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Mill drives: the desire for increased power and the associated limits and conditions

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Abstract

Experience has shown that many of the recent large mill drives have not been adequately matched to the process requirement of the associated mills over their intended operating life, and especially with respect to the variability of comminution test parameters over the longer term mine life (precluding a plant expansion). This paper provides/offers an approach to resolving such mismatching with respect to restrictions which result from sometimes inappropriate selection of mill and motor sizes, drive components, and equipment specifications. It will also feature specific examples of options for resolution of such problems where this has been possible in existing operating plants. Some guidance will be provided to avoid such problems in new designs.

Keywords

"Payback", specifications, risk, power rating, torque output, design mill speed, torque demand, limitations, stresses, guidance

Mill Drive Review

Background

With ever – decreasing mineable ore grades, increasing mining and processing rates, the use of larger unit size equipment, and a minimal number of grinding lines in the plant, risk assessment, (in terms of achieving a rated design mill throughput on budget), requires detailed study. The principal objective, therefore, is to attempt a guaranteed payback of capital investment within a specified period, and following a program of sensitivity analyses.

Unfortunately, some installations have failed to reach design mill throughput rates because of inappropriate selection of test samples, testwork, design criteria and/or equipment, leading to prolonged financial loss and recovery period. Retrofitting additional equipment, e.g., pre-crushing, is becoming commonplace in an attempt to rectify such losses.

Normally, operators require some confidence in predicting mill throughput rates in the context of wide ranging variability in "ore hardness" about a "design point." Typically, mill throughput rates from a large open pit can vary considerably during the course of a few days, e.g., from 40,000 tonnes per day (tpd) to 80,000 tpd through a single grinding line. Over the last 30 years, DJB Consultants, Inc. has proposed and executed programs which have assisted mining companies in achieving their production goals and which have involved:

- A dedicated drilling program (PQ dia., core is preferred), separate from resource drilling, which will adequately encompass the proposed "Payback" period and the first 10 years of mine production. Contiguous samples are selected by bench level and within the desired pit envelope for comminution testing, e.g., for a Bankable Feasibility Study, it is recommended that the density of drill hole locations be such that one sample per week of mine production is taken as a minimum, each 15 meters (one bench height) to 30 meters in length (depending upon the variability of lithology, and particularly the intensity and variability of mineral alteration)
- Simulation of comminution test results by established methods for confirmation of design criteria and required power levels, particularly for the distribution of power between primary and secondary mills about a "design point." These selected power levels and the total circuit specific energy consumption, kilowatt-hours per tonne, and expressed as "E total kWh/t" per sample, can be entered into the Mine Block Model for non-linear geostatistical prediction of intermediary values of E total into blocks between the locations of known samples. Thus, prediction of mill feed rates can be linked with enhanced precision for optimization of mine production schedules and utilization of mine equipment
- Selection of a "design ratio" of primary mill power to secondary mill power that permits the range of variability samples to be processed according to whether a "SAG Mill limiting" condition, i.e., harder ore, or a "Ball Mill limiting" condition, i.e., softer ore exists. For example, a ratio of 1:1.5 or up to 1:2 would indicate a trend away from processing harder ore types and an increasing bias toward processing softer ore types, whereas a ratio of 1:1 or higher would indicate a bias toward processing harder ore types in selecting a "design point." This process is particularly important in selecting power levels and sizing grinding equipment for processing ore during the designated "Payback" period, as well as in determining possibilities for any future plant expansion, e.g., add pebble crushing, a second SAG Mill, or a third Ball Mill
- Due diligence reviews of equipment specifications and life cycle durability for mills and motors prior to manufacture; this process began in the late nineteen-seventies and early eighties with the move away from fabricated SAG mill heads and more detailed specifications for non-destructive testing (NDT) of welds.

Matching Mill Drive Description to Mill Requirements

Once the power level for the primary (SAG) mill has been set, i.e., design tonnes per hour (tph) x design E_{total} kWh/t from the "geo-comminution" sample profile, serious thought can be applied to sizing the required grinding equipment. Space here does not permit a detailed discussion of all the associated topics and the reader is referred to Barratt (1989), Hanks and Barratt (2002), Barratt and Sherman (2002), Barratt (2009), and Barratt and Zuñiga (2013, 2014)

Primary Mills

The iterative process of sizing primary mills is based on testing the sensitivity of mill length, i.e., the effective grinding length (EGL) inside feed end liners and discharge grates, motor rated power output, torque output, and rated speed (expressed as mill speed in the case of gearless mill drives, (GMDs), and shell liner/lifter wear so that the expected range of operating conditions can be accommodated once the mill diameter has been set. In this respect, the ratio of mill diameter to mill length EGL is important as it affects selection of the rated speed. The progress of moving to larger diameter SAG mills with decreasing D:L ratios is illustrated in Figure 1. As indicated, these progressive delays in the use of larger diameter mills (please see in the next paragraph) have coincided with a trend toward processing harder ore types and higher mill throughputs which have influenced selection of the number of grinding lines and capital cost vis à vis the use of HPGR and intended pre-crushing.

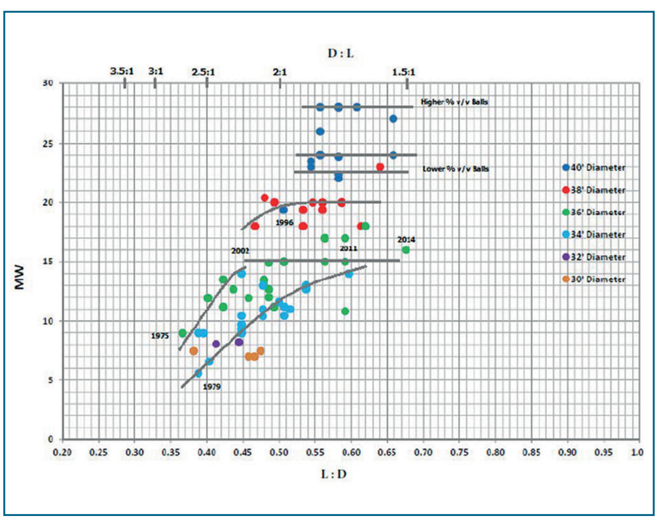

Figure 1: History and Development of Large Mill Power and Mill Sizes for Primary Mills in SABC Circuits

In general, for high-aspect mills, higher ratios of D:L permit operation at higher mill speeds for a given rated power output. Lower ratios of D:L have been frequently rated at 72% C.S. to 74% C.S. but, as will be seen in Figure 2, there is an advantage to be gained in raising the rated power output and increasing the rated speed to 78% C.S. Both MacPherson and Turner predicted optimum ratios of 3:1 for D:L, whether for wet or dry operation. At the time (1964), these gentlemen were dealing principally with single-stage mills processing iron ore to final product. For two-stage circuits, D:L has been progressively moving toward 2:1 or less as perceived and time-dependent design limitations on mill diameter have been exceeded. For example, the D:L ratio for 32 ft dia. mills decreased from 3.00:1 to 2.17:1 over 35 years until the advent of 36 ft dia. mills in 1973. The D:L ratio for 36 ft dia. mills decreased from 2.53:1 to 2.06:1 over 23 years until the first 38 ft dia. mill was purchased in 1996. The 38 ft dia. mills are 1.87:1, with special cases at Freeport (2.08:1) and Olympic Dam (1.60:1), and the Cadia mill (the first 40 ft dia.) is 1.97:1 and rated at 74% C.S. and 20 MW (Jones, 2001).

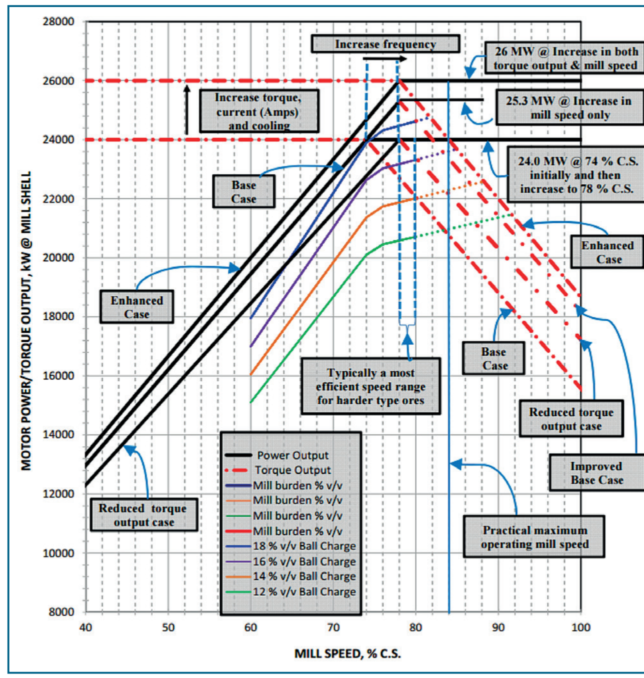

Figure 2: On achieving enhanced operating capability to 18% v/v ball charge volume or better (from 14% v/v) by increasing mill speed to 78% C.S. and then torque output, to bring power output capability to 26 MW for a 40 ft dia. x 22 ft EGL SAG Mill

Lower D:L ratios in Figure 1 correspond to an increase in mill volume for a given mill diameter. Any increase in power output, however, is related more to $D^{2.5}$ rather than to $D^{1.0}$. Therefore, many of such longer mills have and will experience restricted mill throughput instead of former consideration of a larger mill installation with diameter at the design stage.

Between 2001 and 2008, a limit of 22 MW was placed on SAG mill drives (as GMDs) by some operators and principal motor designers/manufacturers until the reasons for known problems in design or manufacturing were better understood and resolved. Accordingly, the latest 40 ft dia. SAG mill is rated at 29 MW and 78% C.S., with a 42 ft dia. mill built but not yet operational. The more recent option of operating at higher ball charge volumes (15% v/v to 20% v/v) has in turn led to higher motor power ratings.

Secondary Mills

The standard method for sizing secondary ball mills (usually the overflow type) in AG/SAG circuits follows published mill supplier information with aspect ratios in the range 1:1.5 to 1:2.0, depending upon product sizing and pulp flow, i.e., the highest expected circulating loads (Morrell, 2001). The applied net power, calculated from testwork and power-based modelling, as well as iterations of transfer size to balance the distribution of power output between primary and secondary grinding, will have been based on mill speed and shell liner/lifter simulations and, particularly, ball charge volume and ball top size, both of which are dependent upon the contingency applied to the transfer size in the SAG circuit product. Iterations of these parameters can be performed in some models (e.g., DJB's "Reduced Recovery" and "Millpower2000") to determine the desired motor power and drive rating, the maximum design mill speed, and the maximum design ball charge volume (Barratt, 1989).

For single pinion and dual pinion drives, with 21 MW now a distinct possibility, the probability of pinion changes to a higher mill speed should always be considered when setting gear ratios, service factors, and motor power ratings. For gearless drives, motor torque output at the maximum desired operating mill speed and ball charge volume has to be determined.

Primary Mills:
Torque Output (by Motor) vs Torque Demand (by Mill)

For the purposes of this discussion, "drive speed" refers to the output speed of any mill drive system, whereas that of a GMD refers to actual motor speed in rpm or mill speed in% of critical speed, (% C.S.), depending upon the extent of shell liner/lifter wear.

The charts in Figure 2 (after Barratt and Brodie, 2001) illustrate the following lines in examples for a 24 MW Base Case GMD at 74% C.S. in the first instance and then at an enhanced capability of a 26 MW GMD with increased torque output and mill speed at 78% C.S. for comparison, e.g.:

- Increasing power output capability in MW up to the design mill speed, beyond which power output capability remains constant at the rated value
- Increasing torque demand of the mill charge on a per unit basis at variable levels of ball charge volume as the mill speed increases, initially on a straight line relationship and then at a diminishing rate as mill speed increases beyond a certain threshold
- Constant torque capability of the motor at 1.0 per unit up to the rated mill speed (@ 74% C.S. for the 24 MW Base Case), and at 78% C.S. for the 25.3 MW Improved Base Case, beyond which torque output capability declines in each case in proportion to an increase in mill speed
- Operating limits are indicated by the "tent" of power output capability and torque output capability, at which point the DCS current display would turn from "blue" to "red," as follows for the 24 MW Base Case: 74% C.S. for 18% v/v ball charge volume; 77% C.S. for 16% v/v; 80% C.S. for 14% v/v, and 83% C.S. for 12% v/v; and for the 25.3 MW Improved Base Case: 80% C.S. for 18% v/v ball charge volume: 83% C.S. for 16% v/v: 84% C.S for 14% v/v: and 84% C.S. for 12% v/v
- Operating limits are indicated by the "tent" of power output capability and torque output capability, at which point the DCS current display would turn from "blue" to "red," as follows for the 26 MW Enhanced Case: 82% C.S. for 18% v/v ball charge volume; 84% C.S. for 16% v/v; 84% C.S. for 14% v/v, and 84% C.S. for 12% v/v.

Accordingly, the operating limits for both Cases are within the power capability at constant torque output capability, but only the 26 MW Enhanced Case would allow the motor to drive the SAG mill for the full range of ball charge volume levels at higher motor torque output and mill speeds. Improvement of the 24 MW Base Case to 25.3 MW at constant a torque output and for operation at a design mill speed of 78% C.S. would improve operation of the mill at little additional cost. Alternately, a change in rated mill speed for the 24 MW Base Case to 78% C.S. from the original 74% C.S. would result in a cheaper motor, i.e., less copper would be applied to provide the same rated power, but at a reduced torque output capability. The disadvantage of this alternative, however, would cause operation with 18% v/v ball charge volume to be sacrificed.

In these examples, the mill charge volume is held constant at 25% v/v and the maximum operating mill speed is held to 84% C.S. Operation with the 26 MW Enhanced motor offers a wider range of processing capability under the "tent" of power and torque outputs for a more cost-efficient purchase of power output, e.g., an 8.3% increase in power output capability for a 5.4% increase in mill speed, in comparison with the 24 MW Base Case motor. This capability is especially important in a context of processing harder ore types at higher mill feed rates within a defined range of geo-comminution variability samples and lower grade ore reserves.

Primary Mills: Operating Philosophy

The most important factor in the selection of the motor for variable speed AG/SAG mills is, in the authors' opinion, definition of the design or rated speed of the motor or, in other words, definition in the "peak" of the "tent"; i.e., the power output capability at a particular motor speed or, in the case of GMDs, mill speed. This is very often an iterative process (Barratt and Brodie, 2001), especially when bids from mill suppliers are being technically reviewed. Figure 2 illustrates the difference between selecting a lower mill speed at 74% C.S. and a higher mill speed at 78% C.S. for a 40 ft dia. x 22 ft EGL SAG mill with a 24 MW GMD and fitted with 54 or 36 rows of Hi-Hi lifters at 30° relief angle. Figure 2 also takes the issue to the next step of ensuring that the motor power output and torque output are sufficient to accommodate an 18% v/v ball charge volume at 30% v/v total mill charge volume with worn shell liners and raising the rated power to 26 MW and the rated mill speed to 78% C.S.. This arrangement will allow the mill operators more flexibility in processing a range of softer to harder ore types, in optimizing shell liner/lifter design, and defining the range of "sweet points" for optimum power efficiency at higher mill speeds. It is also important to involve the mill vendor, liner supplier, and liner handler supplier early in the design process for optimization of liner design and liner replacement time, in as much as any change in shell liner design may impact on motor requirements.

Review of Mill Drive Limitations

This part of the review will not dwell on the relation between any given mill size and the associated drive capacity but it will explore the possibility of modifying a given drive to operate at higher power and/or speed than the purchased specification. It will attempt to show how the various components are limited and how changes in service can be expected to affect the life of each component. This applies generally to single pinion and dual pinion drives, but specifically to GMDs.

Effect of Cyclic Stress

The various parts of the equipment are subject to different stresses. Depending upon the constraints used, if there is any cyclic variation there will be a fatigue life. This is established for each material by testing and it is illustrated by plotting stress versus cycles or time. The tests cover the range of stress over which the material is to be used.

The most recognized stress is mechanical, which affects all of the parts including the stator structure, the windings, and many of the auxiliaries. In the case of steel, the testing and the plotting will demonstrate an increasing cyclic life as stress is reduced until the "endurance level" is reached. At and below this stress level, life becomes infinite.

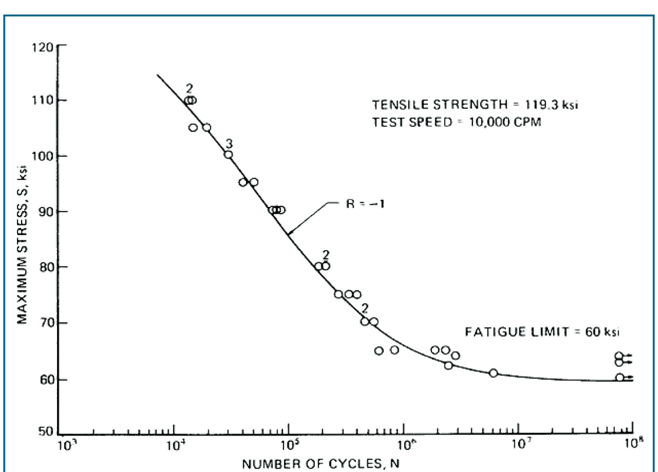

Figure 3: S-N diagram for typical high-UTS, low-alloy steel, and failure data with best fit curve
Source: ASTM Manual Series, J. Barsom & S. Rolfe

The second form of stress is thermal. For this discussion, the material involved is the insulation of the windings. For example, and considering specifically contemporary Class F insulation, increasing the temperature increases the rate of breakdown of the chemical binders in use. The stress is defined by the absolute temperature and life is typically given in hours. The thermal stress is evaluated according to Arrhenius' relationship within the operating range of contemporary insulation materials, and this indicates that an increase in temperature of 8°C will halve life and correspondingly a decrease of 8oC will double life.

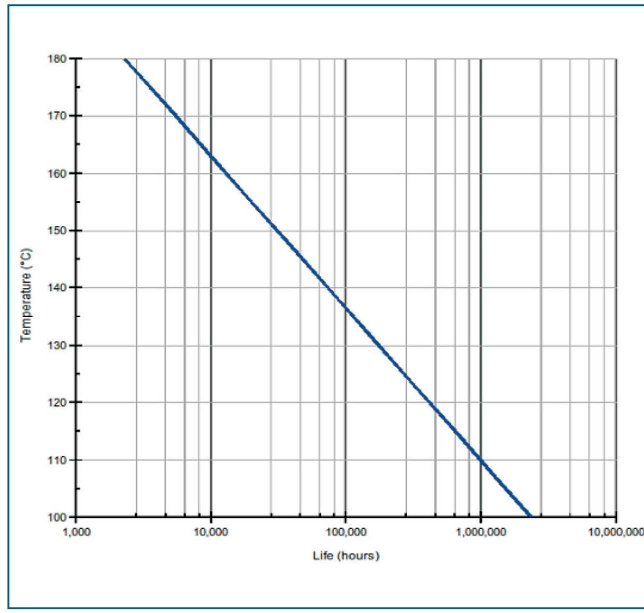

Figure 4: Typical thermal endurance for Class F insulation as a function of temperature, using single factor testing and according to industry standards

The third form of stress to be considered is potential (voltage). Every insulating material will severely limit current flow as long as the stress is below its breakdown value. This refers specifically to the passage of current through the material but not to any current that might pass on a contaminated surface.

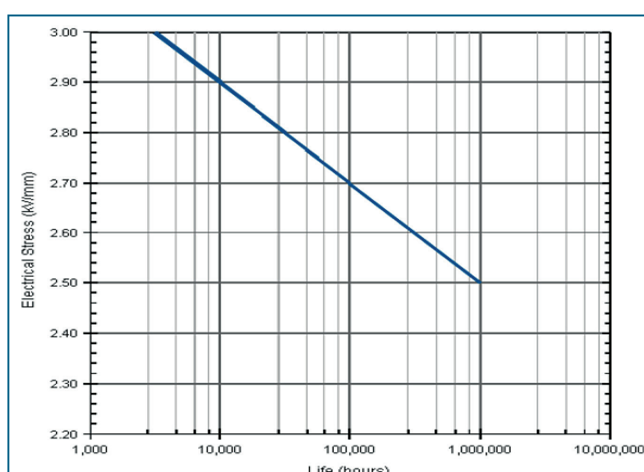

Figure 5: Typical voltage endurance curve for m-v, epoxy, VPI winding

Where there is a series of different insulating materials between an energized conductor and ground, the potential will be divided inversely to the product of the specific conductivity and thickness of each of the materials. A particular problem arises when one of the layers is air. As the stress approaches the breakdown value, it reaches the Corona Initiation Voltage, whereby the air is ionized and produces ozone. Ozone is an active oxidizer and will erode the adjacent material. The breakdown stress for air is dependent upon the air pressure as described by Paschen's relationship. A contemporary designer will avoid having air as part of the insulation by application of vacuum pressure impregnation (VPI) within the insulation as well as a conductive outer coating during manufacture to establish the ground surface.

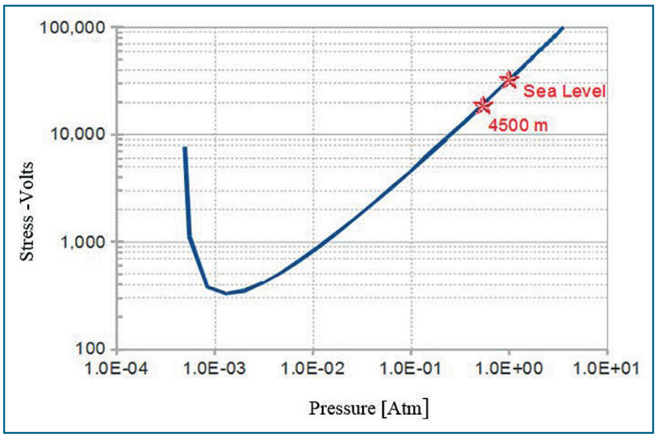

Figure 5: Typical Paschen's curve for air; shown as a function of air pressure

Motor Structure

The stator frame must resist unbalanced radial forces both in normal operation and during electrical faults with deflection limited to less than the air gap. No part, section, joint or fastening can be stressed beyond its endurance limit – this varies for typical steels depending on alloying and treatment, both of which are selected by the designer. In addition to resisting radial deflection, the structure must not have a mechanical resonant frequency in the operating speed range to avoid damage from vibration. The designer will ensure that the least resonant frequency is more than 1 Hz above the rated speed. The design of the frame must allow for the change in size with change in absolute temperature including both ambient temperature and that due to losses in the machine.

The field poles are attached to an extended mill head flange. They are installed to be concentric with an air gap of the order of 5/8-inch (15 mm).In service, the concentricity cannot be maintained so provision is made to operate with a minimum air gap of about 5/16 – inch (8 mm).The attachment must transmit the torque and accept the varying radial force during every revolution. The stator is constrained horizontally but not vertically so the bore in operation is not circular. In addition, the rotor is not always concentric because of bearing clearances and any deflection of the structure because of loading. It must also be recognized that current designs have no means for differential adjustment of the air gap along the axis of the machine. As the required power has progressively increased from 5 MW towards 35 MW, the corresponding increase in axial length is causing concern amongst designers and users

There have been some notable problems in operating motors that have led to enhanced design practices, specifically: stator joints that have loosened, stator securing bolts that have loosened, and stator flexibility that was excessive. There have also been field pole welds that have failed. All of these problems have been recognized, explained, and not repeated.

Motor Windings

Stator windings are generally classed as high voltage but there are two distinct design approaches in use. Single turn coils allow relatively easy replacement of a damaged coil side. Multi-turn coils permit the use of a higher voltage, which may reduce the sizing of auxiliary equipment and the interconnecting conductors. Parallel winding would reduce stress during faults. Each designer can make a case for the most appropriate selection.

The insulation of the windings is subject to all of the different stresses. Depending upon the constraints used, if there is cyclic movement there will be a fatigue life just as for the steel frame. Abrasion results from movement of the coils primarily within the core slots whether it is caused by thermal change or magnetic forces. The effect of movement is limited by tying or blocking to restrict movement. The temperature to be experienced is dependent upon the ambient temperature, the losses, and the cooling.

In addition to mechanical stress and thermal stress, the insulation is subject to potential (voltage) stress. A designer must consider all gradients both within the core slots and at each approach to any other surface at a different potential.

The field pole windings are low voltage but subject to the same stresses. A field pole might occupy only 30 of the circumference but be several feet long. The limited space between poles makes it difficult to constrain the windings without restricting the cooling.

There have been some notable winding failures in both stator and field poles. These have been explained and should not be repeated.

Slip rings and brushes require polishing and replacement, respectively. Similarly, the seals protecting the rotating elements require servicing. These are the only consumables associated with a GMD motor.

Motor Auxiliaries

Cooling depends on forced circulation of air to carry away the heat of the losses. The heat is absorbed through a heat exchanger supplied with a cool medium (typically water or a mixture of water and anti-freeze). It is ultimately transferred to a heat sink through another heat exchanger (e.g. a radiator).The air may be circulated by one or more fans. At high altitude, reduced density of the air requires a correspondingly increased volume to transfer the waste heat with limited temperature rise. This system will require conventional servicing of motor and fan bearings, etc. It will also require servicing of the heat exchangers and pumps.

Electronics

The power to the stator is supplied as low variable frequency 3-phase electricity. The frequency depends on the desired motor rotation speed but could be in the range of 6-10 Hz. This has generally been obtained from gate-turn-off (GTO) thyristor – equipped cycloconverters (CCV). Consideration is now being given to isolated gate base transistor (IGBT) voltage sources because they can control power factor and greatly reduce harmonics.

Cycloconverters along with other electronic equipment must be kept dry, clean, and cool. They are generally provided in separate enclosures with their own cooling system, fire protection, etc.

One industry guideline suggests that component development is limiting the economic service life of major electronic assemblies to about fifteen years. Associated with this is the developing need for manufacturer support for maintenance because failures are so infrequent that operating staff get no practice.

Transformers

The transformer(s) for the stator power supply are generally outdoor oil-filled units with radiators but no fans. The oil is not pumped. Limiting temperature rise raises the efficiency and extends transformer life.

The transformers are typical multi-winding power units with allowances for harmonics resulting from the commutation of the thyristors.

There have been some early transformer failures resulting from a misunderstanding of the service and some later failures from overloading. Both causes can be avoided.

Cables

The cables between the electronics (CCV) and the motor should be limited in temperature rise for efficiency and life expectancy and have upgraded insulation due to the harmonics in the current from the CCV.

Drive Investigation

Every drive has a limiting part because each is a particular combination of commercially available components. As an example, the development of a CCV will use a single thyristor rather than either parallel or series combinations as the size increases to the maximum available thyristor. The selection of each component of a drive has an effect on the efficacy, efficiency, and life of the drive. This can be further affected by the manner in which the drive is used.

Every drive is purchased with a nominal service rating. This defines the power to be delivered to the mill shell and the rated speed. If more torque is required, more current must be provided. If more speed is required, frequency must be increased. If both torque and speed are to be increased, current, voltage, and frequency must be increased. These changes affect every part of a drive and accordingly every component. The effect on each component must be weighed against its corresponding life expectancy, whether the limiting stress is mechanical (structural), thermal, potential (voltage), or magnetic. These tend to be interdependent but the following discussion will examine the effect of each separately, as follows:

- The rated temperature rise of the motor might be 60oC. If the current is increased by 10%, the heating will increase by 21% and the temperature rise will increase by about 12oC, which is within the nominal permitted temperature for Class F insulation but the life of the insulation will be less than half of the design value.
- The maximum current for a CCV depends upon the rating of the selected thyristor. Thyristors have a very short thermal time constant so that small excursions beyond the rated current are limited to seconds and larger excursions to milliseconds. A given CCV will be used with a range of drives and the available margin would depend upon whether the drive is using its maximum rating or a fraction of its capability. A small increment might be obtained with enhanced cooling but the benefit would be limited.
- Transformers are generally selected to operate at nominal insulation life temperature rise at rated load. If 10% more current is drawn, the life of the transformer will be reduced to less than half of the designer’s intended life. The effect can be reduced by making provision for fan-forced cooling and/or forced oil circulation, but it should be understood that the life expectancy will be reduced.

Operating in excess of rated speed (in excess of rated frequency) gives a constant power output by directly reducing the available torque output. This will require adjustment of the operating conditions (i.e., torque demand, ore charge and/or media mass).

Here it must be recognized that the wear of mill linings causes a significant change in mill performance. The working diameter of a mill with new lining is typically one foot (0.30 metres) smaller than the nominal mill size (inside shell diameter).The working diameter of a mill with end-of-life lining is typically only 0.5 foot (0.15 metres) smaller than the mill diameter. This change reduces the speed at which the onset of centrifuging will occur (i.e., critical speed or C.S.).The larger diameter will hold a larger ore charge/media mass which dictates a maximum torque demand and the mill must be slowed to maintain a constant percent of C.S. Unless a drive has been selected to serve a torque demand for a maximum ore charge/media mass and a speed of about 80% C.S. with new shell lining, it will be limited over some part of its potential operating range.

Conclusions

Existing installations have allowed drive designers to refine the requirements for components and reduce the margin for ignorance. A designer will use the smallest commercially available component that exceeds the design requirement. When considering the possibility of operating a drive beyond its design rating, every component should be reviewed to ensure that the increased stress will not unreasonably reduce the life expectancy of the component and, therefore, the availability of the drive.

It should be recognized that these considerations affect every change in operating conditions; as an example, having a Service Factor greater than 1.0 indicates that operation beyond the nominal rating is possible without explaining that the life will be reduced and other characteristics such as power factor will be adversely affected. These problems are avoided if a drive is selected with adequate torque output to support a maximum fluidized ore charge/media mass with worn liners at a rated speed about 80% C.S. with new shell liners, and a Service Factor of 1.0.

Manufacturers Response to Requests for Increased Drive Output

The request to increase the operating power of a grinding mill and its GMD results from the owner's experience in operating and grinding performance. Siemens realized several projects of power increase of their GMDs after having them in operation for months or years. The components of a GMD have standardized sizes of capacity and therefore may have natural reserves for the specific application.

The power increase of a GMD requires a detailed study to:

- investigate and determine the possible reserves of components in actual operation
- verify electrical and mechanical limitations of the equipment
- re-design components of the deficiency in capacity to achieve increased power of the GMD.

A principal goal of this study is to continue the reliable operation of the GMD with increased power over the lifetime of the plant.

The main component of the GMD is the Ring motor, which is wrapped around the mill like a ring. Siemens investigates the conceivable reserves of the Ring motor as part of the study for a power increase. The main ageing process of an electrical motor is the ageing process of the winding insulation. As has been explained by Brodie in the previous section under "Limitations", the main ageing reserves of a Ring motor refer to the temperature reserves of the winding system and the state of the insulation of the winding. The standard design of the winding insulation of a Ring motor is according to Class F and it is also common to use an insulation with a temperature rise according to class B. This concept shall not be changed by the power increase of the motor.

The power loss of the motor creates heat, which increases the temperature of the motor. The cooling system of the motor limits its temperature rise to the specified class.

If the winding temperature of the motor does not reach the temperature limits of class B insulation during nominal operation, the motor has thermal reserves which can be used for a power increase. Siemens investigates the temperatures of the stator and the rotor windings, respectively. The temperature of the stator windings are continuously measured by Resistance Temperature Detectors (RTD), which are installed in the winding slots. This temperature indication is available on the Human-Machine Interface (HMI) and it is easy to protocol them. To get a useful measurement, it is necessary to wait until the winding temperature has reached a steady state at the rated power or close to it. The real power should also be protocoled as a basis of the calculation of temperature reserves. As rotor windings do not contain temperature detectors, temperature of the rotor windings is measured by a heat-run test, which is in this case a cooling-down test. After several hours of nominal operation, the motor is switched off and the ohmic resistance of the rotor winding is measured in steps of several minutes. The curve of resistance values over time is extrapolated back to the time of operation. As the ohmic resistance of copper depends on temperature it is possible to calculate the average temperature of the rotor winding from the resistance during operation.

Normally Siemens does not measure the partial discharge of a Ring motor for the investigation of a power increase because all of its Ring motors are equipped with VPI insulated stator windings, and these are designed to exhibit minor ageing. Furthermore the voltage is hardly changed for a power increase.

An increase in rated power can utilize the detected temperature reserves. Siemens Engineering can also increase the rated power through re-design of the cooling system of the motor. The cooling fans as well as the heat exchangers may be replaced to increase the cooling capacity of the motor. The higher cooling capacity allows higher power losses, created by a higher rated current. The higher rated power requires a higher rated current because the voltage is hardly being increased.

The electrical and cooling design, however, is not the only part to be investigated. The mechanical design of the motor should be able to resist higher forces and higher cyclic forces due to higher power and torque outputs. Any increase in rated power of a motor at the same rated speed increases the rated torque output of the motor and consequently all forces in the motor structure increase with a consequent increase in the forces on the foundation. Many of those forces are cyclic loads on material and welding. Cyclic forces cause material fatigue, so the reserves for material fatigue must be conserved.

The power increase will also modify the electrical characteristics of the motor. The magnetic pull in the air gap will be different. Consequently, the behaviour of the air gap requires verification to keep it within its limits. The modification of the magnetic pull also changes the natural frequencies of the motor stator. Therefore, Siemens also studies the modified resonance behaviour of the motor after a power increase to ensure a safe minimum difference between the maximum operating frequency and the natural frequency of the stator.

Part of the power increase study is also verification of the cycloconverter. Siemens design their fuseless – and – short-circuit-proof cycloconverters according their resistance to short-circuit currents. Consequently, the rated current for normal operation rarely reaches its application limit and it may be increased. The cycloconverter is investigated, however, for its resistance against short-circuit currents. Therefore, Siemens asks for the value of the short-circuit capacity of the power supply as an input for the study.

With the short-circuit capacity of the power supply, it is necessary to calculate its impedance as one of the limiting values of the short-circuit current. The other main impedance which limits the short – circuit current is the impedance of the transformers of the GMD.

The transformers of the GMD are sized according to the data of the GMD Ring motor. The main input is the rated power of the Ring motor, additionally the power factor of the motor and the cycloconverter are important inputs to the design. To increase the rated power of the GMD, the power increase of the transformers is required. As all transformers of Siemens GMDs are designed to provide their rated power with natural cooling (AN; ONAN), it is possible to increase their power by installing cooling fans and to increase their power by forced air cooling (AF; ONAF).

Depending upon the requested extent of power increase of the GMD, it may be necessary to replace the transformers by others of higher power rating. This is a major investment and would be evaluated.

During a study for power increase Siemens also investigates the excitation system of the motor, which consists not only of the field poles of the motor, but also the excitation rectifier and its transformer, both of which provide DC supply to the field poles. Considering the modified design data of the motor, both the excitation transformer and rectifier are investigated for their capacity to provide the modified excitation supply.

	Example 1		Example 2		Example 3	
	before	after	before	after	before	after
Mill inner diameter [ft]	**34**		**36**		**36**	
Ring motor						
Rated power [MW]	**10.6**	**13**	**12.7**	**15**	**15**	**15.6**
Power increase	22%		18%		4.5%*	
Rated speed [rpm]	10.6	9.8	9.55	10.06	9.48	9.48
Rated torque [kNm]	9,549	12,667	12,684	14,245	15,110	15,722
Rated voltage stator [V]	1,900	1,900	1,900	2,000	3,900	3,900
Rated current stator [A]	1,733	2,145	1,986	2,310	2,331	2,566
New fans	Yes		Yes		Yes	
New heat exchangers	Yes		Yes		No	
New chiller	Yes		Yes		No	
Transformers						
Rated power [MW]	6,040	7,400	8,650	10,380	8,850	9,200
New transformers	No		Yes		No	
Cooling	ONAN	ONAF	ONAN	ONAN	ONAN	ONAF
Rated voltage HV [kV]	13.8		23		23	
Rated voltage LV [kV]	1.22		1.31		1.27	
Cycloconverter						
Thyristor change	No		No		No	
New heat exchanger	Yes		Yes		No	
Downtime for modifications (contemporaneous with mill maintenance)	approx. 7 days*		approx. 6 days*		2 days (planned)**	
Comments	*E-house extension for new MCCs		*Exchange of transformers		*limit of 4.5% set by mill **most modification work done during operation	

Table 1: Examples of power increase of Siemens GMDs

cate the range of achieved changes it has experienced. In these cases, the achieved torque output increased 33%, 12%, and 4%, respectively. In the first example the speed decreased (8%), in the second example the speed increased (5%), and in the third example the speed did not change. These new ratings may not be the best match to the associated mills, but they were considered to be optimal adaptations considering both cost of equipment and cost of down time. (Please see the following table for details):

Guidance for Operators

When an Operator and/or the Process Consultant find that plant capacity is limited by an installed drive, a review by the manufacturer should be requested. For this to be reasonably limited in scope, the manufacturer should be provided with a description of the design and operating requirements. The correlation between torque, speed, and power demand vs outputs has been indicated by Barratt in the previous section under "Matching Mill Drive Specifications to Operating Mill Requirements." The request to the manufacturer must include at least two of these three, and some other related data including:

1. What power is desired? (MW)
2. What speed (rpm) is desired? Has it changed from the original specification?
3. What torque output is desired? It should be noted that the available torque will be essentially constant from zero to rated speed then will drop proportionally as speed is increased above rated speed.
4. What is the heat sink in service? If it is water, what is the maximum temperature? If it is air, what is the maximum temperature of the air?
5. What is the anticipated life of the mine in case the insulation temperature is the controlling limitation?
6. An indication of the cost of down time. This will help crystallize the selection of alternatives. For example, adding fans to a transformer should require less downtime than replacing the transformer.

It should be recognized that design refinements have gradually reduced the margins for easily increasing the rating of newer drives, but the manufacturer will still be able to establish options to consider.

References

Barratt, D. J. (1989). An update on testing, scale-up and sizing equipment for autogeneous and semi-autogeneous grinding circuits. In A. L. Mular & G.E. Agar (Eds.), *Proceedings of the First International Conference on Advances in Autogenous and Semi-Autogenous Technology* (Vol. I, pp. 25-46). Vancouver, BC: SAG.

Barratt, D. J., & Brodie, M. N. (2001). The "tent" diagram, what it means. In D. J. Barratt, M. J. Allan, & A.L. Mular (Eds.), *Proceedings of the Third International Conference on Autogenous and Semi-Autogenous Grinding Technology* (Vol. IV, pp. 368-379).Vancouver, BC: SAG.

Barratt, D. J., & Sherman, M. (2002). Factors which influence the selection of comminution circuits. In A. L. Mular, D. N. Halbe, & D. J. Barratt (Eds.), *Proceedings of Mineral Processing Plant Design, Practice, and Control Symposium* (Vol. I, pp. 539-565).Vancouver, BC: SME.

Barratt, D. J., & Sherman, M. (2002). Selection and sizing of autogenous and semi-autogenous mills. In A. L. Mular, D. N. Halbe, & D. J. Barratt (Eds.), *Proceedings of Mineral Processing Plant Design, Practice, and Control Symposium* (Vol. I, pp. 755-782).Vancouver, BC: SME.

Barratt, D. J. (2009). Grinding circuits: What to look out for in design. In D. Malhotra, P.R Taylor, E. Spiller & M. Levier (Eds.), *Proceedings of Recent Advances in Mineral Processing Plant Design, Plenary Session* (pp. 15-33). Tucson, AZ: SME

Barratt, D. J., & Zuñiga, M. (2013). Geometallurgy vs plant development and Geometallurgy vs plant design. *Proceedings of the Segundo Encuentro Internacional Metalurgia, Plantas y Procesos,* Lima, Perú.

Barratt, D. J., & Zuñiga, M. (2014). Geometallurgy for comminution studies. *Proceedings of IOM3 Geometallurgy* 2014. London, United Kingdom.

Barratt, D. J., & Zuñiga, M. (2014). Comminution testwork in a geometallurgical plan and assessment of confidence in projections of mill feed rates. *Proceedings of GEOMET2014,* Santiago, Chile.

Hanks, J., & Barratt, D. J. (2002). Sampling a mineral deposit for metallurgical testing and the design of comminution and mineral separation processes. In A. L. Mular, D. N. Halbe, & D. J. Barratt (Eds.), *Proceedings of Mineral Processing Plant Design, Practice, and Control Symposium* (Vol. I, pp. 99-116). Vancouver, BC: SME.

Jones, S. M, Jr. (2001).Autogenous and semiautogenous mills 2000 update. In D. J. Barratt, M.J. Allan, & A. L. Mular (Eds.), *Proceedings of the third International Conference on Autogenous and Semi-Autogenous Grinding Technology* (Vol. I, pp. 362-400).Vancouver, BC: SAG.

Morrel, S. (2001). Large diameter SAG mills need large diameter ball mills: What are the issues?. In D. J. Barratt, M. J. Allan, & A. L. Mular (Eds.), *Proceedings of the third International Conference on Autogenous and Semi-Autogenous Grinding Technology* (Vol. III, pp. 179-193). Vancouver, BC, SAG.

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