among the variable speed dc drive system's disadvantages are its high capital cost, its high maintenance cost, lower power efficiency than the ac synchronous system and its poor lagging power. And it cannot be operated from the main power supply if power conversion equipment should fail.

Variable speed ac synchronous drive system

Advantages of the variable speed ac synchronous drive system is its motor efficiency is higher than the dc drive, and the mill speed can be optimized to suit ore conditions. Maintenance costs are relatively low, and the system provides inching capability. This system can be operated at a fixed speed if LCI should fail.

However, it a relatively new technology with some disadvantages. The minimum mill speed is about 15% of full speed, thus making for a fast inching drive. Also on the negative side, the system can develop large transient loads during startup. And a twin-pinion, variable-speed drive system has not been used in operation.

Ringmotor

Advantages of this system are that the pinion gear, pinion bearings and ring gear are eliminated, gear lubrication is not required, mill speed is adjustable and motor bearings are eliminated. It has the highest motor efficiency of all variable speed drives and provides inching capability.

Maintenance costs are low and reliability is high. Power that is applied to the mill is not limited to gear design, but limited to mill design. And mills with this drive have been installed and are operating.

Disadvantages of the ringmotor system are its high capital cost and long installation time. Extra care is also required during installation because of the large components being assembled within close tolerances. The ringmotor also takes reactive power from the electrical system.

Electrical considerations

For the electrical engineer, the single, large drive creates several problems of compatibility with the power source.

A single, large mill may require a drive motor that represents about 50% of the total connected load of the processing plant. Starting such a motor may result in excessive voltage drops within the rest of the plant and, more importantly, for other customers of the electrical utility supplying the power.

This problem must be discussed with the utility as early as possible in the design stage. Where power is to be generated on site, the problem must also be given high priority since the capacity of a local generating system is usually much smaller than that of a utility, even at the end of a long overhead line.

Within the plant, the effect of excessive voltage drop at starting may cause the malfunction of electronic equipment, such as programmable logic controllers (PLC) and variable speed drives. It might even cause the contactors of other drives to drop out or overheat due to insufficient holding force. Fortunately, the use of a cycloconverter limits the inrush to not more than 120% of full current due to the effective "soft-start" method of increasing frequency from zero to the operating range.

The cycloconverter supplies the appropriate frequency to the motor from the mains supply. It reflects harmonics back into the supply system. Such harmonics may cause adverse effects on other equipment connected to the system. Typically, lamp ballasts may burn out and power factor correction capacitors may fail — all for no apparent reason. A harmonic study should be performed. Where necessary, filters must be installed to alleviate the effects of these harmonics.

To minimize utility charges, it is important to maintain a high power factor at the electrical service entrance. A high power factor also limits voltage drop on the plant distribution system.

Adequate power factor correction, usually in the form of static capacitors, must be included to supply the reactive power required by induction motors. Mill synchronous motors are often used to supply a significant portion of this reactive power. This is achieved by operating the motor at leading power factor — increasing the excitation to the "overexcited" condition. Such correction is only possible where the machine is supplied directly from the mains supply. It is not available when a cycloconverter is interposed between the power supply and the motor stator, as in the ringmotor.

However, the secondary grinding mills that are often associated with the large primary mill will likely be driven by low-speed synchronous motors. These machines can be designed to offset a significant proportion of the reactive power demand of the plant.

Mechanical and environmental considerations

Several mechanical and environmental considerations must be addressed in the application of ringmotor mill drives. Most require close coordination between the mill builder and the motor manufacturer. Some involve the layout of the mineral processing plant within its building envelope.

The mill shell and its bearings must support the additional weight of the ringmotor pole pieces mounted on a specially designed flange forming an extension of the mill head casting. This may not be a major design consideration in terms of the additional weight relative to that of the fully-charged mill but the following factors must be considered in the design.

The pole mounting flange must be designed to transmit the tangential forces due to the reaction between the stator ac rotating field and the field produced in the pole pieces by the DC excitation current — the motor torque effect.

A more important design consideration, and perhaps less obvious, is the radial force imparted to the head of the mill by the electromagnetic effects of the stator and rotor fields. Any eccentricity of these forces will be transmitted to the trunnion bearing through the mill head.

Control of the air gap between the pole pieces and the stator iron is important. The gap must be adequate to allow for thermal expansion of the mill shell, yet be small enough to obtain a high motor efficiency. Such a gap will be the order of 13 mm (0.5 in.) and must be held within a tolerance of ±10% to avoid excessive cyclical forces on the mill bearings. Consider this dimension and its tolerance in relation to a mill diameter of 10.3 m (34 ft).

The ringmotor must operate in an electrically hostile environment. The wet grinding process is prone to spillages and high humidity. When the slurry dries, then an equal hazard of fines dust is prevalent. Sealing between the enclosure of the rotor pole pieces, mounted on the rotating mill shell, and the motor stator is vital if damage to insulation is to be prevented.

The headroom for a ringmotor driven mill is greater than that required for a gear driven mill. The stator housing is significantly larger in diameter than the mill shell in order to accommodate both the salient pole pieces of the rotor mounted on the mill flange and the surrounding stator frame with its steel laminations and windings. Lifting height must be provided to maneuver the large segments, into which the stator is usually split for shipping and future repairs purposes.

This problem was overcome in Chile by assembling the mill and the motor in the open air and then erecting the building afterward. Even with this procedure, headroom for future repair lifts should be provided.

At a plant expansion in Canada, it was reported that the additional building height required for a ringmotor was one reason for selecting the twin dc motor drive option .

Conclusions

The NPC calculations and the discussion on advantages and disadvantages of the mill drives demonstrate that a SAG mill with a ringmotor drive is the best system when comparing the drives presented here. Although the NPC is slightly higher for the ringmotor than for the twin, fixed-speed drive (lowest cost option), the benefit obtained from the variable speed capability of the ringmotor plus the elimination of the pinion gears would offset the higher cost.

Whether this conclusion applies to other SAG mill operations that use smaller mills and lower tonnage rates or have a shorter mine life, can only be determined by performing a similar type of analysis.

With the power draw for new mills reaching large values, many power supply systems — especially in remote areas — cannot cope with the demand imposed on them. Therefore, the engineer must make every effort to involve the power supply companies at an early stage in the design of the overall system to ensure that a reliable power supply is available at the lowest cost. ♦

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