A mechatronic Solution Design and Experience with large gearless Mill Drives

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ABSTRACT

In the mineral processing industry the use of large gearless cycloconverter drive systems for SAG-Mills has become more and more common in the recent years. Very high power ratings with excellent dynamic performance and high efficiency over a wide speed range allow advanced optimization of the process. The design of such large mill drive systems requires modern simulation tools to verify the system behavior. An optimized design must take into account the mechatronic interaction between all individual mechanical and electrical components. Calculation methods and related design targets must be defined in a very early stage of the project to allow simultaneous engineering.

INTRODUCTION

Since the late sixties, the development of larger autogenous, semi-autogenous and ball mills in the mineral ore processing and cement industries, was done by enlarging the traditional drive system incorporating low speed motors, driving mills via a mechanical drive train with single or dual pinion and girth gear. This solution reaches its economic and design limits with increasing drive sizes. Today mills are powered by up to 20,000 kW (Figure 1) and mills with up to 32,000 kW are in the engineering stage. Additionally, variable speed has become more and more desirable for optimized process control of the concentrator. The main advantages of cycloconverter drives compared to a conventional gear drive are:

- very high power ratings
- low maintenance and high reliability
- wide speed range with high efficiency for all operating points
- excellent dynamic performance and surge load capability
- low starting current
- no contribution to short circuit current
- no mechanical connection between motor and mill
- clock and counterclockwise rotation of the mill

The main area of application of gearless drives is the high power low speed range, where an extremely smooth operation, also at minimum speed is required combined with outstanding control characteristics for an optimized process.

The SAG mill drive is normally designed and optimized for the individual project. The requirement of the special process defines the size of the drive, the requested power and the operating speed range. The electric motor creates tension forces in the air gap that tries to pull the stator towards the rotor. Therefore the stiffness of the individual components of the drive system – motor, mill, bearings and foundation – must be adjusted to get a sufficient safety margin against inadmissible deformation. On the other side the interacting forces between the components must be kept to a minimum for economic design.

Incidentally, large SAG mills installed as on date are located mostly in critical seismic zones. The structure must withstand these severe acceleration loads without any harm as well as other faulty conditions like electric short circuit loads. A control system monitors the drive continuously and shuts down the system in an emergency.

FUNCTIONAL REQUIREMENTS

The SAG mill is the heart of the concentrator. Normally there is no redundancy in the plant (Figure 2). So very high reliability and availability is required under all operating conditions. The cycloconverter and its control system allows additional features for operation and maintenance, like creeping and inching (Figure 3).
In the beginning of Gearless Drives in the late 60ties the individual components were designed nearly independent. Only very primary interface information between the component vendors were interchanged, like foundation forces under operating loads and faulty conditions, mechanical and magnetic spring constants, mostly only as one way information. At that time, only small mill tubes were manufactured and also the magnetic forces were less compared to today's large high power mills. Mechanical design calculations were based on static load cases in terms of forces and acceleration loads. The simulation models were very coarse due to the rudimentary computer capacities which were available at this time. Also the pre- and postprocessing of simulation programs did not allow detailed modeling. Mostly 2D-FE models or axisymmetric shell models with Fourier loading were used. At the end of the 70ties larger mills were manufactured for wet grinding, the foundation data was calculated in much more detail and exchanged with the mill builder and the civil engineers and allowed iterative optimization of the mill systems. The engineering complexities increased because the gearless drive could no longer be designed according to the stress principles alone but also incorporated stiffness principles as well. Stiffness criteria should be defined and exchanged between the motor supplier, the mill manufacturer and civil works contractor. At this time all calculations were based mostly on linear static assumptions.

In the mid of the 80ties, even larger mills (32 ft/36ft) with power ratings of 12,000 kW and larger were engineered and therefore the diameter and the active length of the electrical motor increases also. With increasing size of the units, the dynamic behavior of the mill and its drive system became more and more important to prevent the drive from inadmissible resonance amplifications. Also the revised standards for seismic design like US Uniform Building Code (UBC) required detailed dynamic response spectrum calculations. The first steps to a overall 3D system model were done to examine dynamic seismic response of the complete SAG mill unit including foundation, mill & bearing as well as the electric motor. The analysis was also exchanged, reviewed and discussed with independent specialists.

**Design Of Converter And Control System**

The basic circuit of the converter is a cycloconverter in 12 pulse configuration. It has been selected considering low fault currents at remote mine sites and as it gives a smooth operation to the system. The control principle is based on orienting the phase angle of the stator currents in reference to the effective flux axis. To calculate flux conditions, the motor is simulated by two supplementary models. This enables the motors to be fed optimally across the entire speed and load range including positioning at speed zero. Based on a multiprocessor control system providing parallel processing of tasks superior current and torque characteristics are achieved. The control and converter equipment is shipped as a tested unit installed in a containerized e-house to the site to minimize erection and commissioning time and guarantee start-up in time.

**Electrical Design Of Motor**

The motor is designed for high efficiency, but also effective material utilization factors must be taken into consideration to get an optimized design. The efficiency factor of such a mill drive is governed by winding (copper) losses. Due to the small stator frequencies, the iron losses are low. The low speed of these mill drives leads also to negligible air friction losses of the rotating parts. Therefore the copper in stator and rotor must be increased to its maximum. That means for the stator winding: small no. of slots with high winding cross section and low terminal voltage to minimize the thickness of insulation. Limitations of winding cross sections due to cooling purposes must also be taken into consideration. The conductor cross section has to be split in several strands to limit the current displacement losses. In view of optimization the number of strands of one winding on top of the other is also to be limited. These tasks are fulfilled by coil windings which consist of high number of discrete windings. This design principle allows a high number of parallel branches of the stator winding leading to an effective damping of unbalanced magnetic pull when motor is rotating. The ohmic losses of the rotor are minimized based on the following design principles: low no. of poles and low no. of turns per pole combined with a small air gap. However there has to be taken in account that a lower no. of poles leads to higher yokes in stator and rotor and therefore to an increase in diameter and weight of the electrical machine and a minimum of air gap has to be defined in regard of tolerances for installation and functional aspects. A small no. of turns can lead to a detrimental ratio between excitation voltage and excitation current. Long term experience in designing these drive systems shows that efficiency of 97% with utilization factors of more than 10kVA/min/m³ are state of the art.

**Mechanical Design Of Motor**

The non-rotating part of the electric motor (stator) is a welded steel structure, which carries the active parts (core, winding, ...) and the auxiliary parts (terminal boxes, bus bars, fans, coolers, ...). The structure is split into three or four parts, depending on size of the drive, due to handling and transportation limits. Opposite to the mill design, where
fatigue and stress limits govern the design, the stator is designed for sufficient high stiffness and therefore the stress level in most of the areas is very low compared to material fatigue and yield. Due to stiffness and deformation larger mills require special foundation piers to shift the stator feet near to the center line. The most economic compromise between enlarging the foundation and/or stator structure must be found.

Detailed evaluations must be performed to get an optimized structural design. Mechanical calculation starts with the simulation of handling the parts in the workshop. The design must be able to withstand transportation handling, like turning, without any harm to the sensitive parts. Keep in mind, that these heavy stator parts with weights of up to 100 metric tons are “light weight structures”. The ratio of thickness of sheet metal to length is less than 2 ppm. Figure 4 shows the stacking of the stator core of a 36” foot mill drive.

Also the fixtures for transportation and handling on site must be integrated into the structure. Restrictions in size and weight have to be taken into account. The stator must be designed for minimum erection time on site. A reduced number of splits and special elastic winding coils help to minimize the closing of the windings by brazing on site. The erection procedure must be planned very carefully to get a sufficient roundness of the stator and a low tolerance for air gap deviation at the circumference. This reduces the air gap to an allowable minimum. Larger air gaps will lead to higher excitation currents and a decrease of efficiency.

The stator structure must have a sufficient high resistance against deformation under various operation conditions. The non-linear force vs. deflection relation of the magnetic field can cause inadmissible local reduction of air gap. These deflections can be promoted by assembly tolerances and eccentricity of the rotor. During operation the air gap distribution around the circumference is monitored by sensors continuously which shuts down the drive in case of emergency.

The converter driven motor allows the mill to run within a wide speed range from very low speeds for maintenance purposes up to the maximum speed required from the milling process. The stator structure must withstand the various forces and excitation frequencies generated by the process and by the electric motor itself. Restricted and non-uniform thermal expansion of the individual parts must be taken into account as well as high loads and dynamic amplifications in faulty conditions like short circuit and seismic events.

The interface between stator and foundation must also be designed for the related reaction forces. The bolted connection must withstand these loads without any relative movement, which can cause problems with the alignment of stator to rotor. The stator is erected in an axial shifted position at the end of the foundation piers to have sufficient access to the active parts of stator and rotor. The stator can be shifted in its final position by special roller plates and also back for maintenance access. Safety against seismic events must be also given for this shifted position.

Every electrical machine creates inevitable thermal losses. An effective cooling system must guarantee an uniform temperature distribution at the whole circumference of these large machines. Motor driven fans and air to water heat exchangers are distributed around the circumference of the stator housing. This patented satellite ventilation system guarantees uniform cooling air distribution in every sector of the machine. Thus temperature rise of the stator winding is equal along the large stator circumference. A high number of fans secure operation of the mill in case of fan failure.

The rotor is wrapped directly around the mill body. Pole segments with four electrical poles are fitted together to pre-assembled units to get a minimum erection time. These pole segments are connected to the mill flange by four bolts. The outward bolts are fitted with special adjustable bushings to allow local adjustment of air gap. All operational forces must be transmitted by friction to the mill flange to avoid the joint from abrasive ware. The effect of non-uniform thermal expansion between mill flange and rotor segment as well as ovalisation of the mill body has minor effect on SAG mill systems and is covered by the necessary safety factor for faulty conditions. The rotor coils consist of a solid copper bar with extended surface areas for cooling purposes. The fixation of the coils must allow thermal expansion but must have sufficient resistance against electromagnetic forces in case of a short circuit.

Special attention must be paid to the interface between the rotating and the non-rotating parts of the electric motor: the air gap. The magnetic field creates high radial tension forces between rotor poles and stator bore. The force vs. deflection behavior of this magnetic pull is extremely non-linear. Therefore possible deviations from the small nominal air gap generated by deflection or shifting of parts leads to significant differences in local magnetic forces along the circumference and to additional deflections. Local deflections during start up are much more severe than those at normal operation due to the non-linearity of the iron saturation curve. The influence of these electromagnetic forces is in general much higher than any gravity effect generated by the dead weight of the
In addition varying tangential forces will be generated by the magnetic field under each pole. The mean value of all these forces around the circumference is equal to the torque of the motor.

**Simultaneous System Engineering**

In the design phase of a mill project many different vendors must work together to get an optimized design of the system in very short time. Therefore in the early design stage, validated target values for the interaction between the major components of the drive system (motor, mill, bearings and foundation) must be defined to allow simultaneous engineering of the individual parts. Simple substitutes for very complex structural assemblies and processes must be found to allow a sufficient accurate forecast of system stability (Figure 5). For static load cases, linear stiffness and interface forces/moments or deflection are suitable. Any of these values needs an accurate definition to avoid misinterpretation. Safety margins must be defined to compensate deviations from final design. The mechanical design of a mill drive system starts with a simple spring diagram, which includes the compliance of the components and the assembly/operational tolerances.

With increasing size of the mill drives this simplified linear spring model must be substituted by a more accurate model, which includes the non-linearity of the local air gap force vs. deflection relation and allows the examination of natural frequencies. A principle of such a model is shown in Figure 6. The stator is modeled as a shell structure supported by linear foundation springs. The mill is added as a rigid body supported also by springs, which represent the stiffness of the mill body as well as the bearing and foundation stiffness. In the air gap local non-linear force vs. deflection relations were modeled according to the electro-magnetic behavior of the machine. Special FE calculation methods must be used to integrate the magnetic and mechanical behavior and to allow quick response times for optimization of the system in terms of deflection and vibration.

**Design Tools**

The analysis of such a complex mechatronic system consisting of mechanical and electronic components requires modern design and calculation tools. Normally the simulation programs have no features for direct accurate modeling of all requested effects. An useful simulation program system must have an open architecture to allow the integration of special effects, like local electro-magnetic behavior of motor and converter with sufficient accuracy. The FE program ANSYS allows direct access to the individual subroutines. Complete integration of the user controlled subroutines is necessary to get acceptable short processing times. In our case the non-linear force vs. deflection relations in any locations of the air gap were manipulated in each step of integration. A substitution with the electromagnetic equations for the motor components (rotor poles and stator windings) allows the direct calculation of the static and dynamic response of the mechanical structure by putting in the dynamic values for stator and rotor currents. Large deflections must be taken into account. Note that for example 1mm deflection of a 20m high structure is "small", but 1mm in a extremely non-linear air gap of 15 mm is "large". It is necessary to describe the magnetic forces acting between the rotor and the stator winding individually for each pole, as there is an interaction of local stator deflection, magnetic forces and air gap. Therefore a special subroutine is required, calculating the radial and tangential magnetic forces, being strongly nonlinear dependent from the actual air gap. Not only the radial air gap has to be considered, but also the local tangential displacement of the rotor/stator-system must be taken into account. Both values are time dependent, if the stator frame starts vibrating. Under normal running conditions the poles are partly saturated, which influences the excited magnetic forces. It is essential to include this effect into the model. The time dependency of the current generated by the converter also affects the magnetic forces, especially the local tangential torque component. This current con-
tains pulsations which can create excitations in a medium frequency range below the variation of the stator field. Finally it should be mentioned, that the stiffness of the mountings, supporting the stator frame, is of importance and needs to be modeled. Especially if the rigid body motion of the stator frame is in the same frequency range as its first elastic modes, this must be included.

**Verification Of System Stability**

Well known are in system dynamics "monotonous" and "oscillating" instability. Both situations can occur in large gearless mill drives, when the structural behavior of the system is not optimized.

**Monotonous Instability:** Radial magnetic forces between the rotor poles and the stator windings occur in the initial run up phase during the magnetization of the rotor, even if the stator field is zero and before the rotor turns. These forces increase, while the magnetization current grows. These radial forces start to deflect the stator structure (figure 7). The deformed shape is very similar to the transverse natural bending mode of the stator ("mode II"), but does not vibrate.

If the forces increase further and system stability is not given, this shape can become monotonous unstable. In this case the unstable growth of the bending of the stator structure starts slowly and increases rapidly later on, as given in the time presentation in figure 8.

**Oscillating Instability**

The tangential, "torque generating" forces, which are produced by the circulating field in the stator frame, and induce the turning of the rotor, may cause several, different dynamic effects:

Weak tangential, elastic vibrations of the stator frame (especially in mode II), excited by inequalities of the milling process, cause the

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**Figure 7:** Deflection of the stator structure under radial load (the deformed shape is very similar to the transverse natural bending mode, hereafter called "mode II")

**Figure 8:** Unstable growth of the stator structure bending, shown in its time behaviour.

**Figure 9:** Air gap deformation at standstill during increase of excitation current in steps of 10% of nominal value.
torque at the rotor (and stator frame as well) to vibrate along the drag angle curve with the same frequency. If the steepness of this curve is sufficient strong, self excitation of the stator frame may occur. If the sensor of the speed control is fixed at the stator frame measuring to the rotor surface, tangential motions of this sensor are induced, if the stator structure vibrates in the related mode shape. Also under such conditions self excitation can arise. Also fluctuations of the current by internal means of the converter may generate harmonics of the torque and excite the stator frame. If the converter produces a current, which contains a partition with double frequency of vibration – mode II, we can have an essential excitation of sub-harmonic origin of the order $\frac{1}{2}$. In this case the curvature of the drag angle curve is important for the stability of the stator frame motion (Figure 10).

Figure 10 presents an oscillating instability of the stator frame of the sub-harmonic type $\frac{1}{2}$. This simulation was done, using the FE-Program ANSYS, including the mentioned subroutines. Also this effect is strongly nonlinear, it depends additionally on the stiffness of the mountings, which supports the stator structure. Again the vibration mode II is excited to instability.

Most of the described effects are examples of starting oscillations of mode II, which seems dominant in the stability investigation. But one should be aware, that also combinations of these excitations, perhaps not strong enough to create instability by itself, can interact together to produce undesirable consequences. All these results demonstrate, that the design of the mechatronic gearless mill drive needs a careful layout, prediction of the dynamics (especially stability) and optimization, using modern computer simulation tools. A good knowledge of nonlinear vibrations is necessary.

Field Experience
Since 1980 the mineral processing industry has ordered 26 gearless drives of a total capacity of more than 300 MW. 20 systems in the power range of 4 to 20.4 MW designed for mills of 16.4 ft to 40 ft inner diameter are in operation. The largest installations in operation since 1998 are a 20.4 MW drive for a 38 ft mill at Freeport, Indonesia and a 20 MW drive for a 40 ft mill at Cadia, Australia.

The gearless drives are well established in this industry for their very high reliability. Experience in installation and operation and the demand of the industry for higher production rates by increasing the throughput have aroused the need for design improvements and challenged the engineering methods. In particular the first drive for a 40 ft mill was an encouragement to develop more sophisticated methods of engineering as preliminary measures had to be taken to make the system available in the full operational range of speed. This and the special attention of the maintenance team during the start up sequence allowed a production exceeding the designed value in the first year of production. Permanent solution is implemented and the validity of this measure is proven. Extensive investigation on site was performed.

All the findings are integrated in the design process as presented in the paper. Valuable experience was gained as system prediction and measurement taken on site matches the constellations in original, preliminary and permanent measure.

Conclusions
The engineering methods as developed and confirmed are concurrent even to the tasks of the upper range of rating of gearless drives giving as the following perspectives:

- Overall system optimization of foundation motor and mill considering soil characteristics at the site.
- System performance guarantee from the very beginning.
- Straight forward design ideas of larger systems. In the engineering stage at the moment are gearless drives of powers up to 32 MW for mills up to 44 ft inner diameter.

Figure 10: Oscillating instability of the stator structure of sub-harmonic type $\frac{1}{2}$
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