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RING-GEARED MILLS OPERATED WITH FREQUENCY CONVERTER (MUCH MORE THAN JUST VARIABLE SPEED)

T. R. von Ow, ABB Switzerland Ltd, Baden-Dattwil, Switzerland
B. Gerhard, ABB Switzerland Ltd, Baden-Dattwil, Switzerland

ABSTRACT

The method of powering mills such as AG, SAG and Ball has a long and technically interesting history. It can be said that almost every decade in the last half century had its own trend. The trends were dominated by the market demand, the advanced process development and requirement of the mechanical and the electrical technology but mostly by the price of the applied technology. The increasing size of the ring geared mills in the last years requires more awareness on the drive train solution. Special attention must be paid to the mechanics and the requirements of the power grid. Operational challenges such as soft starting and controlled operation as well as the protection of the equipment have gained importance. Frequency converter drive solutions dedicated to single or dual pinion ring-geared mills offer significant advantages over conventional drives due to their application specific features and controls. Solutions with low speed motors as well as high speed motors cover all possible configurations available for ring geared mills.

INTRODUCTION

Depending on the power required to turn the mill, different configurations of the mechanical set up are possible. It can be said that the mill configuration is defined by the maximal transmittable torque to the mill via pinions.

Nowadays this is restricted to approximately 9 MW for single pinion solution. Above this power a dual pinion configuration is required. This also implies that mills above 18MW can only be driven by GMD's.

The gearless mill drive is covering the upper power range of the mills. The torque is transmitted to the mill directly through the magnetic field in the air gap of the motor, eliminating the gear reducer, the ring-gear and the mechanical related issues faced by maintenance with ring-geared mills. In fact the rotor of the ring motor is the mill itself and the stator is built around the mill shell. This is also the reason why the ring motor is also known as wrap-around motor.

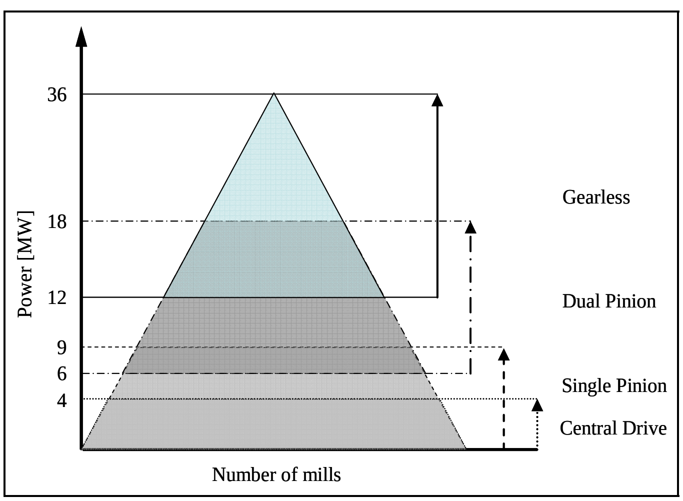

Figure 1. Quantity versus power of mill systems.

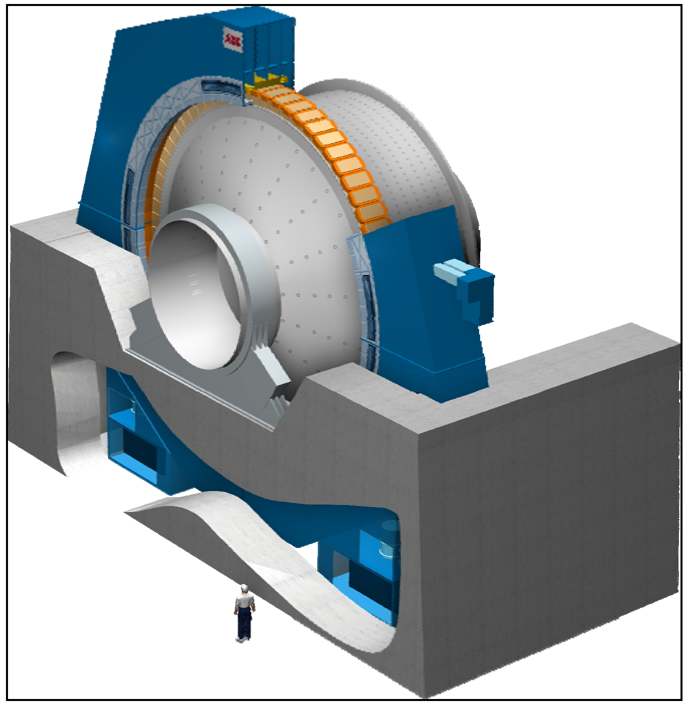

Figure 2. Gearless Mill Drive.

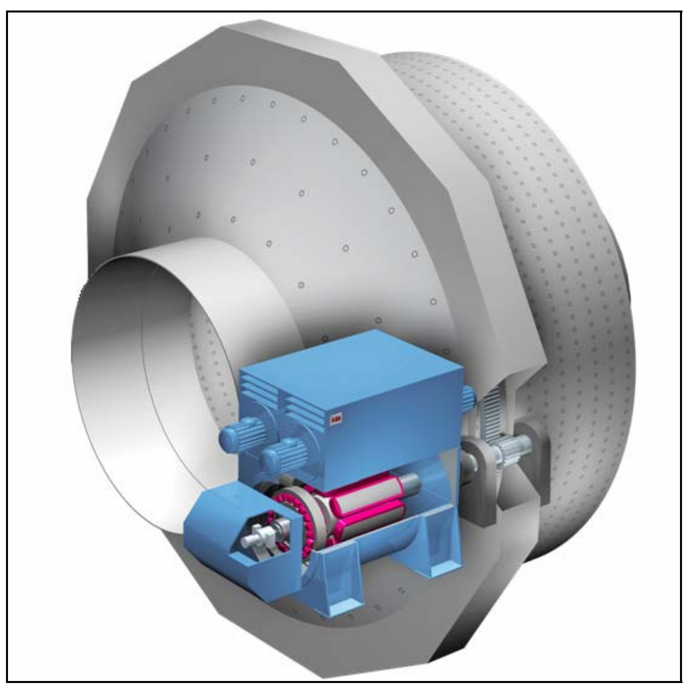

Figure 3. Single Pinion Drive.

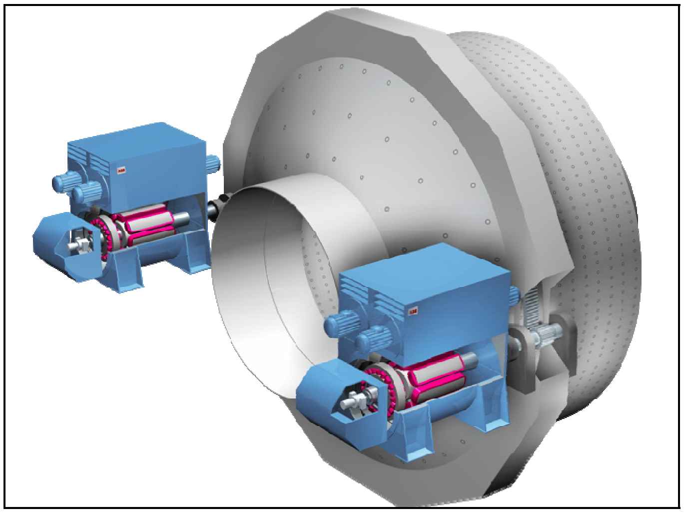

Figure 4. Dual Pinion Drive.

SINGLE AND DUAL PINION MILL DRIVES

If we concentrate on the single and dual pinion configurations, we can see that these two configurations can be powered by low speed motors connected directly to the pinions driving the ring gear or by high speed motors that require a gear reducer between the pinions and the motors. Low speed motors are synchronous motors whereas the high speed solution is normally equipped with an asynchronous squirrel-cage motor.

Fixed speed drives, with wound rotor motors or synchronous machines, were the common way of turning mills in earlier times. Even if these are the simplest and the lowest capital cost solutions, they do not allow any flexibility in the operation of the mill and produce high stress on the network and mechanical equipment during the starting phase.

Nowadays, the frequency converter technology has taken over the industry. The volume of installed converter solutions increases every day. The evolution from fixed speed to variable speed brings additional advantages for the mechanical equipment, the electrical network and from the operation and maintenance point of view.

Presently SAG mills are mainly driven with variable speed drives, allowing the operator to react easily to the changes in ore characteristic and throughput.

Ball mills on the other hand, as far as process requirements are concerned, did not require variable speed. However, frequency converter based drive systems provide benefits that improve the ball mill operation.

FIXED SPEED CONFIGURATIONS

The key issue to operate a mill in a fix speed mode is the starting. A squirrel-cage motor or a synchronous motor started direct on line without any help of a frequency converter normally cannot produce sufficient starting torque. Therefore it is required to accelerate the mill without load until the rated speed and then, by means of a clutch system, couple the motor to the mill. Another possibility is to use a motor that can develop sufficient torque such as the wound rotor induction motor with rotor resistor starter.

There are some drawbacks to be considered while using such a fix speed direct on line alternative independently if a high – or low speed solution is selected.

Fixed speed solution with synchronous or squirrel cage induction motor starting directly on line requires a clutch

- When clutch system are there needs to be air or another media being provided
- Engaging the clutch generates high wear and heat what means unnecessary losses, especially where the mill is started very frequently
- Even if the motor is started at no load; the starting current is high an can endanger the electrical network stability if it is too week

Wound rotor motors solve the above issue however the motor is more complex and requires high maintenance.

- Complex rotor design (Rotor winding, slip-rings and interconnections)
- Possibility of carbon dust build-up in the rotor area
- Brush configuration (number and suitable quality) as well as brush life in view of temperature and humidity
- Brush wear, surface of slip rings as well as possible presence of carbon dust build up must be carefully watched. Regular cleaning required and replacement of brushes is required to insure a good operation
- Liquid Resistor Starter (LRS) are containing agitated mechanical parts requiring maintenance. In addition the consistency of the electrolyte needs to be watched

The High Speed Motor configuration

- The bearings of the gear reducer (failures on input bearings are the most common) have a life time of down to 3 to 4 years mainly reduced due to the starting ‘stress’ . The change of the bearings is linked to a major overhaul.
- The life time of gear reducers are not matching the life time expectations of the mill and need to be replaced.
- No process control available via the mill speed
- The power factor of the motor is low and changes depending on the load. A power factor correction has to be considered
- The WRIM + LRS system is causing high transient torques during the start-up.

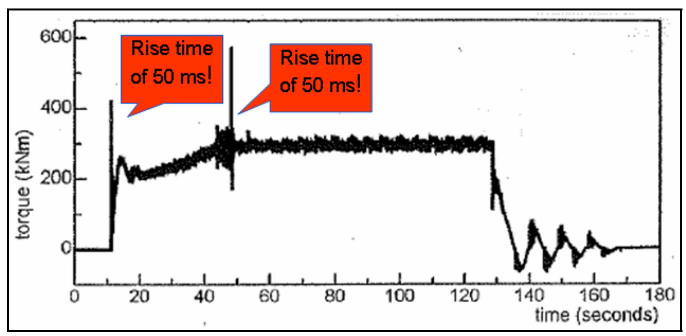

Figure 5. The WRIM + LRS is causing high transient torques during the start-up.

Based on a study done by Anglo Technical Division, presented in a technical paper on the occasion of the SAG 2006 in Vancouver, B. C. Canada: “Lessons learnt from recent failures of gear drives on mills in South Africa”

This study came up with the conclusion that failures occur in five main areas of a mill drive train:

- Gear reducers
- WRIM rotors
- Pinion bearing housings
- Pinion shafts
- Girth gear failures

The starting transients are significantly influencing the predicted life time of drive train components, specially in installations with a high number of starts

The Low Speed Motor configuration

- Synchronous motors provide not sufficient torque to start the mill directly coupled
- Clutch system required which leads to higher maintenance

- In case of dual pinion drive no inherent load sharing available. Special equipment required to allow load sharing
- Synchronous motors however support the short circuit capability of the network once started

THE FREQUENCY CONVERTER SOLUTION

Adjustable speed geared mills have two main different drive configurations; the high speed solution with an AC induction motor and the low speed solution with a brushless synchronous motor. Both solutions are fed by a frequency converter connected via a transformer to the medium voltage distribution.

The converter transformer can be connected, irrespective of the voltage of the motor, to any medium voltage level. However is not recommended to exceed the 36kV. This additional flexibility can have a big impact in the design of the complete medium voltage distribution of the plant and offers additional optimization potential. Having the mill drive system (one of the bigger consumers in the mine) connected to higher voltages, allows reduction in costs on the transformation of voltages and reduces transmission of currents and hence losses.

The mills are typically single quadrant application. Some are designed for running in both directions. Depending on the mill power and the network strength 12- or 24-pulse diode rectifier configurations or active front end drive are used.

In case of a dual pinion mill two single drive or a multidrive configuration is available. The multidrive solution has the advantage to have only a common supply unit and two inverter units provide a compact solution with the need of only one medium voltage circuit breaker.

THE HIGH SPEED MOTOR SOLUTION

Squirrel cage induction motors are the most common motor used in the industry due to their versatility, reliability, robustness and simplicity. The maintenance is reduced to a minimum. Typically a 6 – 8 pole induction machine is used to turn the mill. The motors are generally forced cooled; this allows running the motor at very low speed (approx. 5-10% of nominal speed) for service mode. Automatic positioning for liner changes and creeping for visual inspection can be performed with the main drive without the need of additional equipment. Depending on the environment, air cooled motors or water cooled motors are used for these powers (up to 9MW). The advantage of a totally enclosed motor is that the cooling air inside the motor is not affected by the external dusty environment. These motors are equipped with flange mounted bearings installed on the end shields of the motors. Antifriction or sleeve bearings are used. To prevent bearing damage from circulating currents, bearings are electrically insulated. The shaft is grounded to avoid static charges of the stator.

THE LOW SPEED MOTOR SOLUTION

Due to the high torque required by the mill, low speed motors are generally synchronous machines. The mill is a low dynamic system therefore a brushless synchronous machine is best suited for this application. Brushless synchronous motors have no wearing parts, and the AC/ AC excitation power is kept small. The drive provides the supply and the excitation control as well as the necessary protection. The brushless exciter is a separate rotary transformer mounted on the motor shaft. For these high torque low speed motors, efficient cooling is required. The choice is between water cooled totally enclosed motors or open machines weather protected type II enclosure and filter air inlet. In addition to their high torque capability, synchronous motors offer a wide field weakening range. The low speed solution motor used with the drive has a nominal frequency varying from 10 – 20Hz.

The main benefits of the low speed motor solution with only 8 to 12 poles, beside the lower capital cost compared to the traditional low speed motors with 30 to 40 poles, is the compactness of the motor. Less weight, smaller dimensions and therefore easier installation create less demand in the foundation design and less issue for the transportation of the equipment on site.

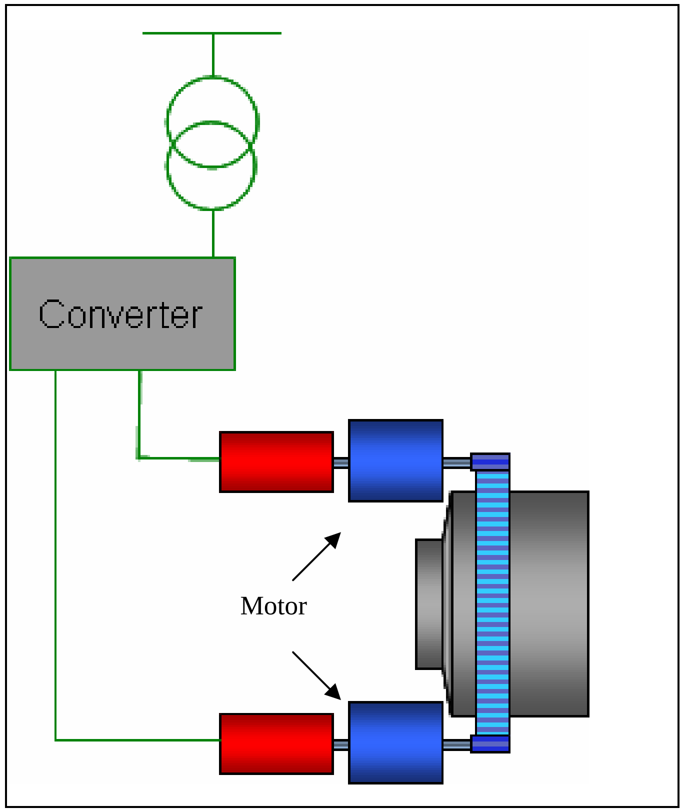

Figure 6. Arrangement drawing of high speed solution.

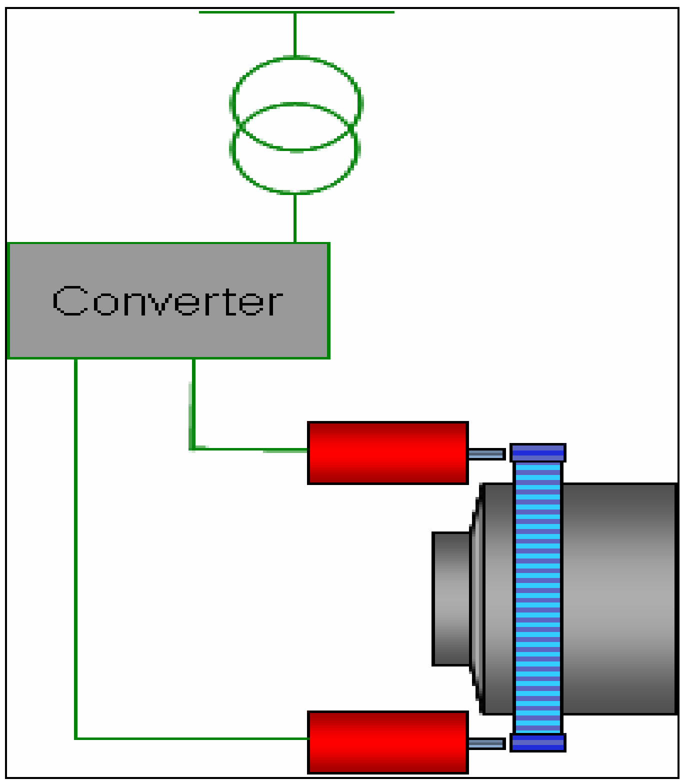

Figure 7. Arrangement drawing of low speed solution.

Depending on the power, flange mounted sleeve bearings mounted on the end shields of the motor, or pedestal mounted sleeve bearings, are provided. The motors with integral pedestal bearings are as easy to mount and align as motors with flange mounted bearings; no further assembly is required on site. A jacking oil pump permits operation of the motors at low speed (approx. 5-10% of nominal speed) both during the starting sequence and service mode. Also for the low speed solution the bearings are electrically insulated and the shaft is grounded.

PROCESS – FLEXIBILITY IN OPERATION

As the size of mills driven by ring-gear has increased, the network and the mechanical equipment are getting more and more sensitive to rough operation. The challenges to operate and protect the mill are getting bigger and require special attention. In addition the maintenance has to be optimized in order to keep shut downs and the loss of productivity to a minimum.

The use of frequency converter allows process optimization and brings flexibility for the operation, while reducing the maintenance by extending mechanical components lifetime. Furthermore, maintenance time on the mill can be reduced by using the main drive system to perform the visual inspection and the positioning of the mill for liner changes, allowing more production time.

The electrical and mechanical implications of mill operation, considering the actual size, can not be neglected. Controlled operation and soft starting behavior are nowadays practically a must to keep or to increase the system overall availability. The inherent advantages that come with a frequency converter combined with mill operation features and protections programmed in a dedicated controller have met the requirements of these demands.

Process optimization

The aim of the optimization of a grinding circuit is to increase throughput, lower variability of the resulting particle size, diminish the energy consumption and reduce grinding media utilisation and wear (such as balls, water, liners, etc.). The process gets an additional and easy to change variable: the speed. This improves the complete grinding circuit and reduces at the same time the consumables.

The inherent feature of a frequency converter is to be able to vary the speed of the mill to meet the process requirements. The system can rapidly react to changes in quantity or quality of the ore characteristics allowing the operator to adjust the speed accordingly.

These variations can be caused by different ore hardness, type of granularity, or the content of other ores and non-soluble products, etc. or by a different feed size distribution. Even if variable speed during operation is not required, it gives the opportunity to tune the speed of the mill for optimal grinding and maximum throughput, without needing to change any mechanical components (e.g. pinions or ball charges) during starting of mine operation or over the years as the ore characteristics changes. If the mill is operating with partial load, the drive is capable of adjusting the speed according to the fill level of the mill. This ability means the grinding throughput can be matched to the up- and down-stream process requirements without stopping the process and also energy is saved.

Fine tuning of the speed of a mill optimizes the process, leading to a much more efficient use of grinding power and thus to significant energy savings. It decreases the need to regrind the ore that does not reach the required particle size and therefore increases material recovery and lower the grinding media consumption and increases in the same time the productivity and efficiency of the flotation (in case of copper). Speed variation of the ball mill avoids over grinding and affecting down stream processes in cases the SAG mill cannot compensate ore variations.

When a ball mill is overloaded for whatever reason (hydro-cyclones short-circuited for example), the operator has the chance to increase the speed to the mill and reduce the mill load and keep the process running. On mills without variable speed, when a mill is overloaded it has to be isolated and the ore feed to the SAG mill has to be reduced impacting the production. If the opposite occurs, and the mill is under loaded the speed can be decreased as described above until the mill speed correlates with the throughput again

In case of a short stoppage of the SAG mill just for checking something on the shell, drum, etc. the ball mills are not stopped, as would be the case for fixed solution, only the speed is reduced and as soon as the SAG mill is in operation again the process starts smoothly just by increasing the speed of the ball mills, avoiding production loss draining out the mill and sumps. This allows reducing the consumption of fresh water. Variable speed also allows a controlled clean out of the mill, and to drain the sump if the mill has to be stopped for a long period, permitting a faster restart.

Increasing the availability of the mill operation is also a factor that increases the mill throughput. A less network sensitive and relatively maintenance free drive such as the voltage source inverter with the possibility of a ride through functionality allows operation and starting with reduced supply voltage or to overcome voltage dips during operation requiring fewer restarts and achieving more grinding time.

Speed control allows the mill to run faster or slower to find the optimal operating point, maintaining a constant output particle size despite of changing of ore grade or liner wear effect. These variations can be caused by different ore hardness or by a different feed size distribution. Process optimization can lead to more efficient use of grinding power and thus to significant energy savings, by providing higher quality of milling and therefore reducing the need of regrinding circuits.

Two types of optimization come into consideration: off loop and on loop. Off loop speed control gives the possibility to optimize the initially calculated speed as well as to change the mill speed over the mine life-time reacting to the different ore changes. On loop speed control allows the dynamic control of the complete grinding circuit.

Process flexibility

Beside the optimization of the process that increases the quality and the throughput by turning the mill at its optimum speed, the other key of success which allows maximization of the overall production of a mine is the flexibility grade of the grinding circuit.

Within traditional fix speed (FSD) process, as it is not possible to adapt the speed, the bottle-neck for the whole process line is set by the limitation of one of the mills. With variable speed process, all mills can be adjusted to their optimal performance, which leads to a debottlenecking of the line and to a higher production rate.

Another very important point to consider is that the load distribution on ball mills fed by a SAG mill is not equally distributed; with a frequency converter it is possible to run each ball mill with different speed according to their load.

Speed regulation allows circuit feed rate control and the balancing of the whole circuit. Moreover, partial load operation at any speed is possible. This ability means the grinding throughput can be matched to the up- and down-stream process requirements.

Speed variation of the ball mill, for example, avoids over-grinding which affects down stream processes. Over-grinding occurs when the SAG mill cannot compensate ore variations, and the adjusting of the ball charge is impractical.

Furthermore, on short SAG mill stoppages, the ball mills can be kept in operation with reduced speed, avoiding unnecessary shut-downs linked to production losses.

MILL OPERATION AND PROTECTION

The increasing size of mills requires particular attention on the stress that the selected drive equipment can generate to the mechanics. This applies especially on ring-geared mill drive solutions. Frequency converters can protect the mechanics during normal operation and starting by limiting the torque.

Starting

One of the main challenges is to have a smooth start with low starting currents and low mechanical stresses especially for high power and dual pinion mills.

From the electrical point of view high inrush currents and low power factor create high stresses and voltage drops endangering the other consumer in the plant.

From the mechanical side the torque pulsation and peak torques generated by all types of fixed speed solution during starting ages the mechanical equipment.

With a voltage source inverter the start is not anymore a problem. The power factor is kept at > 0.95 lagging under all conditions during starting and operation. Even if the non linear load generates harmonics, these are kept to a minimum thanks to the 12 and 24 pulse configurations. The drive can provide full torque from zero speed allowing the machine to start directly coupled to the mill without an air-clutch. This reduces capital and maintenance cost as well as mechanical wearing components.

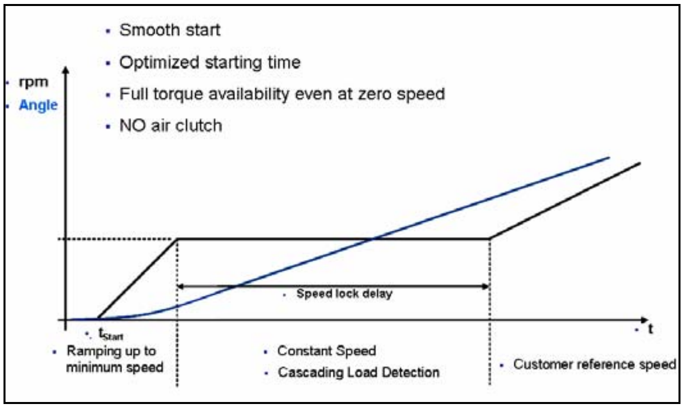

Figure 8. Starting phase of the mill.

The high dynamic performance and torque control over the operating range of a voltage source inverter, specially with DTC control, allows the mill controller to take care of the starting sequence by accelerating the mill to a minimum speed (usually approx. 10% of nominal of speed) while the frozen charge protection is activated. It keeps this speed until it is confirmed that the material has started to cascade, before accelerating to the operational speed. The time frame for the starting is adjustable. Usually it takes less than one minute to bring the mill to operational speed. This allows a really smooth start without high torque steps.

Torque control

Adaptive torque control and limitation, backlash control (also known as damping the gear run out) reduces mechanical stress and contributes to overall life cycle costs. The ring gear and the gearbox are protected from torque pulses by the fast and accurate drive control.

The torque limitation is practical as well during commissioning. It helps to start the mill first time with a limited torque to start up the mill without being exposed to a risk of damage as it is by direct on line switching on. Possible faults in the mechanic can be detected at the beginning and being fixed before a bigger damage happens.

Control Functionalities

The modern ring-geared drive systems provide to the user the same functionalities as the Gearless Mill Drives. Features like

- Service Speed without inching drive
- Load Sharing
- Frozen Charge Protection
- Controlled Roll Back
- Starting Control

are integrated into the drive system and allows a safe and comfortable operation of the system.

REDUCE MECHANICAL WEAR

Another big challenge for the mill operation is to reduce the mechanical wear. This allows a longer life time of the liners, balls as well as pinion and gear. Improving the mechanical wear increases the availability of the mill besides reducing the costs of the consumable. Having the grinding loop designed for running the mill in both directions permits the use of them on both sides and increases the time between replacements, allowing more productivity. With a voltage source inverter this feature is available just by changing a parameter.

The availability of low operational speeds, besides optimizing the grinding quality depending on the ore characteristic and load, allows filling and emptying of the mills during any process interruption while still protecting the liners and minimizing their wear.

Beside liner protection and prolongation of their lifetime, permitting a higher throughput a special attention has to be taken to the drive train.

ELECTRICAL NETWORK FRIENDLINESS

The mills, as already mentioned, are one of the biggest consumers inside a mine; therefore limiting the current requirement specially during starting helps the network stability and reduces voltage dips. In fact, from the electrical point of view, high inrush currents and low power factor create high stresses on the network, endangering the other consumers in the plant. Generally, this occurs when big direct on-line induction motors or synchronous machines are started. Very smooth starting behaviour with low starting currents, indeed are possible by starting the mill with frequency converters supporting the network.

Another advantage of frequency converter solutions is that they are able to operate at reduced voltage and try to stay on-line as long as possible, by reducing the speed and the required torque. While this, the motor acts as generator and utilizes the kinetic energy of the rotating motor and driven equipment. The power loss ride-through time depends on the relationship between the load and the inertia of the rotating masses.

When the supply voltage recovers, the drive starts back normally in speed control according to the speed set point. The surviving time depends on the energy stored in the inertia. Only if the power is lost for a longer period of time or if the situation is dangerous for the converter, the drive system switches off. This feature is especially beneficial for weak networks.

MAINTENANCE AND REDUCED SHUT DOWNS

Equipment with high reliability and availability increases the time between shutdowns improving the productivity of the mine. Gearless mill drive and the low speed motor solution for geared mills offer the highest availability. With the reduced mechanics for these solutions (no air clutch and no gear reducer) the maintenance requirements and possible root cause for failures are minimized.

To prevent major shutdowns, regular inspections and maintenance of the ring-gear, pinions, bearings and gear reducers are required. The high speed motor solutions (FSD), in the earlier design with gear reducer and inching drive, are due to the more complex drive train, the most maintenance intensive solutions. The lifetime of gear reducers is not matching the lifetime expectations of the mill and need to be replaced earlier. Furthermore, the bearings of the gear reducer have a standard lifetime of down to 3 to 5 years.

The electrical equipment itself does not require high maintenance. Frequency converters and transformers today are designed and built to be as maintenance free as possible, virtually without wear parts. From the motor point of view, beside the annual visual inspections and the standard measurement, no major maintenance is required. In order to keep the equipment in good condition regular planned maintenance shall be done according pre-defined maintenance plans.

For the pinion solution, brushless synchronous motor and induction machine require minimal maintenance such as replace filters, oil and other consumable if needed. This would not be the case for wound rotor induction motor (WRIM), where maintenance on motor itself and starter are higher.

Liners replacement represents a major cause of mill shutdown. Bi-directional operation of mills prolongs the liners replacement and it is easily achieved with a converter. Furthermore, during commissioning and startup while running with only partial fill, the speed can be lowered, avoiding liner damages and limiting unnecessary wear. Harder liners with longer life-time can be used from the beginning, eliminating the need of softer starter-liners and the associated costs related to their replacement. The variable speed solution also avoids damage to the liners during filling, emptying and process interruptions by lowering the mill speed.

During commissioning the torque can be set to a low value and be limited in order to prevent serious damages in case there are mechanical problems not seen before starting.

The frequency converter solutions support the maintenance activities by providing service modes for creeping and accurate positioning. No additional inching drive is required, simplifying the whole drive train. Creeping mode (slow rotation of the mill) can be used for visual inspections or grinding out the mill. Fast and automatic positioning of the mill based on angle or liner reference reduces the down time needed for changing liners. This is supported by a so called "controlled roll-back" function which brings the mill smoothly into a rest position where both speed and torque are zero. Having the mill in balance load condition, allows safer and faster maintenance procedures. To ensure the complete safety of maintenance personnel and equipment required performing liner changes inside the mill mechanical park brake system or a dynamic brake system are recommended. However the dynamic brake system is only required for big GMD mills where in case of absence of lubrication, they support the stoppage of the mill, preventing damages on the mill bearings.

Preventive and predictive maintenance, however, are necessary to keep production alive and to maintain the equipment reliable in operation. Therefore, the combination of shorting maintenance time and having reliable equipment is essential.

Remote access to the equipment through a secure internet connection allows fast access to check drive status from any global location. This remote supervision and diagnostics option supports site maintenance personnel during service and trouble-shooting and minimizes downtime and production losses.

OPERATE BALL MILLS WITH A FREQUENCY CONVERTER?

Even if from process itself the use of frequency converters on Ball Mills is not the most common thing there are many good reasons to think about using variable speed drives for Ball Mills as well.

Some comments from users that have already installed variable speed drives at the Ball mills:

Sometimes - when harder or softer ores enter the mill - it is impractical to change the ball charge. Its much easier to vary the speed".
Senior Process Engineer, EPCM AU

Speed variation allows circuit feed rate control if required downstream

In case of inventory load up in the SAG mill (lot of reject), the large particles can be send to the Ball mill, operated at a higher speed."
Representative of a US mill builder

Speed variation of the Ball mill avoids over grinding and affecting down stream processes in cases the SAG mill cannot compensate ore variations

When a Ball mill is overloaded for whatever reason (e.g. hydro-cyclons short-circuited), the operator has the chance to increase the speed of the mill and reduce the mill load within a certain time and keep the process running...on mills without variable speed, when a mill is overloaded, it has to be isolated and reduce the ore feed to SAG Mill... Impact in the production".
"The opposite, when a Ball mill is not sufficiently loaded, the speed can be decreased and adjust the circuit sump pump / mill / hydro-cyclons".
"The load distribution to the Ball mills is a non ideal process , so it is possible to run each Ball mill with different speed according its load.
Operator, Large Copper Mine CL

Variable speed allows to balance the whole grinding circuit

When the Sag Mill is stopped for a few minutes just to check something in the shell, etc... the ball mills are not stopped, only the speed is reduced in order to avoid problem with the liners and the material is re-circulated....then as soon as the SAG mill is in operation again, the process start smoothly just increasing the speed of the ball mills..... otherwise with fix speed ball mills, you have to stop them, then the time to re-start the plant is longer (loss of production). Besides when you stop the mills the operator has to drain out the mills and sumps.... It means to send all this slurry to the tailing thickners... increase the consumption of fresh water
Operator, Large Copper Mine CL

For short SAG mill stoppages, the Ball mills are kept in operation with reduced speed, avoiding unnecessary shut-downs linked to production losses

It was found that the mill speed calculated in advance was not optimal. …the mill speed was finally set lower than that calculated … resulted in a saving in energy costs of about 5%
Copperplant, Papua New Guinea

Possibility to optimize the speed over the life time of the mine for different types of ore

Ore hardness changes as you dig deeper into the ground. It obviously depends on the site, but the ore near the surface is typically softer and gets harder the deeper you get. Lake Cowal in NSW (Barrik Gold) use VSD on the Ball Mill because of that. The Mill was designed for the hard ore they expect further down - but at the beginning they are grinding softer ore. Now, to adapt to softer ore - you either reduce the ball charge and keep the speed the same OR you keep the ball charge the same and reduce the speed. In Lake Cowal, the ore was so soft that the resulting ball charge would have been too small and grinding efficiency would have suffered.
Senior Process Engineer, EPCM AU

The control of the grinding circuits is aiming for higher throughput, lower variability of the resulting particle size, lower energy consumption and lower grinding media consumption.

This requires the manipulation of the following variable flow rates:

- Freshfeedrate
- Waterpumprate
- Mill speed

Therefore an installed frequency converter on a Ball Mill provides the user additionally flexibility in the process and should be seriously considered while designing the grinding circuits.

LIFE CYCLE COST

The forehand mentioned issues shall in this section now being verified based on a mill installation of 26foot and a power of 16MW.

It is focused on the four different drive solutions, namely:

- gearless mill drive solution (GMD)

- low speed brushless synchronous solution 200 rpm, dual pinion (LSS)
- high speed induction solution 1000 rpm, dual pinion (HSS)
- high speed induction fixed speed solution 1000 rpm, dual pinion (HSS-FS)

Capital expenditure (CAPEX)

In this article, the *CAPEX* is defined as the amount of money spent to acquire a mill and its corresponding drive and bring it into operation. In other words, it is the cost to buy, install and commission a mill in order to get it ready for production. It is assumed that it is a green field project, thus all grinding equipment, building, cabling, etc need to be acquired and nothing can be re-used from an existing plant.

In the *CAPEX* calculation, the following elements were included:

a) mechanical and electrical equipment

Table 1. Equipment considered for Capex calculation.

MECHANICAL	GMD	LSS	HSS	HSS-FS
mill drum	x	x	x	x
mill auxiliaries (lube system, etc)	x	x	x	x
flange to connect the rotor poles	x			
girth gear		x	x	x
pinion		x	x	x
low speed coupling		x	x	x
gearbox			x	x
highspeed coupling			x	x
set parking brake	x	x	x	x
inching device with mechanical equipment				x

ELECTRICAL	GMD	LSS	HSS	HSS-FS
motor	x	x	x	x
converter	x	x	x	
main tansformers	x	x	x	x
excitation transformer	x	x		
harmonic filters	x			
power factor correction	x			x
starter				x

In GMD, LSS and HSS, no inching device is needed as this operation can be done with the main drive, which has the capability to rotate the mill at the needed creeping speed.

For GMD, a harmonic filter and power factor correction unit was considered in order to have the voltages and currents comply with the demanding network standards. In the HSS-FS a power factor correction (capacitor bank) was included in order to get the power factor to an acceptable level of 0.95 lagging.

b) foundations

The complete foundations for the mechanical and electrical equipment are considered. For the GMD, the ring-motor is foot-mounted and its foundations need approx. 15% more concrete and steel than for the three other systems.

c) cabling hardware

The cable is extremely site dependent. However for the three variable speed solutions the cabling cost was estimated to be the same. For HSS-FS, the cabling is simpler as there is less equipment to be interconnected. Therefore, shorter cables and less connection material, such as cable lugs, are needed for the fixed speed solution.

d) installation

There is a difference in the mill and motor installation time for the different drive systems. This time is about 4-6 weeks longer for the GMD because the motor will be wrapped around the stator on site.

The installation of the rest of the electrical equipment is considered to be the same for the three variable speed systems. For HSS-FS, there is less equipment and cable installation work because the system has fewer components.

e) commissioning

The commissioning of GMD, LSS and HSS was considered to be in the same range. As for the HSS-FS, the commissioning is shorter.

f) not considered

The following items were not considered in the calculation: set of capital spare parts, programmable logic controller (PLC) for monitoring the alarm and trip signal, motor control centre (MCC) to power the auxiliary systems of the mill, motor and converter and buildings.

However, the cost of these elements is in the same range for the four selected configurations and does therefore only marginally influence the *CAPEX* ratio between the four systems.

The relative comparison of the *CAPEX* is shown in the figure below. The GMD is clearly more expensive as far as the initial investment costs are considered. The additional costs are mainly driven by:

- higher motor cost
- need of a harmonic filter system
- more bulky foundation
- longer installation time

These high costs of the GMD on one side are partly compensated on the other side by the cost of the expensive girth-gear, pinions and gearbox in LSS, HSS and HSS-FS. However a difference of at least 20% still remains.

Some parts of the CAPEX are strongly country dependent, namely the concrete price (for the foundation) and the labour cost (for the installation and commissioning) – under the assumption that local work forces are used and concrete is produced locally. A sensitivity analysis was carried out on these two figures: doubling and halving them. Surprisingly, the *CAPEX* ratio for the different solutions only changed by maximum 3%. The reason for this is the fact that most of the *CAPEX* is driven by the mechanical and electrical equipment which is not influenced by the end-user's country

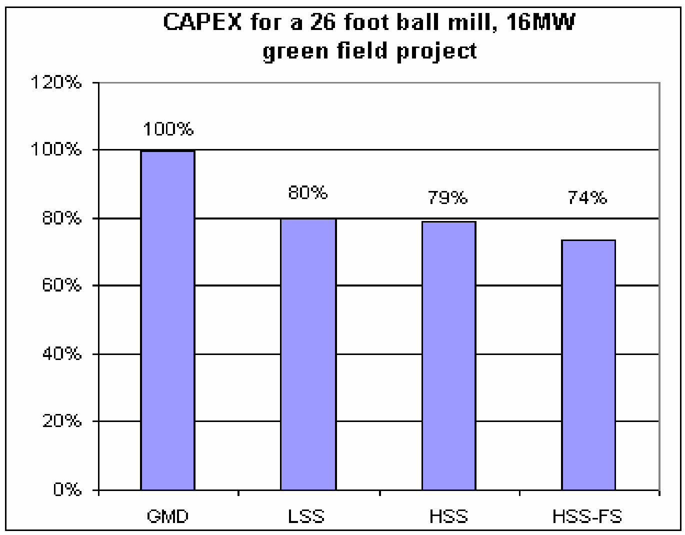

Figure 9. Capex comparison.

Operating expenses (OPEX)

In this article, the *OPEX* is defined as "the company's expenses associated with the operation of the mill and its drive in order to grind ore". The focus of this calculation is based on the differences of *OPEX* between the four considered systems.

In the *OPEX* calculation, the following elements were included:

a) efficiency

Table 2. Efficiency comparison.

	GMD	LSS	HSS	HSS-FS
mechanical efficiency [%]	100.0	98.5	97.0	97.0
electrical efficiency [%]	95.3	94.9	95.4	96.6
total efficiency [%]	**95.3**	**93.4**	**92.5**	**93.7**

The electricity cost was assumed to be 0.075 US$ / kWh

b) availability

Table 3. Availability comparison.

	GMD	LSS	HSS	HSS-FS
yearly availability [%]	94.8	94.5	94.1	94.1

The availability takes into account the time needed for regular maintenance such as liners change, visual inspection; unplanned stops due to equipment failure and process stops due to factors external to the drive system.

The cost of lost production due to non-availability of the grinding equipment was assumed to be 1 MUS$ per day. This figure corresponds to a large concentrator plant in South America, assuming in case of a failure of one ball mill.

c) maintenance

Table 4. Maintenance comparison.

	GMD	LSS	HSS	HSS-FS
grease for pinions and gearboxes		x	x	x
other consumables and spare parts	x	x	x	x
maintenance manpower	x	x	x	x

For LSS, HSS and HSS-FS maintenance manpower is needed for pinion alignment (or at least checking of the alignment). 8 hours each 4 months were considered.

d) major overhaul of the LSS, HSS and HSS-FS

It is assumed that after 10 years of operation, the girth-gear, pinions and gear-boxes must be replaced due to the wearing.

The replacement of the girth-gear takes typically 288 hours (i.e. 12 days x 24 hours). This is considered as time during which the grinding equipment is not available (i.e. loss of production). The gearbox can be replaced in parallel to the girth gear in order to save time.

Table 5. Overhaul comparison.

	GMD	LSS	HSS	HSS-FS
girth gear & pinion replacement after 10 years - equipment cost		x	x	x
work to replace the gears & pinions		x	x	x
gearbox replacement after 10 years - equipment cost			x	x
work to replace the gearbox			x	x
cost of loss of production during gear change		x	x	x

e) increased grinding efficiency due to variable speed operation

For HSS-FS the grinding efficiency was considered to be 3% lower than for GMD; LSS and HSS. This is an estimation based on the fact that with a variable speed configuration, the motor speed can be adapted to match the exact process needs. In fixed speed configurations, however, the electrical energy might be wasted when the motor operates at a higher power than needed. The cost of these wasted 3% was converted in kWh and priced

f) not considered

Apart from item e) above, several other benefits are present in variable speed configurations compared to fixed speed system. Some of them are:

- Soft start of the mill in order to reduce mechanical fatigue on the gears
- No torque transients over the whole speed range (as opposed to torque pulses when the resistor-starter is short-circuited in HSS-FS)
- Precise frozen charge detection
- Controlled roll-back in order to stabilise the mill quickly for liner change
- Automatic positioning of the mill for liner change
- Match the ball and SAG mill throughput
- Fast reaction of the grinding circuit depending to ore hardness variations
- Liner lifetime increase

These benefits have not been quantified in this paper, but they clearly will make the variable speed solutions even more attractive to the operators.

Some other general items were not considered for the *OPEX* calculation, namely:

- rental of building and other infrastructure
- manpower for normal operation of the grinding circuit
- cost of liners due to normal wear
- interest rate on the *CAPEX*

The results of *OPEX* calculation is shown in the Figure 10 below. They represent the **additional** operating costs compared to GMD. It can clearly be seen that the cost are the lowest for GMD, mainly due to the higher efficiency and availability.

The impact of the major overhaul of the girth-gear, pinions and gearbox can clearly be seen after the 10th year of operation.

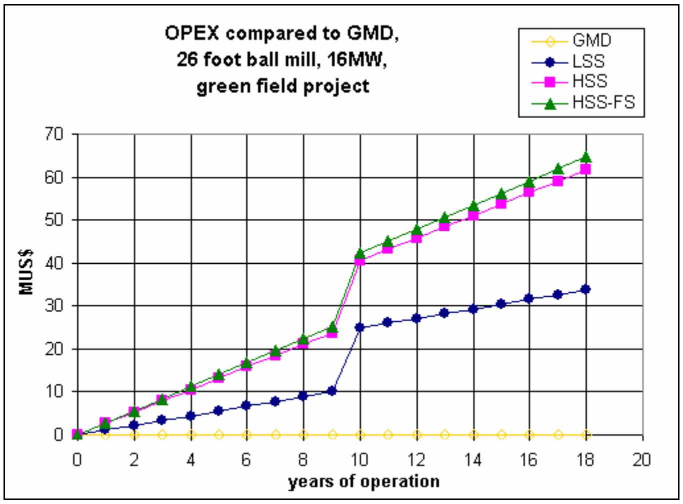

Figure 10. Opex comparison.

Payback time

A crucial question to be asked is: “after how many years is it more cost effective to have a GMD, LSS, HSS or HSS-FS ?” Such a question is raised more and more as mine owners become aware of the fact that a lifecycle analysis will optimise their cost on the long run. The table below gives the answer of the payback time of the different solutions compared to each other for a 16MW, 26 foot ball mill.

Table 6. Payback time in years for different solutions driving a 16MW, 26 foot ball mill.

	LSS	HSS	HSS-FS
GMD	5	2	3
LSS		1	2
HSS			8

Examples how to read the above table:

– after 3 years of operation, the total cost (i.e. CAPEX and OPEX) of GMD becomes lower than HSS-FS. In other words, the payback time of a GMD versus a HSS-FS is 2 years.
– after 1 year of operation, the total cost (i.e. CAPEX and OPEX) of LSS becomes lower than HSS. In other words, the payback time of a LSS versus a HSS is 1 years.

As mentioned earlier, several benefits of the variable speed solutions were not quantified and therefore not included in the above calculation. Including these benefits would increase the payback time of the variable speed solution compared to the fixed speed one.

Choosing a solution based on *CAPEX* will optimise their cost for the first few years **only**. But if the cost needs to be optimised for the entire lifetime of the equipment, the *CAPEX* **and** *OPEX* need to be looked at.

REFERENCES

1. ABB (2003), AC Drives Technical Book.
2. Errath, R. A., (2005), Cycloconverter operation.
3. Ahrens, M. & Gonser, J., (2007), Technical and Commercial Benefits of Gearless Mill Drives for Grinding Applications, SME 2007.
4. Brosch, P.F., (2008), Moderne Stromrichterantriebe, Vogel 5. Auflage.
5. Ravani von Ow, T., (2009), Milling - Energy intensive and high maintenance; Overcoming the Challenges Using Frequency Converters, Mapla 2009.
6. Anglo Technical Division, technical paper on the occasion of the SAG 2006 in Vancouver, B. C. Canada: “Lessons learnt from recent failures of gear drives on mills in South Africa”.
7. Ravani von Ow, T., Bomvisinho, L., (2009) Use of the latest technology to overcome the demands of mill operation, CMP 2009.