

SmartMill™: Exceed your performance limits

Take full control of your grinding mills to increase productivity



Increasing demand for higher productivity and energy efficiency in comminution requires constant innovation. With over four decades of experience, ABB's dedicated mining experts developed SmartMill™ — an embedded solution that combines the state-of-the-art and fully variable-speed mill drive system with advanced process control. SmartMill™ simplifies your operator tasks helping you achieve maximum grinding efficiency for your mills.



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Abstract

There are many compelling reasons why productivity and energy efficiency in today's mining and mineral processing environment have to be improved. To help make these improvements, ABB offers advanced process control that can increase grinding efficiency, decrease energy consumption and extend equipment lifetime throughout the entire grinding circuit. ABB has now also developed an embedded, advanced control for variable-speed mill drives — called SmartMill™ — that utilizes real and online data for continuous, standalone control of mills. This paper describes the advantages of ABB's advanced process control when applied in a copper mine processing operation and extrapolates these to demonstrate the benefits SmartMill™ brings, including tests performed in a hardware-in-the-loop set-up.

Keywords

Mill drives, energy-efficient comminution, process control, variable speed drives, predictive control.

Introduction

The business of mining and processing minerals is getting progressively more competitive: accessible, high-quality ore is mostly gone and that which remains is hard to get at and is often of poor quality. Commodity prices do not help the situation either. Over the past five years or so they have mostly remained fairly flat, or declined. Further, volatile energy prices and tighter emission standards mean production and processing methods have to be modified to reduce energy consumption and lower carbon dioxide output. To add to the difficulties, the workforce in this industry is aging and retiring workers take valuable know-how and experience with them. This all means that mineral processors have to work harder to maximize both the productivity of their assets and the efficiency of their process. One way to do this is to improve the process control strategy by having full control of the grinding mills.

Somewhat surprisingly for a process that has a reliance on a plethora of variables (and which is usually by far the biggest power consumer in the entire processing operation), current best practice in the grinding process is rather basic — multivariable process control is largely absent; local, isolated and non-ubiquitous control loops (e.g., conventional Proportional-Integral (PI) controllers used to control motor torque) are rather limited in what they bring to the overall efficacy of the process; and much of the intelligence and stability in the grinding process is provided by the operators — an input that can be subjective, with operator reactions to similar situations varying between individuals. Indeed, operator interaction with the grinding process often results in oscillating process parameters because the system behavior is simply too complex for a human to fully master. For instance, the operator must often cope with rapidly varying ore feed quality while trying to maximize throughput without producing too much recirculating load — and at the same time preventing excessive equipment wear.

The specific variables to be accommodated and the best strategy to control the grinding process will depend on the actual process circumstances, and the type of mill and drive involved. In modern grinding, ball mills and SAG mills are two types of mill commonly found.

Grinding mills

Ball mills

Ball mills vary in their details and size but the basic design consists of a horizontal hollow cylinder, with an abrasion-resistant interior, that rotates about its central axis. The grinding is performed by stone, metal or rubber balls that are free to move in the cylinder (Figure 1). The balls form around 40 to 45 percent of the load. As the cylinder rotates, the material to be ground, e.g., ore, and the grinding balls are lifted by natural adhesion to the inside of the cylinder and, at a certain height, they fall, causing the material to be ground by impact attrition and abrasion caused by the balls. The ball mill cylinder central axis is usually slightly tilted — this allows continuous operation by feeding material in at the high end and having it exit at the lower end. The length of the mill is approximately one to two times its diameter. The mill will have an upper critical speed, at which centrifugal forces will prevent the balls and material falling, and grinding action will cease.



Figure 1 – Ball mill principle

Ball milling has several advantages over other systems: installation cost, power requirements and grinding medium usage are low; it can be used for both batch and continuous operation; it is suitable for open- and closed-circuit grinding; and it is applicable for materials of all degrees of hardness. Ball mills of almost 30-foot diameter have been built.

AG and SAG mills

Autogenous (AG) mills look like ball mills and function in a similar way — with the additional assistance of lifting plates that line the inside of the cylinder — but they use large ore particles as the grinding media. If the ore is too hard or abrasive, a small charge of steel balls may be added to aid the process — the mill is then called a semi-autogenous (SAG) mill. AG/SAG mills are often used as the first stage in a two- or multiple-stage grinding process, where the second stage is carried out by the ball mill, but they can also be used as a one-stage grinder. The absence of, or reduction in the number of, balls means they can be less costly to operate than ball mills. SAG mills of over 40-foot diameter have been constructed. Like the ball mill, the AG/SAG mill will have a critical rotation speed above which grinding ceases.

Mill motor types

There are three common motor types that drive the grinding mills described above:

- Gearless motors. These variable-speed motors range up to 30 MW and have the highest system efficiency. They are normally the most effective solution for high power mills, especially when the total cost of ownership is considered.
- Synchronous motors, single or dual pinion. These motors, fixed or variable-speed, are limited in power (currently to around 9 MW per pinion) by the pinions.
- Induction motors with speed reducer and one or two pinions. These motors have the lowest capital costs, but the complete solution performs on the lowest overall efficiency mainly due to the losses in the gearboxes.

The mills used as an example later in this paper are ring-gear, dual-pinion mill applications (see Figure 2). ABB was awarded the contract to equip mills of this type — at 18 MW, the most powerful ring-gear mills ever built. The huge advantage of ABB's solution is the variable speed aspect — it will be seen below that the ability to vary speed is critical when it comes to optimizing mill efficiency and overall productivity.

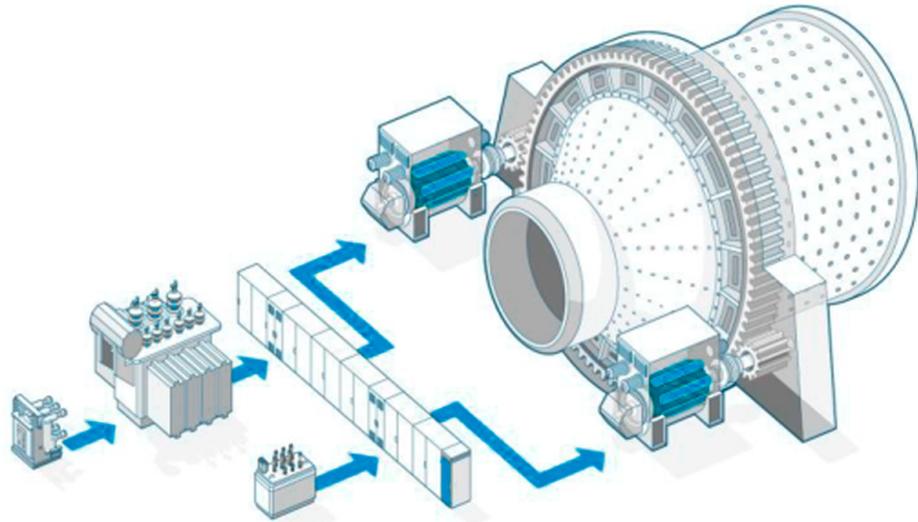


Figure 2 – A dual-pinion, ring-gear mill with ABB drive system

Advanced process control and SmartMill™

As mentioned, multivariate control in grinding mills is largely absent – despite the complexity of the grinding process, in which feed rate, mill rotation speed, ore hardness and purity, total load and, in wet mills, water addition rate, all have to be taken into account in order to obtain better productivity and efficiency. Localized PI control loops are found in some operations, but sometimes there is no automated control at all and things are left to the experience and judgement of the operator. This all changes with the introduction of SmartMill™.

SmartMill™ is a special case of advanced process control (APC) – namely nonlinear model predictive control (NMPC), where the control algorithms are embedded in the drive system in order to create a standalone solution for the mill. As its name suggests, NMPC tracks multiple important process variables, and the dynamic, and often highly nonlinear, relationships between them, and uses control and optimization algorithms to decide on what actions should be taken to drive the system to an optimal state. See Figure 3.

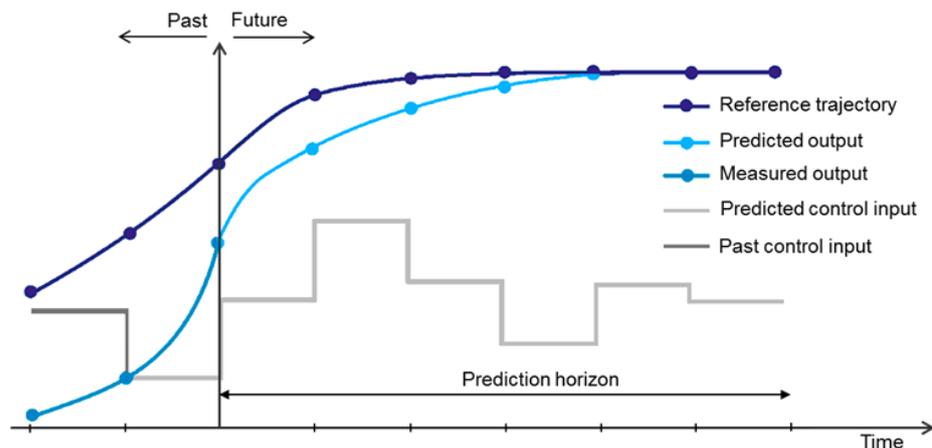


Figure 3 – An APC approach steers the system trajectory towards optimal operating conditions by continually monitoring and adjusting process parameters

Specifically, the mill's dynamic behavior is modelled by a set of nonlinear differential equations that describe all relevant system states such as the load, power or torque of the mill. These equations allow the controller to predict the future mill behavior. By solving a mathematical optimization online, the SmartMill™ controller is able to choose the manipulated variables (feed and speed) in an optimal way while respecting operational constraints and ensuring stable operation. The model description contains a number of plant-specific parameters that can be adapted to the actual setup at commissioning to ensure that the plant's behavior is modelled sufficiently accurate.

As NMPC is a feedback control strategy, the optimal choice of the manipulated variables depends on the most recent dynamic states of the mill. As measurements of these states may be subject to significant noise or may even be unavailable, the current dynamic states of the mill are estimated by moving horizon estimation (MHE). MHE is a well-established estimation technique that solves an optimization problem for determining system states that match past and current measurements in the best possible way. Roughly speaking, MHE generalizes an extended Kalman filter by not only considering the most recent but also a number of other past measurements when computing state estimates. Moreover, MHE can incorporate the knowledge of operational constraints to discard state estimates that may be infeasible. At each sampling instant, the SmartMill™ solution first determines an estimate of the dynamic states of the mill by means of MHE and passes this information to the NMPC controller for determining optimized values for mill speed and feed.

The grade and hardness of the ore supplied to the mill often vary considerably. In addition, equipment wear and drift will introduce uncertainty into the process management. This makes it difficult for a fixed-speed mill to operate efficiently and is one of the reasons why SAG mills and some ball mills utilize variable-speed drives (VSDs). It is this “actuator” — i.e., varying mill speed — that is exploited by SmartMill™ to increase grinding efficiency, reduce energy consumption, increase throughput, decrease particle size variation, reduce overgrinding, improve product quality consistency, eliminate shift-to-shift variation and extend the lifetime of liners. And all this while monitoring, and staying within, the given bounds for parameters such as power consumption, bearing pressure, feed-level indicators and ore granulometry. Augmenting manual operation of grinding mills with SmartMill™ can be compared to using an autopilot on an aircraft: the pilot is still present, and necessary, and he will perform certain tasks, but he is able to use the autopilot to manage routine, complex or fast-moving situations in a very smooth way, as the circumstances dictate.

ABB has the advantage of being able to supply not only the advanced process control for grinding operations, but also all elements of the VSD (transformers, frequency converters, motors, etc.), and the special mill application features (see below). Also, in many cases, ABB supplies the higher levels of automation in the plant and the electrification. This allows for a deep knowledge of the entire process, which, in turn, leads to a very tight and effective integration of the NMPC into the process.

It is important to note that no additional hardware is required for the SmartMill™ control itself, as ABB utilizes the same embedded controller for both the mill application features and for the model predictive control.

Mill application features

Since the introduction of the gearless mill drive solution in the 1960s, ABB has developed a number of application control features that help to protect the mill and the network from electrical and mechanical damage, as well as support the operation and maintenance procedures of the mills. Later on, the same mill application control features were also implemented in the ring-gear mill drive solution, in addition to other ring-gear related features like coupling supervision and precise load sharing control.

These features are implemented in an application controller with a very short response time, which is required to perform some delicate functions like the automatic positioning by mill angle. This specific application controller is actually placed inside the frequency converter panel and is now being used to run the NMPC algorithms required by the SmartMill™ solution too.

The variety of mill protection and operation features is described below. These run in parallel with the NMPC software. With this advanced control philosophy ABB ensures that the mill runs at its optimum speed and feed, while maintaining the electrical and mechanical smoothness and all protection functions that prevents any unexpected downtime like, e.g., frozen charges.

Creeping mode

Creeping mode is an adjustable low speed that can be used to perform visual inspections. Fast stop ramp can be individually set to avoid overshoot which would occur if the mill is stopped too slowly. Upon request, the creeping mode can be dimensioned to go down to 1 percent of nominal speed when needed.

Automatic positioning

To perform liner changes, the drive can automatically bring the mill to an operator-selected angle or liner reference. This function includes cascading compensation and a fast-stop ramp for accurate and rapid positioning — hence reducing downtime needed for liner changes.

Frozen charge protection

The mill controller detects frozen charge by analyzing the mill's angle and dynamic torque during the starting period. A dedicated algorithm detects smooth cascading. The mill stops automatically — preventing frozen charge dropping or being accelerated to higher speed.

Frozen charge remover

ABB's patented method for detaching frozen charge from a tube mill applies superimposed torque steps on top of the actual motor torque to loosen the charge from the shell. Both torque and speed are always positive, so the contact between pinion and ring-gear is always maintained, hence no backlash will be seen in the mechanics.

Controlled rollback

This function brings the mill smoothly to a standstill position where both speed and torque are zero. The load then being balanced at the bottom of the mill, mill rocking is prevented and a faster stop without backlash is ensured.

Stand-still detection

To protect mechanical and electrical components of the mill drive system, the motors should not restart if the mill is still rocking or moving after a stop command. This function detects when the mill is standing still and can be safely started.

Coupling supervision

Deviations in torque between the two pinions (or torque characteristics in the single pinion configuration) are monitored. Failure or slippage of one or both couplings, is detected and the drive trips, thus preventing major damage.

Mill power ride-through

Network variations — faced frequently in remote mining areas — can be countered with the mill power ride-through feature. It ensures that the mill keeps running even if the drive supply voltage drops. Additionally, the controller accelerates the mill smoothly back to operational speed when the voltage recovers.

Over-duty cycle mode

In case of mill overloading, the over-duty cycle permits operators to correct the feed rate while keeping the mill running. The drive system generates additional torque for a certain amount of time to overcome the overload.

All these mill application features are performed by software in the ABB AC 800PEC controller. The NMPC software can also reside in this controller, so no additional hardware is required for the SmartMill™ solution.

A pilot project that implemented these features and applied APC technology to the entire grinding circuit was undertaken at a copper mine in Sweden and its results were extrapolated so as to understand the benefits that the mill standalone solution SmartMill™ will bring when it is applied.

APC grinding for copper ore processing

The grinding circuit of the Swedish plant consists of two autogenous mills, a separator and sieves — very similar to that shown in Figure 4. Until the installation of APC grinding, multivariable process control had not been used. The mine processes tens of millions of tons of ore per year, so even a small percentage efficiency gain has a large positive financial impact. The entire site process — including the concentrator, conveyor systems and pumping stations are controlled by ABB's Extended Automation System 800xA. ABB low-voltage switchgear distributes power across the entire site.

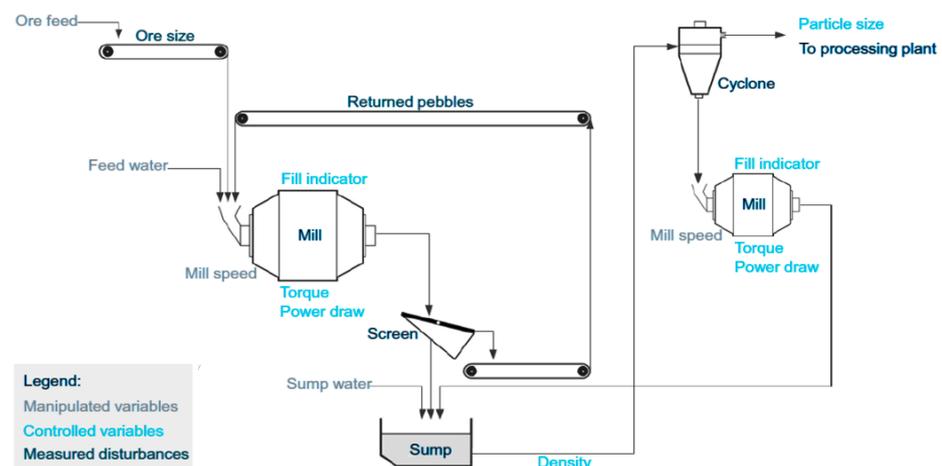


Figure 4 – Typical grinding circuit

Improvements with APC grinding

Particle size is one of the most important process parameters. APC grinding significantly improved control of this parameter – trials with APC grinding control switched off and on showed very emphatically that the actual particle size measured follows the set point very closely when control is on and wanders noticeably when it is off, see Figure 5. It should be noted that particle size control is not being covered by SmartMill™ at this point of time, but will eventually be considered as one possible input to the system – see Figure 6 for APC grinding/ SmartMill™ comparison.

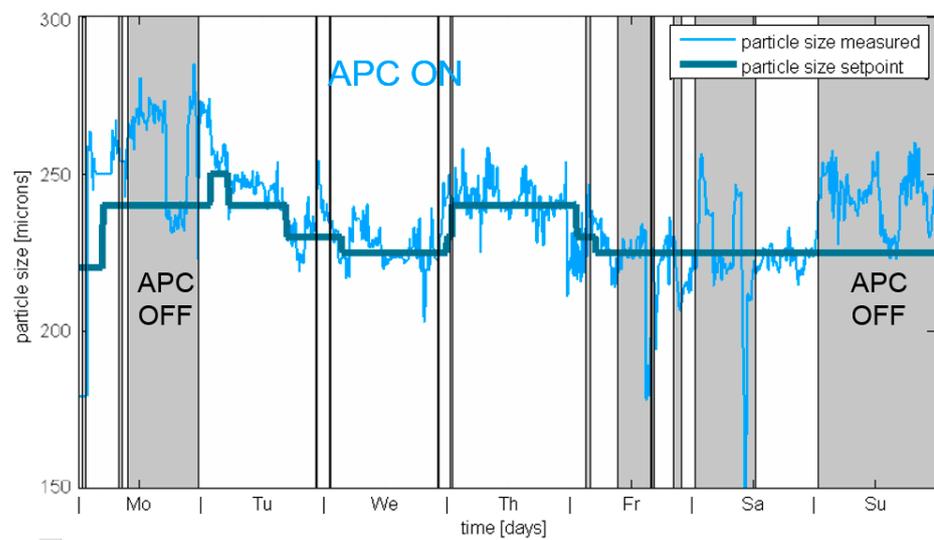


Figure 5 – When APC grinding is operating (“APC ON”) it significantly improves particle size control

SmartMill™	APC Grinding
<ul style="list-style-type: none"> – Stand-alone solution for mills – Variable speed drive as standard – Mill control special features available – Inputs are: power, torque and load – Outputs are: feed and speed – No additional controller required – No additional instrumentation required 	<ul style="list-style-type: none"> – Solution for the entire grinding circuit(s) – Tailor made solution, according to the results of previous site audit to understand what needs to be controlled/modified – Needs dedicated controller and a server – Needs instrumentation on site – Requires constant fine tuning

Figure 6 – APC Grinding/SmartMill™ comparison

A similar trend is seen with mill load, which is controlled by the amount of incoming ore feed, the quantity of water added to mill feed and the rotational speed of the mill. Figure 7 clearly shows how well the measured load tracks the set point when APC grinding is operating and how it deviates when APC grinding is switched off. SmartMill™’s control capability will be very similar to this. At all times the operator is kept fully informed via his display (see Figure 8).

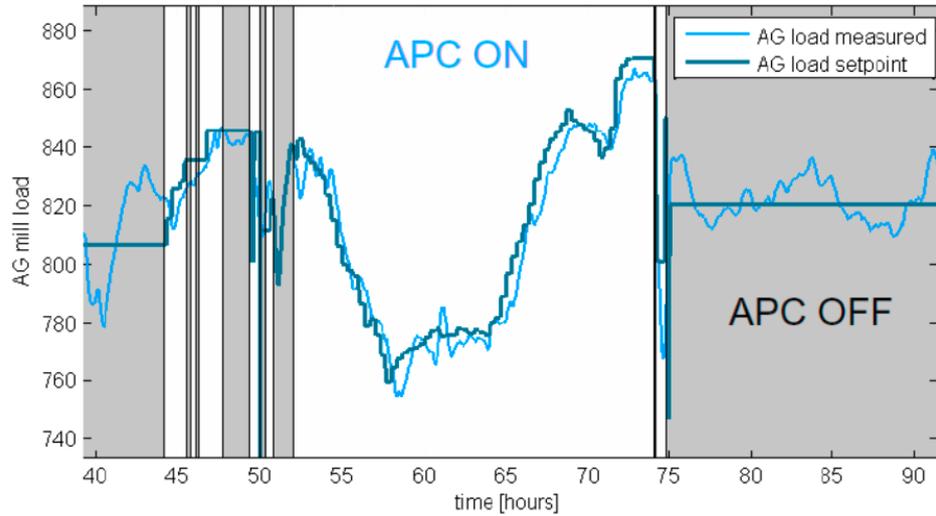


Figure 7 – After APC grinding control is switched on (green vertical line) the actual load tracks the set point much more closely.

Torque control of the mill motors is one of the most critical aspects of the entire processing line – especially at the very high power transfer ratios involved in this Swedish mill. An understanding of torque relationships in a grinding mill involves a complete analysis of the mill, gear train and drive motor with regards to torsional load, inertia and frictional losses. The ability of the drive motor to develop the required smooth torque profile is dependent upon its inherent torque characteristics in combination with the quality of the power supplied. SmartMill™’s performance



Figure 8 – Typical operator display of load set point

will be comparable to the results of the APC grinding solution in Figure 9. The SmartMill™ solution will ensure that the torque delivered to the motors is far more constant (as in “APC on”) than when the operation is run without SmartMill™ (as in “APC off”) and the motor system is subject to torque spikes that can lead to problems in the mechanical components of the drive train, especially where the pinion tooth alignment in this high-power mill is concerned.

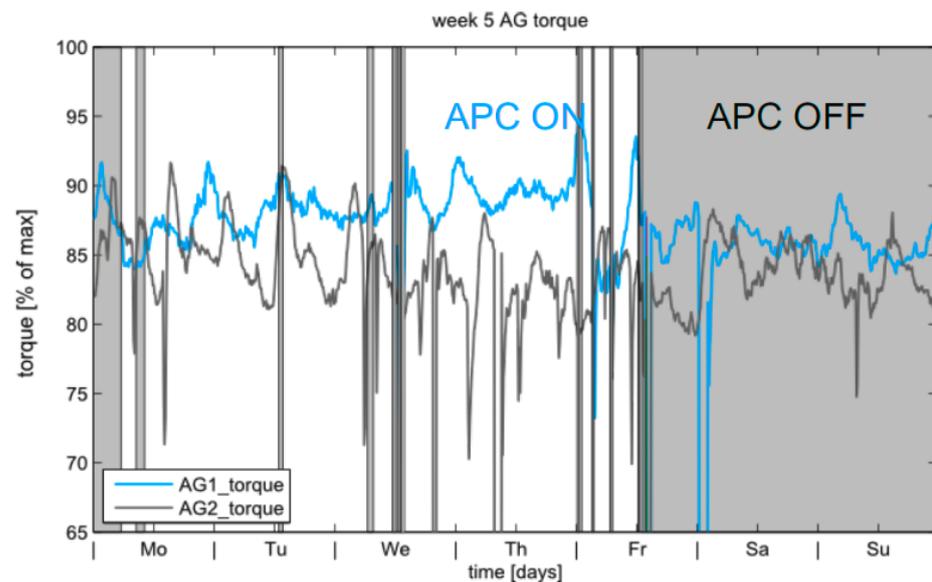


Figure 9 – APC grinding improves torque delivery by reducing the number and severity of spikes

In the bigger picture, by controlling these process parameters better and removing much operator manual intervention, SmartMill™ will reduce oscillations that are caused by operators introducing self-induced oversteer into the system. Further, SmartMill™ can reduce reliance on (and the effect of subjectivity between) individual operators, thus lessening the impact when their know-how is lost to the operation when they retire or are re-assigned.

SmartMill™ proof of concept

The project at the copper mine demonstrates very well the capabilities of APC. In that case, APC is controlling the entire grinding circuit, including more than one mill at a time and using feedback from the particle size analyzer. However, APC cannot be said to be an embedded control, as SmartMill™ is. With SmartMill™, individual mills are controlled by APC software embedded in the drive system controller (an ABB AC 800PEC)

Hardware in the loop test

As a proof of concept, the nonlinear MPC (NMPC) controller has been run in closed loop mode in a hardware-in-the-loop (HIL) setup. For this, the NMPC controller has been deployed on an AC 800PEC (PP D539). Additional functionality such as protection functions usually deployed for mill applications was included. A real mill is mimicked by running the dynamic model of the mill on another AC 800PEC (PP D113).

Communication between the two AC 800PECs is established by using Compact Control Builder. Therein, a basic faceplate also has been programmed that allows

the user to change parameters of both the NMPC controller and the dynamic mill model on the fly. The main components of the HIL test setup are summarized in Figure 10.

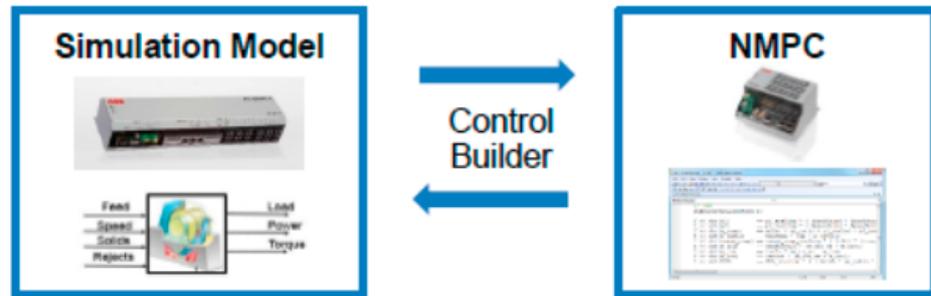


Figure 10 – HIL test setup

Test 1: PI controlled (speed manipulated)

In the first test, a simulation of an operator trying to control the speed of a mill was performed and compared to the results of the SmartMill™, in which the system has the control. In this case, it is assumed that the mill has already a variable speed drive and the difference in performance is mainly due to the NMPC control.

Figure 11 shows the state trajectories of a particular test where two load steps are simulated using an NMPC (SmartMill™) control approach and a PI control approach. The corresponding manipulated variables are depicted in Figure 12. In the case of the PI-controlled solution, only the speed of the mill has been manipulated.

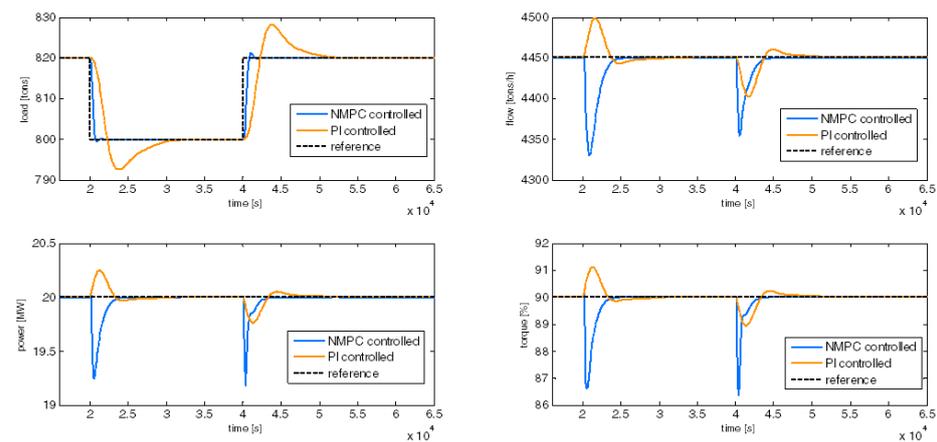


Figure 11 – Mill model state trajectories during simulation test performing load steps. Actual trajectories are plotted as solid lines, reference trajectories are dotted.

It can be seen that in the NMPC-controlled scenario the reference values are smoothly tracked. The PI controller cannot follow the reference values as quickly, due to the fact that it can only influence the speed of the mill. Furthermore, it shows more significant overshoot.

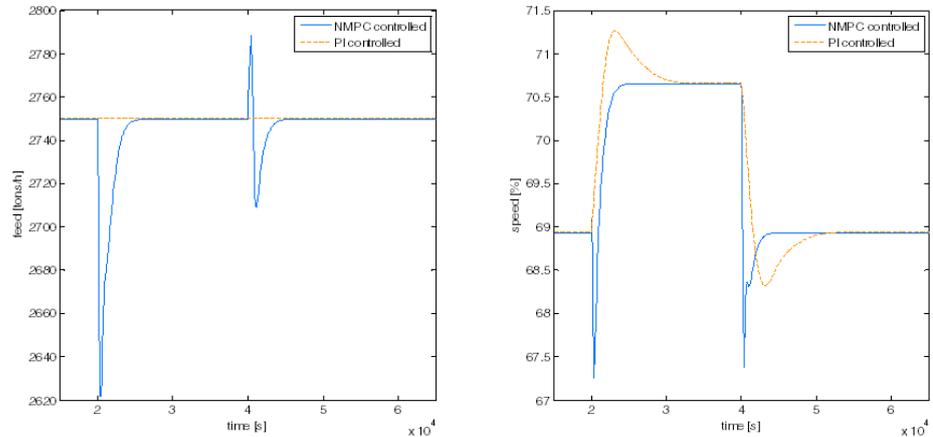


Figure 12 – Mill model control trajectories during simulation test.

Test 2: PI controlled (feed manipulated)

In the second test, a simulation of a mill running in a fixed speed mode was created and compared with a SmartMill™ system.

The fixed speed configuration, which is very common, especially in ball mills, usually comprises of a slip-ring motor and a liquid rheostat or, sometimes, a synchronous motor with clutches. In these cases, the operator has limited scope for optimizing the grinding operation as the mill speed cannot be varied; he has only the mill feed to work with.

Figure 13 shows the state trajectories of a particular test where two load steps are simulated using an NMPC (SmartMill™) control approach and a PI control approach. The corresponding manipulated variables are depicted in Figure 14. In the PI controlled case, only the feed of the mill has been manipulated.

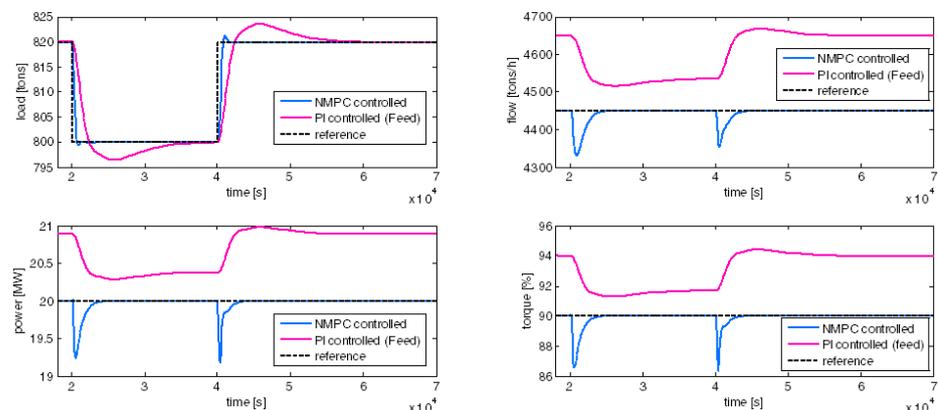


Figure 13 – Mill model state trajectories during a simulation test performing load steps. Actual trajectories are plotted as solid lines, reference trajectories are dotted.

It can be seen that in the NMPC controlled scenario the reference values are also smoothly tracked. The PI controller cannot follow the reference values as quickly, due to the fact that it can only influence the feed of the mill. Furthermore it shows more significant overshoot and certain boundary conditions (e.g. higher torque limits) might not be respected.

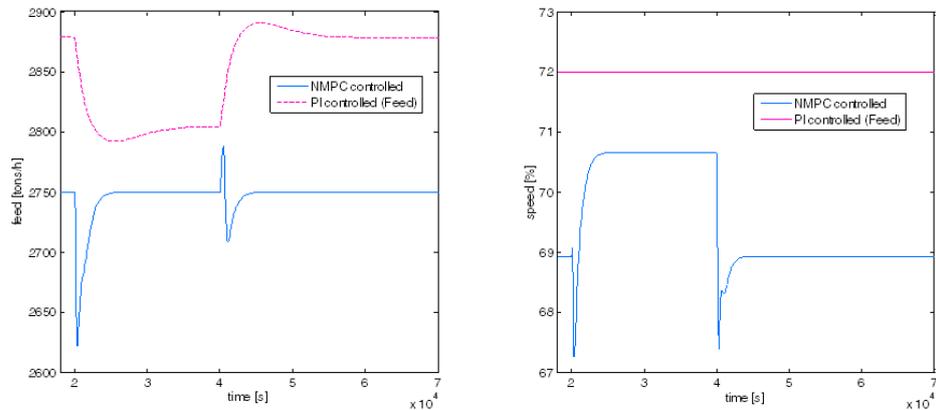


Figure 14 – Mill model control trajectories during simulation test.

Conclusion

Traditionally, for efficient operation of a grinding mill, the process engineer had to achieve a high throughput without producing too much recirculating load. He also had to adjust the mill speed according to the ore-feed and the ore grindability, while trying to prevent excessive wear of the equipment. This was usually performed with only rudimentary control automation, or, indeed, none at all. This approach left room for productivity and efficiency improvements.

ABB's SmartMill™ can now deliver some of these improvements by enabling the adaptation of the actual mill speed and feed rate to current conditions in real time. The speed can now be varied according to an advanced process control concept that keeps the mill solid feed as high as possible while monitoring signals such as power consumption, motor torque, bearing pressure and ore granulometry. Further, the reduced level of operator interaction now needed decreases not only self-induced system oscillations, but also decreases the impact of loss of expertise when personnel leave or are re-assigned.

The measurements made in an APC grinding installation in Sweden showed how the optimized variables improved the mill throughput, decreased the particle size variation and contributed to an overall process stability. Based on these results, it can be concluded that the SmartMill™ solution will provide a simple and robust way of achieving increased grinding efficiency, decreased energy consumption and extended mill lifetime. Indeed, tests conducted in the laboratory have indicated this by demonstrating the efficacy of SmartMill™ control.

Built upon the control concept installed in the Swedish mill, ABB has developed a stand-alone solution that will provide full stability to individual mills, based on an embedded drive control method without the need of additional controllers or sensors.

As an attractive alternative to revamps of existing fixed speed mills, SmartMill™ offers a wide range of benefits, including not only the mill application features already possible with ABB's portfolio of grinding solutions, but now also with the possibility to actively control the speed in a conscious manner in order to achieve operation excellence.

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