STEPPING FORWARD: USING VARIABLE SPEED DRIVES FOR OPTIMIZING THE GRINDING PROCESS IN SAG AND BALL MILLS

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ABSTRACT

Comminution is usually the heaviest energy-consuming process in the mine site. These days when efficiency concerns are becoming more and more important, developing a reliable and highly efficient way to grind and crush ore is a new field being explored by main industrial players. This paper focuses on variable speed operation as the answer to improving current tumbling mill grinding circuits. Benefits related to reliability, sophisticated functionalities for wear reduction and maintenance issues can be obtained using latest technology Variable Speed Drives (VSD). How they work and how they can be easily integrated in the comminution circuit is analysed and discussed. This paper describes how INGEDRIVE VSD systems develop all these features and functionalities, upgrading the grinding process to a new level with higher degrees of productivity and profitability.

KEYWORDS

Variable Speed, Variable Speed Drive, Semi-autogenous mill, Ball mill, efficiency, drive system

INTRODUCTION

Comminution circuits for mining have evolved from basic circuits consisting of simple crushing machines to the current multi-stage, semi-autogenous (SAG) and ball mill circuits. This progression, however, has not always been accompanied by an improvement in the efficiency of power usage in achieving the target grind size. According to the Coalition for Eco-Efficient Comminution (CEEC), sponsored by a wide range of mining sector companies, the process of crushing and grinding ore is the major energy consumer of mine sites (nearly half of the total mine site energy consumption) and represents a minimum 10% of production costs (Natural Resources Canada).

How to obtain the maximum benefit from the impact energy of the material in a tumbling mill is the great question which every designer is trying to answer. Parameters such as water flow, ball size and quantity, material feed… can be properly tuned in order to achieve optimum performance of the comminution chain. However, these adjustments are always time-consuming and imply some kind of media utilization and usually an unavoidable wear increase. In this way, there is a parameter that could also be tuned to maximize grinding efficiency, but due to installation or technological issues it remains generally constant. This parameter could be easily altered with no without extra time or extra wear issues. That parameter has a direct impact on almost all of the parameters in the system, it being able to be moved to another operation-zone just by itself. This easy to change parameter is the mill speed. The whole grinding process is heavily conditioned by the mill speed. The mill charge shape changes depending on it and this has a direct impact on the other variables in the system (breaking rate, volumetric discharge and mill powerdraw), finally affecting the product material size and production rate. Innovation and development efforts over the last few years have resulted in the appearance of a large variety of cost and technically competitive AC frequency converters on the market. Indedrive VSDs are available for the whole low and medium voltage range and from hundreds of kW up to tens of MW milling applications. These Variable Speed Drives (VSDs) can facilitate an optimum usage of power and system parameters in order to meet the expected ore size target, allowing the operator to optimise the media utilization and wear. In fact, VSD systems offer the flexibility to maintain the process performance and product ore size between desired limits by simply adjusting the mill speed.

In addition, further advantages related to electrical grid and wear reduction like electrical friendliness, unitary power factor, controlled stop and load sharing in multi pinion systems are achievable by using modern VSD systems. Finally, latest redundancy concepts based on bypass the VSD and continued operation at fix speed in the uneven case of VSD malfunction, help to achieve ultrahigh availability levels and to reduce any mistrust generated by the introduction of a new high technology system in a mature and consolidated process.

HOW CAN I INTEGRATE A VSD IN MY COMMINUTION CIRCUIT?

Current grinding technology based on tumbling mills is a mature and well-known process which enjoys the confidence of most end users. An electric motor (asynchronous or synchronous machine, depending on the application) is the link between the electrical energy source and the mechanical load, the tumbling mill. Most of the times these systems adopt the so called “fixed speed solution”, that means that the electrical machine is directly connected to the electrical grid, and, consequently, no speed regulation is possible. Unfortunately, this choice considerably limits the operator’s freedom and the system becomes very rigid and difficult to adjust.

The use of VSDs makes it very easy to set the mill speed by just modifying this value on a touchscreen. But this is not only an option for new installations. In installations where SAG and Ball mills have been working for several years at fixed speed, but the speed regulation has been observed to be necessary VSDs can also be integrated very easily. No major modification in the gear box or the electrical machine should be required, only the placement of the VSD in the system and the correspondent rewiring after which everything is ready to drive the mill.

Once the “variable speed solution” is chosen, an important decision to be made by the operator is left referring to the motor: whether to opt for a high speed or low speed solution. Gear driven mills can be motorized both with the high speed solution or the low speed solution. Efficiency, performance, space and cost issues must be taken into account for choosing one solution or the other. Both solutions can be developed for single pinion or dual pinion applications depending on the power of the driven mill.

High speed solution

Typically, a high speed squirrel cage motor with three or four pole pairs is used for this kind of configuration. A gearbox is needed in this solution, where the high speed side is connected to the motor, and the low speed side is connected to the pinion and ring gear. The robustness, reliability and simplicity of the squirrel cage induction motor reduce the maintenance of the motor to a minimum. Although the efficiency of the motor itself is higher than the synchronous motor compared with the low speed solution, the overall efficiency of the drive train is lower due to the insertion of the gearbox the cooling unit needed for the gear box should also be taken into consideration). It is also assumed that after 10 years of operation, the gearbox must be replaced due to mechanical wear, resulting in an important extra cost for 20 years of operation cycle (Von Ow & Gerhard, 2010).

Low speed solution

Typically, a high pole synchronous machine with a rated speed of around 200 rpm is used for this kind of configuration. No gearbox is required in this solution since the motor is directly connected to the pinion and ring gear. A higher overall efficiency is achieved in this configuration since the gearbox is removed (although the electrical efficiency is slightly lower due to the external excitation unit). Brushless or brush type synchronous motors are available. Brush type synchronous motors require periodical maintenance due to the brushes and although brushless synchronous motors do not need any periodical maintenance, they are considered not to be as reliable and robust as the squirrel cage induction machines because they include semiconductors and electronics in the rotor.

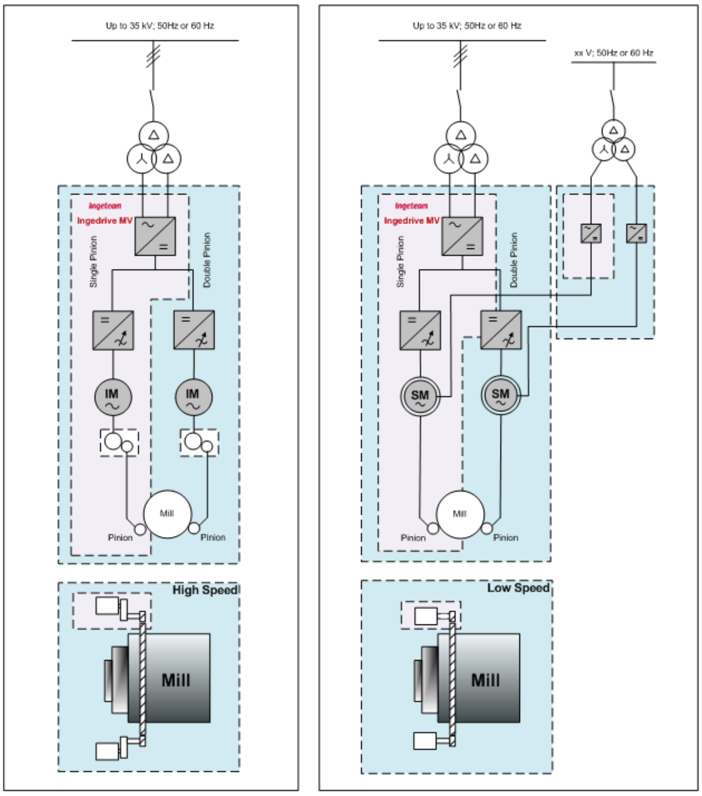

Figure 1 – General overview of the high speed and low speed drive system solutions for gear driven mills (single or dual pinion) (Ingeteam).

WHAT CAN A VSD DO FOR MY GRINDING PROCESS?

Variable speed offers inherent advantages for the grinding process because it is a parameter that directly affects the charge shape and the process variables. But the use of a frequency converter adds extra benefits to the single fact of the variable speed: specific designed functionalities, net and mechanic friendliness, liners wearing minimization, etc.

The mill charge shape changes depending on the mill speed and this has a direct impact on the other variables in the system (breaking rate, volumetric discharge, mill powerdraw…), finally affecting the product material size and production rate. The process by itself becomes more flexible.

Breaking rate

The breakage rate function shape of the SAG mill is largely governed by the mill load particle size distribution and mill speed. The feed in the mill contains fractions of ore that serves as the grinding media. Larger ore fractions break the smaller particles but also breakdown themselves and exit the mill as a product. In due course, the ore competency can change as fresher, harder ore is mined at deeper levels. This will alter the balance between the lump grinding media and the softer components of the ore as the harder lumps will breakdown more slowly. Gradually therefore, steel balls will have to be charged to help break the more competent lumps to retain the balance and maintain throughput.

Variable speed affects this breaking rate shape according to different research works (Comminution, 1994). As shown in figure 2, for the same particle size, the mill speed can alter the breaking rate. This could be very useful specially in grinding circuits where different ore hardnesses are expected, because the ability to change the mill speed could provide the option for a continuous operation with reduced interruptions (need for ball charge modification minimized) keeping the throughput constant.

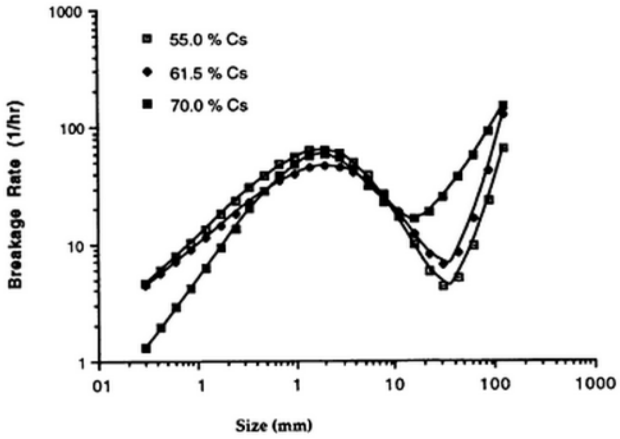

Figure 2 – Breakage rate as a function of particle size for mill speeds of 55%, 61.5% and 70% of the critical speed (Forssberg & Schonert, 1996).

Volumetric discharge

The mill speed directly affects the product material flowrate from the mill. From technical literature (Apelt, 2007), the total volumetric discharge can be defined as the sum of the discharge flowrate through grinding media and the discharge flowrate through the slurry pool according to equation 1. Equation 2 shows the relationship between the discharge flowrate through the grinding media and the speed of the mill, ϕ, as a fraction of the critical speed (King, 2001).

$$Q = Q_m + Q_t \qquad (1)$$

$$Q_m = 6100 \cdot J_{pm}{}^{2} \cdot \gamma^{2.5} \cdot A \cdot \phi^{-1.38} \cdot D^{0.5} \qquad (2)$$

$$Q_t = 935 \cdot J_{pt} \cdot \gamma^{2} \cdot A \cdot D^{0.5} \qquad (3)$$

Where, Q = tTotal mill volumetric discharge (m^3/h)
Q_m = mill discharge flowrate through grinding media (m^3/hr)
Q_t = mill discharge flowrate through slurry pool at the toe of charge (m^3/hr)
A = total discharge grate open area (m^2)
D = mill inside diameter (m)
γ = grate design parameter
ϕ = critical mill speed percentage (%)
J_{pm} = fractional slurry hold up in the grinding media (%)
J_{pt} = fractional slurry hold up in the slurry pool (%)

Mill powerdraw

Mill speed influences the power draw in two ways: on the one hand, mill power is the lineal product of the mill rotational speed and the torque applied, so there is a lineal dependence; on the other hand, the centre of gravity of the charge is shifted with speed, creating a non-lineal dependence. The overall power draw versus mill speed dependence results in a non-lineal function, and it is shown in the Figure 3. The centre of gravity first starts to shift to the shell as the speed of rotation increases. The distance to the gravity centre increases and it makes the applied torque higher for the same rotational speed. The power versus speed function is almost lineal in this first stage, because the influence of the speed is much higher than the torque increase (grinding mills are applications of quasi-constant torque). But as the speed keeps on rising the centre of gravity moves towards the centre of the mill as more and more of the material is held against the shell throughout the cycle. Power gets to its maximum and as the speed goes on rising the power starts to decrease, until the entire charge is centrifuging and the net power draw is zero (critical speed) (King, R. P, 2001).

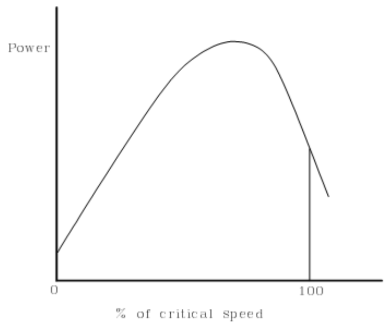

Figure 3 – The effect of the speed on the power draw of a grinding mill (King, 2001).

Charge shape

A kidney type shape could be an approximation for the mill charge shape, as shown in Figure 4. Mill geometry, charge characteristics and the charge filling fraction by the volume are the other factors involved in the charge profile apart from the mill speed. Considering the kidney type shape, the mill speed will make the charge inner surface radius (r_i) being smaller as the faster the mill rotates. The toe angle changes very slightly, but the shoulder angle will rise in accordance with the charge inner radius and the mill speed. The charge shape has an immediate effect on the gravity centre of the charge (and so the torque) and the impact zone of the cascading material. The mill speed with the shoulder angle will almost completely define the impact zone of the cascading material (lifting bars will affect too) and also the impact energy, so it is a vital parameter to ensure an optimum performance of the grinding process. Wearing suffered by the liners will also be deeply influenced by the impact zone of the cascading material (Valery & Morrell, 1995).

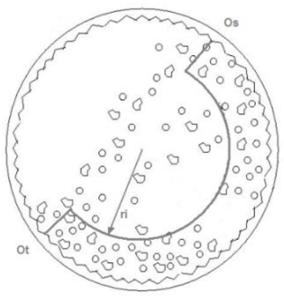

Figure 4 – Simplified kidney shape mill charge model for impact zone analysis (Valery & Morrell, 1995).

Process

The process becomes highly flexible due to the fact that it is possible to vary the mill speed. The material feeding the SAG mill can suffer important variations during the mine lifetime. Deeper ore can be harder and can make the grinding process inefficient. Ore size distribution, non-homogeneous load in the conveyor, content of other ores etc. If fixed speed solutions are adopted, the grinding process becomes rigid and it is necessary to use other alternatives to improve the throughput such us adding balls, water… Variable speed enables the operator to optimize the media utilization and wear, and offers the flexibility to keep the process performance and product ore size between desired limits by simply adjusting the variable speed which is easy to change. Partial load operation or overload conditions can be neglected or controlled adequately. In case of short time ball mill shut downs, it is not necessary to stop the SAG mill. It is enough to run it at low speed and ramp up the speed to its rated value again when the ball mill is operational, resulting in shorter down times and improving process availability.

THE FRIENDLY VSD

The benefits of mill speed regulation have been already discussed briefly. However, there are some extra benefits achieved by the inclusion of a VSD in the grinding process related to electrical and mechanical friendliness. A good example of these facts were seen in the recent Rudnik Alexandrovskiy project (Eastern Siberia), commissioned in 2013. The grinding circuit consists of one SAG mill (Ø6.7m) and one ball mill (Ø6.1 m), both single pinion gear driven and designed and delivered by Outotec. The contractor opted for the high-speed solution with gearbox for both the SAG and the ball mill. A variable speed medium voltage drive system from Ingeteam was set to drive the SAG mill including an MV transformer, MV frequency converter and an MV squirrel cage induction motor. For the ball a fixed speed solution was chosen, with an MV WRIM (wounded rotor induction motor) with an LRS (liquid rheostatic starter).

Figure 5 – Rudnik Alexandrovskiy mining and processing plant in Eastern Siberia (Ingeteam)

Electrical friendliness

On the one hand, the grinding mills are one of the biggest consumers inside the mine as already said. On the other hand, as the easily accessible orebodies are exploited, mining projects are moving into more remote areas of the world, where access to resources as energy or infrastructure is limited and more costly (Natural Resources Canada). Mine plants with high power demands are being connected to very weak network connection points. This situation can generate repetitive shut downs and voltage dips when big induction or synchronous motors are directly connected to the grid due to high inrush currents. Electrical friendliness of the connected devices is a desired requirement for this kind of installation in order to ensure electrical stability for the plant. The use of frequency converters allows the motors to start very smoothly, with very soft inrush currents and generating almost no stress on the electrical network. Although the starting of the Ball mill at the Rudnik Alexandrovskiy project was very smooth mechanically, high inrush currents were achieved when the stator of the machine was connected to the net. Nevertheless, the SAG mill motor, driven by a variable speed drive system, was gradually accelerated with the inrush current being increased step by step from zero until the desired operation point was obtained. No air clutch is required and the motor is able to provide full torque from the zero speed position.

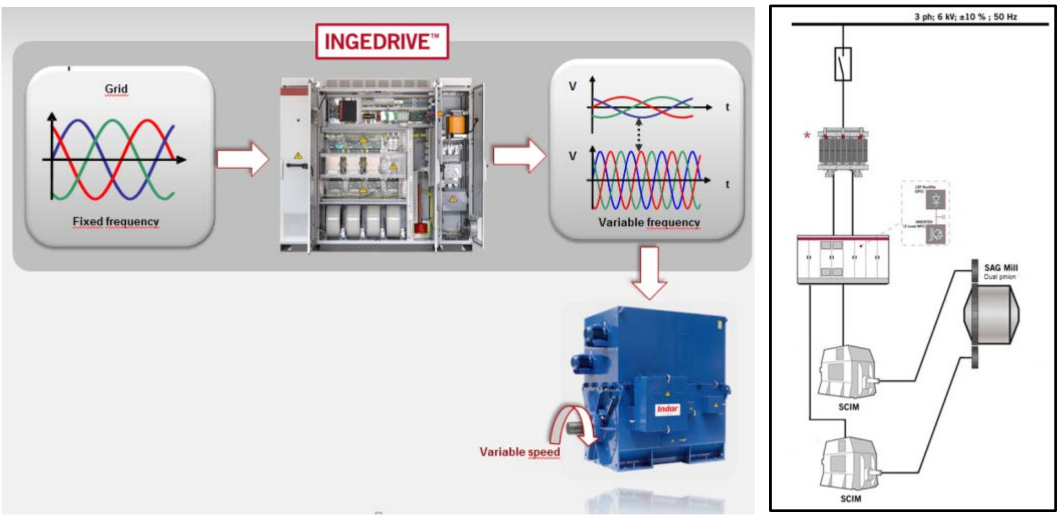

Figure 6 – Speed regulation and load sharing by Ingedrive VSDs (Ingeteam)

Being the most important plant energy consumer, apart from just the inrush current it is important to consider the power quality feeding the mill motors. If variable speed drives are not used and the motors are directly connected to the grid, reactive current that does not generate work will be consumed by the motors (only in induction machines). Squirrel cage induction motors are usually the preferred industrial solution because they are robust and simple motors since the rotor is a closed cage not requiring any maintenance. The drawback, however, is that some extra reactive current is necessary to generate the flux necessary to get the required magnetic field along the air gap. In other words, power facto**r** is not unitary (between 0.85 and 0.9 for most induction motors). This fact translates into two undesired effects for the plant: the cables, busbars, transformer and electrical switchgear must be oversized and in some cases, it is necessary to pay some penalties to the electrical company due to the low power factor. The use of frequency converters solves this problem as the intermediate DC link only supplies active power. Different grid side topologies are available in the frequency converters: the diode based 12-pulse rectifiers have a power factor of 0.96 and the IGBT based Active Front Ends have a unitary power factor, being also able to compensate the reactive consumption of the plant (depending on the current rating of the converter).

Mechanical friendliness

The electrical friendliness also minimizes the stress suffered by the mechanical system in a direct motor starting. Fast torque steps that have occurred during startup can seriously damage the pinions, the liners or the gear box, causing premature failures in the mechanics. Start-ups with frequency converter prevent the mechanical drive train from suffering this kind of deterioration and minimize wearing. Specific functionalities are developed to protect the mechanics from wearing. On the one hand, an antifrozen charge detection algorithm prevents the mill from starting if the charge is stuck, protecting the shell and liners from undesired impacts of the falling material. On the other hand, a properly adjusted impact zone detection algorithm can calculate the impact zone online, where the cascading material is falling and adjust the speed reference to locate it near the toe angle, preventing the shell and liners from wearing due to improper operation.

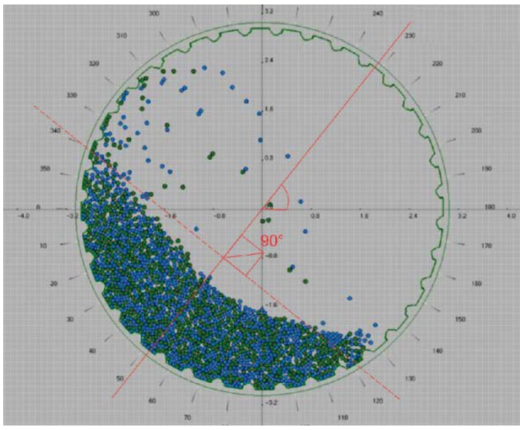

Figure 7 – Impact zone calculation to prevent the shell and liners from premature wear (Ingeteam internal model)

The use of vectorial control provides a high dynamic performance over the whole operating range. Since the flux of the machine and the speed and torque are decoupled in independent control loops, very fast and accurate controllability is achieved. Torque response times lower than six milliseconds can be obtained by the use of vectorial control. This is extremely important when a dual pinion solution is performed. Load sharing is achieved inherently using frequency converter based solutions for dual pinion installations. Other operation events like sudden torque kicks due to bigger rocks or conveyor overloading are rapidly controlled, preventing the motor from possible current imbalances in case of DOL machines; net voltage imbalances can also be filtered providing three-phase balanced supply to the motor, preventing it from possible winding overheating in the case of DOL machines. Accuracy and dynamic response capability are obtained thanks to the use of the sophisticated vectorial control algorithm.

Maintenance and operation friendliness

Specific functionalities have been implemented to meet mining sector customer demands. Starting and stopping the mill are commonly problematic issues when fixed speed solutions are adopted. In the Rudnik project, these mining sector-focused functionalities were adopted, such as the antifrozen charge detection algorithm to protect the mill from stuck charge. The stop was also controlled till the zero torque position. Functionalities for easy maintenance like inching and inspection mode were also included in the control logics.

Starting with Antifrozen charge detection

After the mill operator sends the start command, the drive system starts to rump up the speed reference very slowly. It is first fixed in a certain low speed reference. In the Rudnik project, the SAG mill was turning at 0.625 rpm (5% of the rated speed) at this stage, while the torque and mill angle were being monitored. If the drive system detects the material starts cascading before a certain critical angle is reached, the speed reference is released and the mill will start accelerating (ramps were set during the commissioning) till the speed reference set by the mill operator is reached. A local torque maximum value defines the material cascading. If this torque maximum is not read, the frozen charge detection flag is activated and the mill stops. The mill will be then inched very slowly to loosen the stuck charge. The start command can be sent again and a new frozen charge detection will be carried out till the charge is loosened and does not represent a potential risk for the shell and the liners.

Controlled Stop

After the stop order is received, the mill starts to ramp down the speed according to the deceleration ramp. Once zero speed is reached, the mill starts to run slowly in the inverse direction until no torque remains in the system as shown in figure 8. The complete sequence from the stop command is received till when the mill stops completely takes 87 seconds (nearly one and a half minutes). Nearly half of this time is dedicated to turning in the opposite direction in order to get the zero torque position. A limit speed reference is defined for this mode because since this is a regenerative action it can feed back energy to the DC Bus and increase its voltage value. To prevent the drive from tripping, control logics include an additional controller set up during commissioning time which limits the maximum feedback energy to the DC Bus.

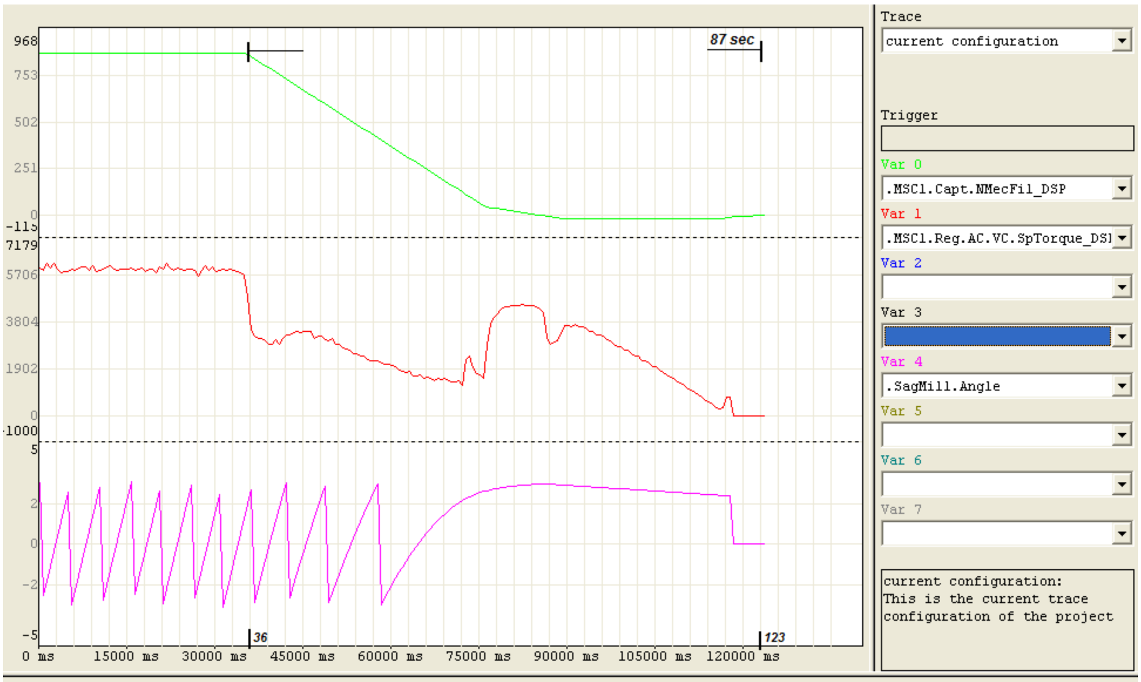

Figure 8 – Controlled Stop sequence in the Rudnik Alexandrovskiy project (Ingeteam VSD data)

Inching

This mode consists of moving the mill very slowly in order to detect any mechanical or other type of problem. A very low speed reference (from 1 to 10% of the rated speed) is set and the drive will start rolling according to this. A Frozen Charge Detection will be performed as the standard start sequence and once cascading is achieved, the mill will move according to the speed reference and acceleration and deceleration ramps predefined during commissioning by Ingeteam. One of the great advantages of this functionality is that the customer does not need the inching motor and the associated small frequency converter any more. The gear box is also simplified and there is no need to perform time-spending mechanical arrangements in the gear box to move it from main motor operation to inching motor operation. Every time the mill needs to be moved, it will be done from the main motor, whatever the speed required.

Inspection mode

This mode consists of moving the mill to a predefined liner number or angle, normally for maintenance issues. The operator can select this operation mode and will be able to set a "liner number" or "mill angle". A "frozen charge detection" will be performed as the standard starting sequence and once cascading is achieved, the mill will move till the defined "liner number" or "mill angle" according to the speed reference of the main mode for this project 15-100%·n_n). As the mill will have its own cascading angle, this value is added to the defined angle value and then it turns back till there is no torque remaining in the system, leaving the mill in the position defined by the user.

LITERATURE EXPERIMENTATION REVIEW

There are many laboratory researches showing the effects of the mill speed on the load shape and the mill torque/power draw. Most of them agree that the mill outputs (product size, throughput, power draw…) are non-linear variables highly conditioned by the process parameters (slurry-media-ore characteristics, filling factor, liners, grinding circuit configuration, etc.)(Monov, Sokolov, & Stoenchev, 2012). In this context, the capability of optimizing the output variables in SAG and Ball mills by easily adjusting the mill speed could result in important improvements.

In Nistlaba & Lameck (2005) an intensive analysis is performed. A pilot mill is used with an 0.54m internal diameter and 0.4m internal length fitted with twelve trapezoidal lifters. The evolution of the different variables is observed depending on the ball size and type, and mill speed. Focusing on the evolution of the charge shape angles as a function of the mill speed and filling factor, a slight difference is visible in the toe angle and a higher one in the shoulder angle (Figure 9).

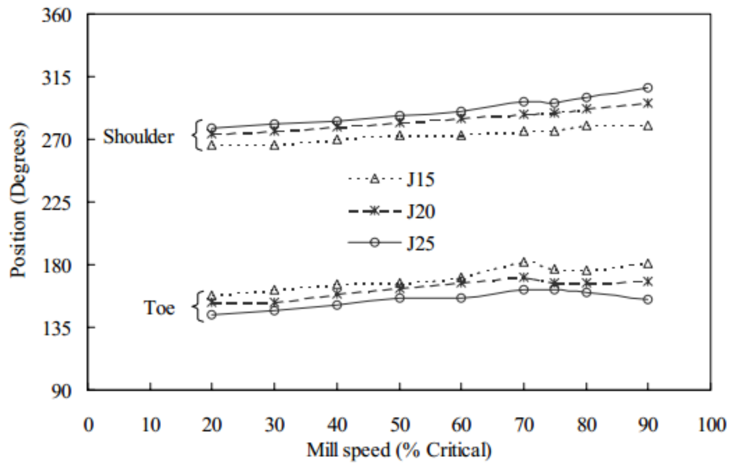

Figure 9 – Evolution of toe and shoulder angles with mill speed at different charge filling levels (Nistlaba & Lameck, 2005).

The influence of the mill speed on the power draw is also analysed (Figure 10). It shows as expected, how the power draw evolves almost lineally till a certain level of speed, around 80% of the critical speed. It means that the torque remains almost constant. Then this power draw becomes nearly constant and as the mill enters into the centrifuging zone, it will continue to decrease.

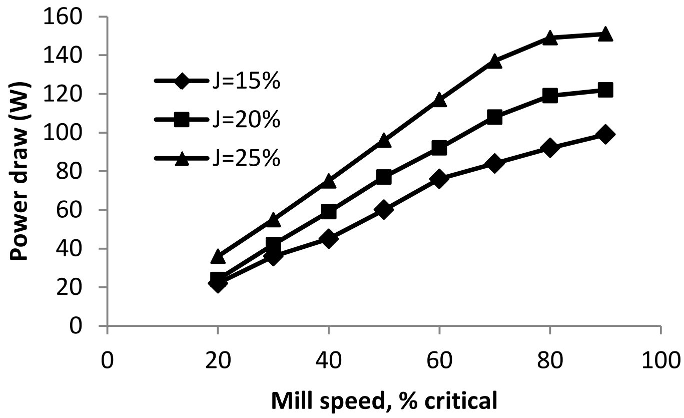

Figure 10 – Power variation with the mill speed at different charge filling levels (Nistlaba & Lameck, 2005).

In Moys (1993) liners design is also introduced as an analysis input. A similar study like in Nistlaba & Lameck (2005) is carried out, but considering two different liner topologies: Liner 1 is a smooth liner with eighteen 20x20mm lifter bars welded to it. Liner 2 has a saw-toothed configuration, ensuring minimal lifting action imparted to the load in the rotational direction of the mill; in fact, substantial slip occurs with this lifter. The medium used is a graded charge of 12 mm,18 mm, and 25 mm balls with a bulk density PL=4700 kg/m3. The considered mill diameter is 0.53m inside the liners, and the mill length is 0.3m.

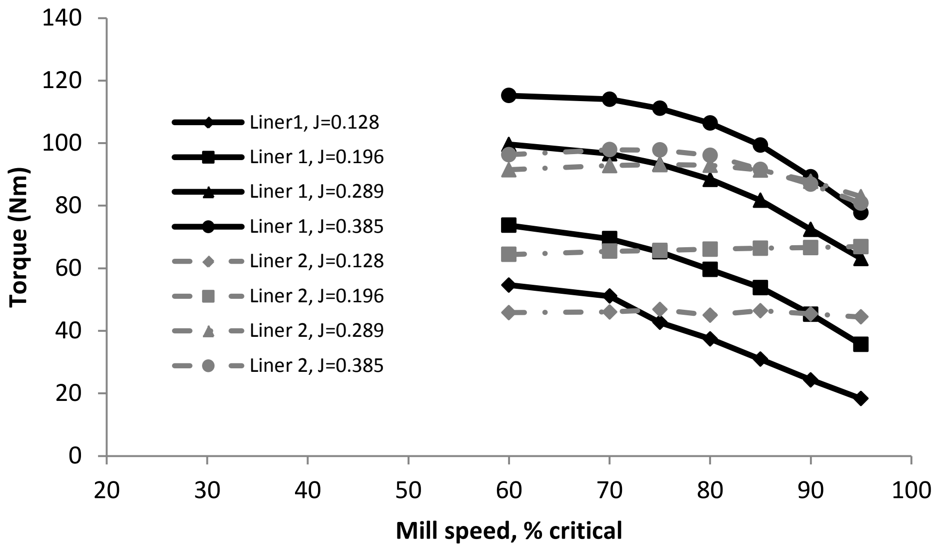

Figure 11 – Torque variation with mill speed at different charge filling levels and two liners topology (Moys, M.H., 1993)

The influence of the liner geometry is easily noticeable. When a large amount of slip occurs (case of liner 2) the simple kidney shape model (Figure 4) can be used to properly describe the charge behaviour. But when lifting bars are introduced, the medium is lifted away and falls away from the lifter only when gravity overcomes the friction between the liner and the material inside the mill. This is translated into a gradual loss of torque (and consequently power) due to a loss in the active mass of the load. But, as discussed in Moys (1993), this loss of power does not necessarily result in a loss of mill capacity, because now grinding is more efficient.

In this way, the effect of the mill speed on important output variables of the grinding process such as torque, power draw and load angles seems not to be disputed. If the inherent variability of the ore entering the mill is added to these concerns, the ability to control the mill speed becomes almost a must in both SAG and Ball mill applications. And VSDs, as flexible and polyvalent elements, arise as one of the most interesting options in order to ensure functionality and adaptability.

RUDNIK ALEXANDROVSKIY GOLD PLANT DATA

According to the power draw response analysed in technical literature, it is evident that speed regulation has a direct impact on the final plant power consumption. Depending on the mill liners design Speed-Power dependence could vary from almost linear to a flattened tendency. At Rudnik Alexandrovskiy, the SAG mill response was recorded from the minimum to the maximum operating speed. SAG and Ball mill main data is shown in Table 1.

Table 1 – SAG and Ball mill operation data in Rudnik Alexandrovskiy project (Outotec).

	Data	SAG Mill	BALL Mill
General data	Mill type	Wet grinding, grate discharge	Wet grinding, overflow discharge
	D_{mill}	6.7 m	6.1 m
	l_{mill}	6.7 m	9.05 m
	Motor power	2300 kW	2100 kW
	Motor type	SCIM 1000 rpm	WRIM 991 rpm
	n_{mill}	12.5 rpm (design)	15.3 rpm
		10.8 rpm (min); 13.3 rpm (max)	
	Nº of liners	20	20
	Liners type	Metallic	Rubber
	Water flow required	> 50 m^3/h	
	Mills feeding material flow	91.15 tn/h	

Different scenarios and operating points are shown in Table 2. On the one hand, commissioning time data is shown, were the plant was not working at full load yet. The SAG mill power was around 500 kW at that time. On the other hand, full load data is also shown, after two years of successful operation.

Table 2 – Torque and Power variation with SAG mill speed in Rudnik Alexandrovskiy project (Ingeteam VSD data).

	SCIM speed (rpm)	SAG mill speed (rpm)	% Critical speed	SCIM Torque (Nm)	Power (kW)
Low Load	750	10	60.61	6113	491
	850	11.3	68.69	6324	574
Full Load	825	11	66.67	15762	1375
	865	11.53	69.9	15542	1420
	937	12.49	75.72	15807	1572
	990	13.2	80	15742	1652

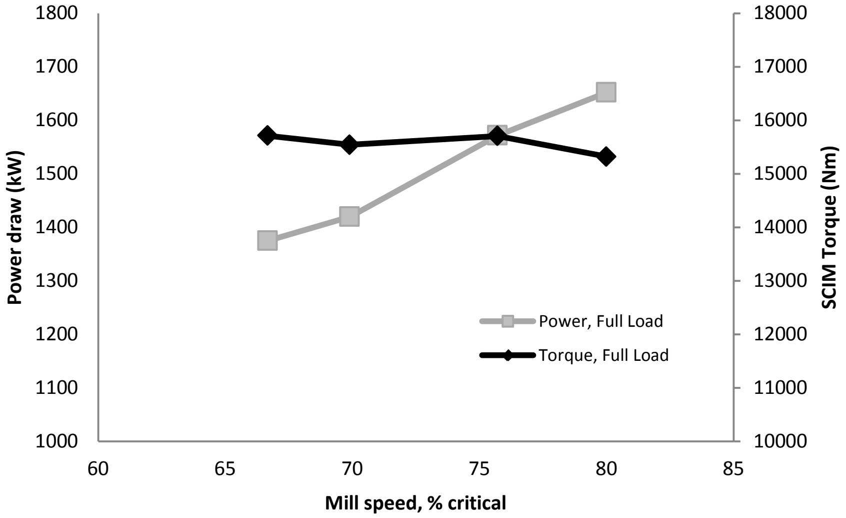

Figure 12 – Torque and Power variation with SAG mill speed in Rudnik Alexandrovskiy project (Ingeteam VSD data).

The mill was running at 75.72% of critical speed at the remote connection moment. It is possible to notice how a 5% shift on mill speed could result in an important impact on power consumption, in the range of more than 100 kW. Obviously an overall compromise between all the system variables is necessary, but a remarkable plant energy optimization could be achievable adjusting properly the parameters affecting the whole grinding process.

CONCLUSIONS

Mining processes are increasingly moving towards smart technologies that improve overall efficiency and also offer important benefits to the whole chain. Variable Speed Drives fit perfectly in these conditions contributing to the flexibility and performance of the comminution system. Sophisticated functionalities and high performance control algorithms developed by Ingeteam for mining applications have been discussed. Smooth start and stop sequences implemented to protect the mechanical system from dangerous torque kicks and reduce the wearing of mechanical elements; specific maintenance and operation functionalities such as inching or inspection mode to optimize plant availability and reduce maintenance times. Variable speed by itself offers other important benefits in terms of process flexibility and process continuity, since the material flow feeding the SAG mill has a changeful nature. The whole variable speed drive system constitutes compact equipment that offers flexibility and higher efficiency to the grinding process.

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