Abstract— Mining operations are facing the challenge of competitiveness because of low metal prices and operating costs. The only way to solve the problem is applying new design concepts in management, process operation, R&D and technologies, where industrial electronics and information technologies are taking a decisive role concerning process control, automation and personnel safety. The size reduction, crushing and grinding, is one of the main stages in mineral processing, because of energy, material and maintenance costs. Looking at economy of scale, new projects consider the use of big mill grinding circuits, where large power gearless motor drives with cycloconverters in the range around 20 MW are being applied for semiautogenous (SAG) mills and recently, ball mills are also being considered.

This work addresses some current issues involving design and application of high-power drives employed in SAG grinding mills, highlighting industrial electronics aspects:

• Complex nature of the process with large units
• Reliability and availability
• Operation within weak networks
• Power quality and harmonics control
• Process and knowledge-based instrumentation
• Mechanical and mechatronics aspects

Based on actual cases of application, the main constructive and operation aspects are described and the open problems for improving reliability and availability are discussed.

Index Terms— Drives, power converters, harmonics, mills, mining

I. INTRODUCTION

Cycloconverter-fed Motor Drives have inherent advantages for handling high-power low-speed applications with gearless motor drives intended for grinding mills, employed in cement plants and ore concentrators [1], [2]. Other modern applications in the MW range are flywheel energy and pumped hydraulic storage systems [3]. General considerations and criteria for evaluation of mill drives options have been discussed in [4], [5], [6]. For power greater than 10,000 Hp, mechanical pinion coupled drives have been considered as a limit for single drives because of the risk of long-time outages due to mechanical maintenance. In addition, for variable-speed operation including zero-speed and starting with full torque within limited short-circuit level, high-power gearless motor drives have shown advantages. Installations with units in the range of 20 MW are being recently designed and applied, and higher powers are considered to be feasible. High-dynamic performance has been achieved using field orientation techniques as well as observation methods for sensorless control [7] - [12]. However, the larger grinding units, especially the semiautogenous (SAG) mills have the drawback of being a bottleneck when one unit goes out of service, that is why, reliability and availability are the main concerns. The most commonly used converter is the cycloconverter, because of its inherent advantage to handle high power with low output frequency and 4-Quadrant operation. Under network disturbances, the phase-controlled cycloconverter must be blocked in order to avoid commutation failures, with the same nature of HVDC stations [13]. After a network disturbance, a reclosing may be very dangerous, like the situation which arose by re-closing large induction motors, as reported by [14] and [15]. Operation within a weak network should be carefully taken into account from the initial conceptual project stage, with a design based on specific modeling and simulation for meeting power quality requirements under the variable operating conditions [16] - [19]. There are also issues of mechanical and mechatronics engineering to be faced at the design stage in order to avoid mechanical resonances excited by the electromagnetic torque and forces [20], [21], [22].

II. BACKGROUND: SEMIAUTOGENOUS GRINDING (SAG) MILL WITH A GEARLESS DRIVE

Fig. 1 shows the general scheme of a mill with gearless motor drive. The rotor poles of the synchronous machine are bolted to the mill. There is no gear, because the electromagnetic torque is generated directly to the mill. The stator has a ring form, giving the alternative name “ring-motor” to this wrapped-around configuration. Typical value
of the airgap is in the range of 15-17 mm. A tolerance of +/- 3 mm is considered for setting alarms and protections. The motor is fed with variable frequency by a cycloconverter in order to regulate the torque and operating speed of the mill. The excitation is controlled by a 6-pulse controlled bridge.

Grinding or size reduction of mineral ore is made with large-diameter rotating mills where the mineral itself is used as a grinding media. This process is called “autogenous grinding”. A semiautogenous grinding mill (SAG) uses complementary steel balls of typical 5-inch diameter to support the grinding media. Fig. 2 shows the possible trajectories inside the mill. The tube mill has internal steel liners with lifters for lifting the load. The load builds a kidney form with a cataracting effect with different balls’ and rocks’ trajectories. The cataracting with trajectories impacting at the toe of the load is the most effective grinding effect. For higher throughput, large diameter mills are being employed to use this impacting effect. The movement of the load depends strongly on several operating variables like geometry, viscosity, ore size-distribution and rotation speed. In addition, the wearing of the lifters also plays also a role because its geometry changes with time. There are also harmful impacts because of the ball trajectories impacting in the lifters, with energy loss, accelerated steel ball wear and jeopardizing the life of lifters and the availability of the mill. That is why variable speed is needed for high-power mills. The useful range of operation speed is around 75% and 80% of the critical speed. The critical speed is defined as the speed at which a steel ball remains at the shell of the mill without falling when the centrifugal force equals its weight and is given by:

\[ w = \sqrt{\frac{2g}{D-d}} \]  

(1)

Where \( w \) is the critical speed, \( g=9.81 \text{ [m/s}^2]\), \( D \) is the internal mill diameter and \( d \) is the ball diameter. If \( d<< D \), with \( D \) expressed in [m], a good approximation which gives \( N_c \) for the critical speed in revolutions per minute (rpm) is given by:

\[ N_c = \frac{42.2}{\sqrt{D}} \text{ [rpm]} \]  

(2)

For example, a SAG mill with an internal diameter of 11 meters will have a critical speed of 12.72 [rpm]. For a
nominal speed of 77% the critical speed is 9.8 [rpm]. The bigger the diameter, the lower the nominal speed of rotation.

Fig. 3 depicts the scheme using a synchronous motor with two separated stator windings. There are also applications with only one stator winding. There is a current discussion concerning the advantages and drawbacks of both alternatives regarding issues of: efficiency, cooling, size, short-circuit behavior and reliability, among others.

Fig. 4 shows the connection of a twin 6-Pulse cycloconverter system to a 2-stator winding machine. The transformers have secondary windings with 30 degrees displacement in order to build a 12-Pulse equivalent cycloconverter at the network side. A symmetry current control is needed to ensure the proper balanced operation.

Fig. 5 depicts the use of a single stator winding machine. The 12-pulse cycloconverter is built by the series connection of two 6-pulse cycloconverters.

In both cases, the cycloconverter has a three-phase current control [17] with feedforward scheme using internal voltages of the machine for better tracking of the three-phase current references.

Fig. 6 shows the zero-crossing of the controlled current in one phase of the motor. A deadtime is set for ensuring a safe transition from a positive and negative converter with no-circulating current. The longer the deadtime, the larger the motor current distortion and vice-a-versa. Current distortion produces undesirable torque oscillations. It is very important to meet a trade-off between a desired small deadtime for a good quality of controlled current versus a longer deadtime with a higher safety margin at transition. Offsets in the analog current measurement may jeopardize this key behavior.

Fig. 7 depicts the simplified space-vector diagram of the synchronous machine. Stator resistance is neglected as a first approximation. The α-β axis is fixed to the phase “a” of the stator. The d-q axis is fixed to the rotor of the machine, where the excitation winding is along the d-axis, with relative position \( \theta_m \). The x-y axis is chosen with the resulting flux along the x-axis with relative position \( \theta_s \). The load-angle \( \theta_l \) is defined as the relative position between the flux and the magnetomotive force given by the excitation current \( i_e \). A vector control method is employed in order to have a good dynamic performance with decoupled control of torque and flux of the machine. Torque is commanded with the product of resulting flux \( \psi \) and active current component \( i_y \). The flux \( \psi \) is controlled by commanding the reactive component \( i_x \) and excitation current \( i_e \). The operating power factor of the machine is \( \cos \phi \), where \( \phi \) is the angle between the current \( i \) and voltage \( e \) at the machine terminals.

Fig. 8 shows a scheme for the vector control of the machine. There are three main control loops: speed controller, Flux-controller and a second flux controller for the excitation control. For sensorless operation, a voltage- and a current model are employed in order to construct the internal variables of the machine. There are other internal control loops (not shown here) for improving the performance of the three-phase stator current control and for reducing the
errors of the observed internal variables. Dynamical performance depends on the effective construction of flux and angular positions for the decoupled control. An important issue is operation at a very low speed (frequency) because the “inch” and “creeping” functions concerning the accurate positioning of the mill for maintenance and milling changes. Chapter V (the next chapter) show how vector control variables may help process control

III. POWER QUALITY ISSUES

Reliability, protection coordination, power factor and harmonics are the main issues to be faced at the very beginning of a project concerning new or retrofitting installations. Cycloconverters inject a distorted current \( I_0 \) into the network with superposition of harmonic and interharmonics currents components. For a 12-pulse configuration, a superposition of the harmonic components is given by:

\[
I_0 = \sum_{k=0}^{1} \{f_1 \mp 6k_f_0 \} + \{11f_1 \mp 6k_f_0 \} + \{13f_1 \mp 6k_f_0 \}
+ \{f_2 \} + \{f_3 \} + \{f_4 \}
\]

\( \{f_0 \mp 6k_f_0 \} \) is a term comprising the characteristic frequency component \( f_0 \) and its lateral sidebands. \( f_1 \) is the fundamental current component of the network side \( 50 \) Hz, \( f_0 \) is the output frequency of the cycloconverter, and \( k \) is an integer value \( k=0,1 \). In addition, non-characteristic harmonics components \( f_2, f_3, f_4 \) should also be considered, especially at low-damped networks with high non-linear loads where resonances may be excited. A more complex problem arises with multiple cycloconverter-fed drives operating at different output frequencies. Fig. 9 depicts the simplified electrical system of a modern concentrator plant with 4 gearless motor drives. A careful study for the power factor and harmonic control had to be carried out at the design stage.

A great number of operating conditions of the electrical system were taken into account because of the complexity of the productive system. Special procedures and software tools were needed [19].

General specifications included a minimum power factor of 95% (typical) at the PCC and the compliance of IEEE-Std.519-92 for different productive conditions. Therefore, 4 units of harmonic filter modules were designed (see fig. 10). Each module has 4 steps in order to meet the stringent specifications. A control system gives the ON/OFF command for the different modules for coarse and fine voltage control of 23 kV buses.

Fig. 11 shows the spectral impedance at the bus 3 with one filter module. Branch filters tuned to 2\( n \), 3\( n \) and 4\( n \) harmonic order with C-Type [18] were needed in order to mitigate the resonances at the medium voltage 23 kV buses. Branch filters of the high-pass type tuned to the 5\( n \), 7\( n \) and 11\( n \) harmonic orders were considered to control the charac-

Fig. 10, Harmonics Filter Module.

Fig. 11, Harmonic Impedance \( Z(f) \) at bus 3 with One Filter Module.

Fig. 12, Power Quality assessment of an industrial power system plant with 4 GMDs. Measurement of the Total Harmonic Distorsion at PCC 220 kV.

Fig. 13, Power Quality assessment of an industrial power system plant with 4 GMDs. Measurement of the Flicker PST at PCC 220 kV.
terministic injected harmonic spectrum of cycloconverters including the interharmonics.

Fig. 12 depicts the measurements of harmonic distortion at PCC 220 kV and fig. 13 shows the measured flicker during the power quality assessment of the installation during setting-up and commissioning. Recommendations for improving the performance were made.

IV. MECHANICAL AND MECHATRONICS ISSUES

The trend in mineral processing plants is to employ larger mills: SAG mills and recently ball mills, in order to have economy of scale. Nowadays, mills with diameters 34 feet or greater with powers 10 MW or higher, have been designed with gearless drives. Some major problems affecting availability have been observed due to different causes concerning new problems imposed by size scaling or system compatibility:

a) Stator deformations and foundation issues due to huge short circuit forces. This may happen when the cycloconverter is regenerating and a network disturbance results in a commutation failure or by unstable reclosing as described in [13], [14], [15]. Right coordination of electrical protections and development of new intelligent devices may be considered.

b) Isolation failure of stator windings due to wet moisture. By wet grinding, water splashing may contaminate the windings if seals are imperfect. Development of intelligent isolation surveillance may be considered.

c) Vibrations and deflections due to asymmetrical air gap [20], [21]. Bigger machines are distributed systems with several degrees of freedom. Electromagnetic linear and non-linear excitation forces may be produced under failure conditions. Deformation modes and forces distribution along the poles of the rotor should be carefully analyzed during design stage, in order to ensure global system compatibility without dangerous airgap fluctuations and other non-desirable behavior.

V. PROCESS AND KNOWLEDGE BASED INSTRUMENTATION

Availability and safety together with process stability and optimization are the main issues for ensuring productivity and costs in mineral processing facilities. Non-scheduled maintenance and process instabilities must be managed for reducing risks and losses. Main causes for non-scheduled maintenance and shutdowns are broken liners inside a mill. Fig. 14 depicts a new instrument called “Impactmeter” for assessing the impacts behavior inside the SAG mill (patent pending). The goal is the early detection of harmful impacts on the mill liners based in the measurement of acoustical behavior around the mill in order to control the operating variables to reduce the risk of broken liners. Fig. 15 presents the measurement of a typical acoustical signal from one sensor during 1.2 [s]. A DSP-based pattern recognition scheme is employed for identifying harmful impacts.

The load filling of the SAG mill is a critical variable. Commonly, the bearing pressure signals (weight measurements) are used for forecasting the filling of the mill, but global density is very dependant on size distribution of minerals and their viscosity. In addition, mechanical valves and piping devices are prone to failures and losses of calibration.
bration.

The Fig.16 shows a new monitoring system (MONSAG) intended for indirect measurement of the mill filling based on electrical variables of the motor vector-control and process variables, without dependence on mechanical variables, complementing the typical bearing pressure measurement (patent pending). Fig.17 depicts a better process quality gained at the measurement of the mill filling of a SAG mill. Production average was improved by about 2.5% and specific energy consumption (kWh/Ton) was improved by 2.4%.

VI. COMMENTS AND CONCLUSIONS

Main current issues of cycloconverter-fed gearless drives for grinding applications were presented, highlighting: a) Complex nature of the process with large units, b) Reliability and availability, c) Operation within weak networks, d) Power quality and harmonics control, e) Process and knowledge-based instrumentation, f) Mechanical and mechatronics aspects.

The challenge of improving safety, reliability and productivity, regarding the application of complex and larger grinding mills, requires the integration of multidisciplinary work, with aspects of industrial electronics, information technologies, process-, mechanical- and mechatronics engineering.

Further work must be done for identification and control of critical variables in order to improve robustness against perturbations to the whole grinding process control. Network disturbances, power quality, cycloconverter control, machine control, airgap surveillance, grinding operating variables and excitation of non-desired modes of oscillations must be managed, where new methods and instrumentation systems based on process knowledge play a significant role.

VII. REFERENCES