Abstract—This paper presents the behavior of large power mills (more than 10MW each) fed by cycloconverters. Special attention is dedicated to the protection philosophy to avoid operational interruptions which can produce huge production losses and equipment damage. Several failure possibilities are considered: control failure, complete power outage, if a thyristor fails and cannot block reverse voltage, etc. Simulation studies and field measurements show that large currents and torque can occur under certain circumstances and that motor foundations must be able to support them. As a general conclusion, it can be said that proper protective design effectively avoids equipment damage.

Keywords—Mill Drives, Cycloconverters, Gearless Drives.

I. INTRODUCTION

MATERIAL grinding is one of the most important and critical activities in mineral processing. Economic reasons have motivated the development of very high power units (larger than 10MW) [1] - [4]. Fig. 1 shows the configuration of a typical copper grinding line [10], consisting mainly of a 26000 HP semiautogeneous (SAG) mill feeding three ball mills with a power of 18000 HP each. The power of the machines has been sized to process 110,000 metric tons per day (mtd). Each mill is driven by a synchronous machine. To increase efficiency and quality of the grinding process, it is usual to use power converters to control the energy delivered to the synchronous motor [5]. Over the last few years, the cycloconverter has been the selected alternative, mainly due to its high efficiency and global performance [5], [6], [7]. Because of the high power, these units have a big impact on the operation of the power system and so the interaction with the power supply must be studied carefully [7], [8]. In addition, a failure in this large equipment produces important production losses, making reliability a critical issue in the drive operation. Recently, some mining plants have experienced operational problems with cycloconverter-fed synchronous motor drives, resulting in very large short circuit currents. These problems, in addition to important production losses, have created some concerns among users in relation to this technology.

The purpose of this paper is to study different fault situations that can appear during abnormal operating conditions of the drive. The mechanism of overcurrent generation is clarified and protective actions to avoid equipment damage are studied.

Section II presents the working principles and operational characteristics of a drive for SAG mills. Section III describes the most likely fault conditions and Section IV presents protection schemes and results.

II. BACKGROUND

This part of the paper is dedicated to reviewing the normal operation of the drive. Fig. 2 presents the simplified power circuit of a typical drive for high power SAG mill. The synchronous machine has two three-phase windings, each of which is fed by a 6-pulse cycloconverter. A 12-pulse configuration is obtained at the primary side of the transformer, by using secondaries in delta-wye connection. The field current is provided to the rotor by a 6-pulse controlled rectifier, not shown in the figure.

In order to see the magnitude of the variables involved in these applications, Table I presents the most relevant data of a typical Gearless synchronous motor used in SAG mills. The machine operates with reduced speed, which is achieved with a large number of poles and a reduced output frequency delivered by the cycloconverter. The rated stator current of the machine is approximately 2kA. The synchronous motor presented in Table I was simulated and some waveforms of voltages and currents in one three-phase winding in steady state are shown in Fig. 3. The cycloconverter must deliver a current with a peak value of $i_a = 2698A$ to the stator. The measured currents are
TABLE I
PARAMETERS OF A TYPICAL SYNCHRONOUS MOTOR FOR A SAG MILL APPLICATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>Power</td>
<td>12685kW</td>
</tr>
<tr>
<td>$v_{l-l}$</td>
<td>Rated Voltage</td>
<td>1900V rms</td>
</tr>
<tr>
<td>$i_{a,b,c}$</td>
<td>Rated Current</td>
<td>2x1986A rms</td>
</tr>
<tr>
<td>$i_{\text{max}}$</td>
<td>Max. Current</td>
<td>2x2582A rms</td>
</tr>
<tr>
<td>$p$</td>
<td>Pole pairs</td>
<td>40 pairs</td>
</tr>
<tr>
<td>$\cos(\phi)$</td>
<td>Displacement factor</td>
<td>0.99 at rated load</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Efficiency</td>
<td>0.97</td>
</tr>
<tr>
<td>$n$</td>
<td>Rotor Speed</td>
<td>9.55 rpm</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Excitation Power</td>
<td>215kW</td>
</tr>
<tr>
<td>$V_e$</td>
<td>Excitation Voltage</td>
<td>315V</td>
</tr>
<tr>
<td>$I_e$</td>
<td>Excitation Current</td>
<td>795A</td>
</tr>
</tbody>
</table>

rectified to reduce the vertical size of the figure. The waveform of the motor voltage corresponds to a 6-pulse cycloconverter operating at an output frequency of 6.4Hz. In order to validate the simulation study, Fig. 4 presents experimental results obtained in a real copper plant. The stator variables are measured for a slightly different drive in steady state operation. It can be observed that simulation and experimental results agree very well.

III. Operation under faulty conditions

A. Most common faults

The most common faulty conditions that can appear during the operation of a cycloconverter-fed synchronous machine are:

i. The loss of the input voltage. This is the most relevant transient condition of the drive.
ii. Loss of blocking capability of a thyristor.
iii. False triggering of a thyristor.
iv. Short circuit in the terminals of the machine.

B. Loss of input voltage of the cycloconverter

B.1 Loss of input voltage

The loss in the input voltage is the most important transient condition because it appears in every disconnection of the drive or in a blackout of the distribution system. For this reason, it will be considered with more detail in this paper.

Fig. 5(a) shows the conduction state of a three-phase 6-pulse cycloconverter feeding the three-phase stator windings of a synchronous machine during normal operation. This conduction state corresponds to the situation shown in interval A of Fig. 6. The load connected between terminals x and x’ can be modelled as the voltage source...
Fig. 5. Conduction state of a 6-pulse cycloconverter: (a) During normal operation (b) in short circuit.

Fig. 6. Waveform for the cycloconverter of Fig. 5(a) during a loss of the input voltage.

Fig. 7. Generation of a short circuit current (a) Waveforms of voltage and current (b) Enlarged version of (a).

$v_e$ in series with the impedance $Z_a$, as shown in Fig. 6. In the interval A of the Fig. 6, it can be observed that
the line voltage $v_{ac}$ drives current in the direction shown in Figs. 5(a) and 6. At the beginning of the interval B the current changes from thyristor T1.(1.1) to thyristor T1.(1.3). Now, it is considered that the input voltage is lost. The new supply voltage $v_{bc}$ goes to zero, originating the equivalent circuit of interval B shown in Fig. 6. In this circuit, it can be observed that voltage $v_e$ drives current $i_a$ in the opposite direction, as shown in interval B of Fig. 6, originating the fast reduction of its value. At the end of interval B, thyristors T1.(1.3) and T1.(1.2) avoid the conduction in reverse direction and the current remains equal to zero, as observed in interval C of Fig. 6.

B.2 Generation of the short circuit

The shown case occurs, if the feeding circuit breaker of the drive opens without a signal to the control of the cycloconverter. As the cycloconverter control detects undervoltage by supervising the voltage via potential transformers, connected to the bus of the feeding switchgear, the cycloconverter control needs a signal from the feeding circuit breaker when this is going to open. If this signal is not available, the control continues triggering the cycloconverter although the feeding voltage is interrupted. In Fig. 7(a) it can be observed that current $i_a = 0$ at time $t_a$, due to the loss of the input voltage. The reference current $i_a^*(t)$ keeps its original value, because the control is operating. It must be noticed that the polarity of the reference current determines which rectifier is enabled for conducting.

At time $t_0$ of Fig. 7(b), voltage $v_e$ changes its polarity, rectifier I received gate drive pulses and the thyristor begins to conduct, short-circuiting the stator terminals through the cycloconverter, as shown in Figs. 5(b) and 7(a). At time $t_1$ of Fig. 7(b) the gate drive pulses of rectifier I are disabled, but it keeps conducting because the polarity of the current has not changed. It must be observed in Fig. 7(b) that the stator current reaches a very large short circuit value 30kA (Simulation), which will originate a huge torque. The Gearless Drive and the cycloconverter must be designed to resist the short-circuit current and the generated high torque. The feeding circuit breaker of the drive must provide a signal to the cycloconverter control, when it is going to open. With this signal the control must block the gating pulses of the cycloconverter.

C. Loss of blocking capability of a thyristor

It is possible that a thyristor fails. This happens in the way that it becomes conductive in both directions and cannot block voltages of any polarity. In Fig. 8, thyristors T1.(1.4) and T1.(1.5) are originally conducting the load current. As an example, consider that thyristor T1.(1.4) fails. When thyristor T1.(1.6) receives its gate pulse, transformer T1 will be short-circuited, originating large currents shown with wider lines in the diagram [9].

The overcurrent protection must give a tripping command to the feeding circuit breaker, because the already occurred short-circuit cannot be extinguished by blocking gating pulses. Additionally the overcurrent detection must block all gating pulses to avoid further short-circuits, occurring by triggering other thyristors.

D. False triggering of a thyristor

In the situation depicted in Fig. 9, bridge I is conducting the load current through thyristors T1.(1.4) and T1.(1.5). If a wrong thyristor, in this case T1.(2.6), erroneously receives the gate pulse and has a positive anode-cathode voltage, a short circuit will occur. The value of the short circuit current will be limited only by the reactance of the transformer T1 [9].

The case supposes that the cycloconverter control is operating incorrectly. To avoid the resulting problem the
E. Mechanical effects of short circuit

The circulation of very large short circuit currents through the stator of the synchronous machine originates huge forces, which must be held up by the foundations of the mill. Fig. 10 shows the front view of a typical Gearless Drive used in SAG mills with the direction of the reaction forces, which produce a resulting component in the horizontal axis. The structure of the stator, its winding design, the fixation of the stator to the foundation as well as the foundation must be designed to resist the forces, occurring during a short-circuit.

IV. Protection schemes and results

A. Protection scheme of the drive

The main equipment transformer, cycloconverter and synchronous machine, have the usual protection measures used in this type of application. These schemes include overvoltage and overcurrent protection. Each thyristor has a snubber to prevent destruction by overvoltage. In this application, the length of the air gap in the machine is permanently monitored at 4 points (every $90^\circ$) to ensure that the mill is properly centered. Another important protection is the frozen charge protection. Commonly, manufacturers use fuseless technology and electronic overcurrent protection. Fuseless design requires that the thyristors are designed to carry the short-circuit current without damage until it is off. The electronic overcurrent protection works as follows.

The most effective and used protection action is blocking the firing pulses to thyristors in response to a critical situation represented by an alarm signal. For example, in the case of an overcurrent, loss of input voltage, displacement of the rotor or earthquake, the first protection criteria is to block the gate pulses of the thyristors. With this action, the stator currents reach the value zero very fast and without any transient overcurrents or overvoltages, as shown in Fig. 11, for the case of the loss of the input voltage (Simulation). The voltage appearing in the terminals after the stator currents reach the value zero correspond to the induced voltage by the magnetic flux of the motor.

For a safe back-up the overcurrent protection of the cycloconverter must give a signal to the feeding circuit breaker of the drive. Measurements show that the current reaches faster the value zero by gate pulse blocking than by tripping the feeding circuit breaker. The tripping signal is necessary for the cases III.C and III.D. In addition the feeding circuit breaker of the drive must provide a signal to the cycloconverter control, when it is going to open. In this way case III.B.2 is covered.
B. Experimental results

Two interesting results have been obtained in a real unit of a copper mine. Fig. 12 presents the behavior of 12MW Gearless Drive in response to a power outage (loss of input voltage). The machine is similar to the one presented in Table I. In this case, the voltage at the input of the cycloconverter is monitored and when a voltage reduction is detected, the gate pulses for all thyristors are inhibited. It can be appreciated that the current reaches the zero value very rapidly and in a smooth form, without oscillations or overcurrents. This measurement is in close agreement with the simulations results presented in Fig. 11.

Another very interesting situation observed in the same plant is presented in Fig. 13. This figure shows some data recorded during a power outage in an important part of the power system utility. Fig. 13(a) shows the torque generated by the machine, which is obtained by a mathematical model used for the control system. At time $t_1$, the control system detects the voltage loss and inhibits the thyristors gate pulses, driving torque and currents to zero in a controlled and smooth form. It must be noticed that the field current keeps circulating through the rotor, maintaining the induced voltages in the stator terminals. The protection system detects that the input voltage returns to normality and reconnects the cycloconverter at time $t_2$. Nevertheless an abruptly power outage happens again, overcurrent in the windings of the motor, being generated very quickly, as it shows the Fig. 13(b). This fault condition was explained in section III-B. As shown Fig. 13 the magnitude of these currents increases very fast causing instrument saturation. In this case, the large reaction produced a small displacement of the stator, which was detected by the air-gap protection, blocking the gate pulses to the thyristors. During the investigation, the use of a non appropriate flat washer was detected (8mm width), which was the reason for the stator displacement. This problem was solved by using a correct flat washer with a width of 40mm. As a final improvement, the protection scheme has been improved to ensure that the thyristor will not received gate pulses when the input voltage of the cycloconverter is not present.

V. Conclusions

Blocking the gate pulses of the thyristors is the most effective way to produce the controlled disconnection of the cycloconverter, during a normal shutdown of the drive or as a protection measure in response to an abnormal operating conditions.

A proper coordination of the protection system (measurement points, delays, interlocks, etc.) is very important to achieve a reliable operation.

The control and monitoring circuits must consider all abnormal situations and include them in the protection philosophy.

As short-circuits cannot completely avoided, the Gearless Drive with its cycloconverter must be designed to resist the forces of a short-circuit, as it is required by the common electrical standards.

It has been demonstrated that very large currents can appear when the stator of the synchronous machine is short-circuited. This short circuit can be produced through the thyristor of the cycloconverter. Large shortcircuit currents originate a huge torque, which must be withstood by the foundations and fixations of the motor, to avoid a displacement of the stator.

Finally, it can be said that theoretical studies, measurements obtained in real systems and field experience confirm that this technology is highly reliable and provides a high availability of the installation, if the protection scheme has been properly designed.
Acknowledgments

The authors would like to acknowledge the suggestions and contribution of professionals and colleagues of mining plants, as well as the support of the Chilean Council for Research and Development (CONICYT) for the grant FONDECYT 1040374.

References