Increasing Grinding Circuit Robustness with Advanced Process Control

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ABSTRACT

More complex ore bodies with lowering grades increase the challenges of maintaining high throughput, energy efficiency and required particle size for optimal downstream processing in grinding circuits. Continuous and often rapidly changing characteristics of the mill feed requires constant focus to operate the circuit at optimal level. Modern process instruments, on-line analyzers, monitoring and process control systems provide attractive and managed options to increase the circuits' capability to respond to the challenge, often in phases and in rather short time period. Furthermore, well instrumented and performing base level automation in the grinding circuit enables advanced process control (APC) strategies that utilize measurements from the whole circuit to stabilize and optimize production. In this paper alternatives for incorporating process measurements and controls to typical grinding circuits are proposed. The expected benefits to throughput, availability, energy efficiency and particle size stability are described in recent case examples.

INTRODUCTION

Lower ore head grades increase the challenge of mines to maintain or improve the production targets of concentrates. The increased robustness requirements for efficient processing of varying and more complex fresh ore feeds are also recognized. The objective of grinding is to maximize fine particles with optimal size distribution to downstream processes, with optimum efficiency. Moreover grinding is often the bottleneck for plant capacity and responsible for the majority of the running and energy costs of a mine. Therefore it certainly is an interesting unit operation for performance optimization. Even small, 0.5 – 2 % savings in energy utilization or gains in throughput or avoiding a single unexpected shut down count for a significant annual value.

Opportunity of significant, rapid and controlled productivity improvements have made advanced analyzers and process control an attractive investment option, especially in existing operations' grinding circuits. Often the attractiveness is further increased by rather low investment requirements and fast payback periods.

This paper discusses the structures and options for grinding circuit instrumentation and advanced process control. Three case studies at standard AG/SAG and ball mill grinding circuits with actual production data are used to demonstrate the potential benefits of such systems to respond to the challenge of improving the circuit robustness especially towards feed variations.

GRINDING CIRCUIT CONTROL

As seen from the general schematic in Figure 1, a typical well instrumented grinding circuit, such as a SAG and ball mill circuit, has measurements for all key variables; fresh ore feed tons, water flows for the mills and sumps, mill power, cyclone feed flow, density and pressure, sump level, sump pump speed and particle size at the cyclone overflow. Depending on the grinding mills and circuit configuration, additional instruments such as mill rotation speed (for variable speed mills), bearing pressure, load cell, cyclone overflow flow and oversize return tons are also required. Feed size analysis with image analysis, belt on-line elemental analysis and estimation of the mill charge are used in many circuits to convey more on-line information about ore feed changes to process control.

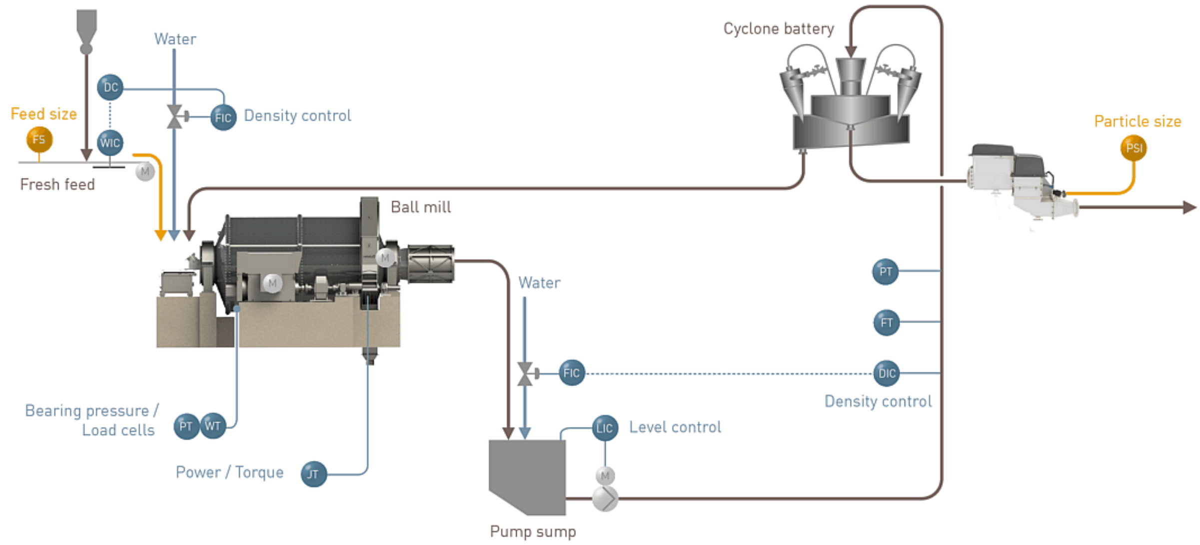


Figure 1 – A well instrumented SAG and ball mill circuit.

Traditional PID controllers are used at the regulatory level to track set-points of individual control loops manipulated by operators. Depending on the circuit design and control philosophy, some control loops are complemented with ratio and feed forward or interlocking signals at this level. The importance of the continuous assessment and re-tuning or configuration of these loops cannot be overemphasized. A badly performing regulatory level controller can have significant deteriorating effects on the performance of the equipment, circuit and downstream processing. These problems are often witnessed as large variable variance, high frequency or long cycle time oscillations, poor tracking or not reaching the set-point and also disturbing interactions with other loops. In worst case scenarios, they even cause unexpected downtime and malfunction of equipment. Well tuned and maintained regulatory controllers ensure the base stability of controlled variables, robustness for reacting, eliminating disturbances and operating the process at operation points defined by key variables. With fundamental instrumentation they also allow implementation of higher level advanced process control and optimization strategies on top.

Advanced process control (APC) and optimization systems have been one of the most beneficial tools in past decades in the minerals processing industry. APC has the capability to take into account multiple variables with time delays, interactions and constraints during multiple changes, typically to set-points of the regulatory level controllers (Thwaites, 2014). A common observation is that APC can keep production at optimum levels that the best operators are able to reach, but on a continuous basis. On the other hand a common misunderstanding is that APC will replace the need for operators. At best, these controls support the daily tasks of operators - allowing them to focus on reaching high overall plant efficiency rather than monitoring individual control loops infrequently.

APC systems and applications run at the highest levels of control system hierarchy and typically utilize advanced calculations, delay compensators and estimators with rule and model based predictive and multivariable techniques. A well instrumented process, tuned base level controls, understanding of the process, mineralogy and constraints are absolute requirements for a successful implementation. It is also important to take operations change management and user training into the plan. Like regulatory controls or basically with any equipment, for the highest utilization and therefore benefit frequent assessment of the performance is required along the lifecycle and re-tuning or configuration whenever decline in performance is identified (Sharifi et. al., 2014).

Typical APC objectives for a grinding circuit are:

- maximize grinding capacity while keeping the particle size between optimal range
- minimize disturbances and stabilize feed to downstream processing
- optimize circulating loads
- minimize energy and consumable usage
- increase the availability of the grinding circuit and equipment

A modularized advanced grinding circuit strategy is shown in Figure 2. It consists of four main modules that can be used as basic templates for an effective implementation of customized control strategies that are fit for the defined objectives of the circuit in question.

The process estimation module assures that only valid and representative measurements are applied in optimization. It also contains several important estimators or soft sensors for instance for the circulating load, mass balancing or equipment diagnosis.

A cyclone controller's task is to stabilize the feed condition of the key variables, which are pressure and density, affecting cyclone operation and to limit other controllers in case there is danger of violating variables' operating limits.

In many plants, particle size has a critical effect on valuable minerals and metals recovery, and usage of the energy and reagents for instance. A common example of the effects of too coarse and too fine flotation feed particle size is shown in Figure 3. Direct mechanical measurement or laser scattering are the most commonly applied technologies for reliable, representative and repetitive on-line particle size measurements. Particle size control module uses on-line particle size measurement to ensure that the set optimum size distribution is produced for the downstream processes. Typically, and depending on the process status and dynamics, cyclone feed density, pressure or mill fresh feed are used to take action when limits are exceeded. Instead of operator or plant metallurgist intervention, the target particle size can also be set externally by a plant wide optimizer responsible for the whole production.

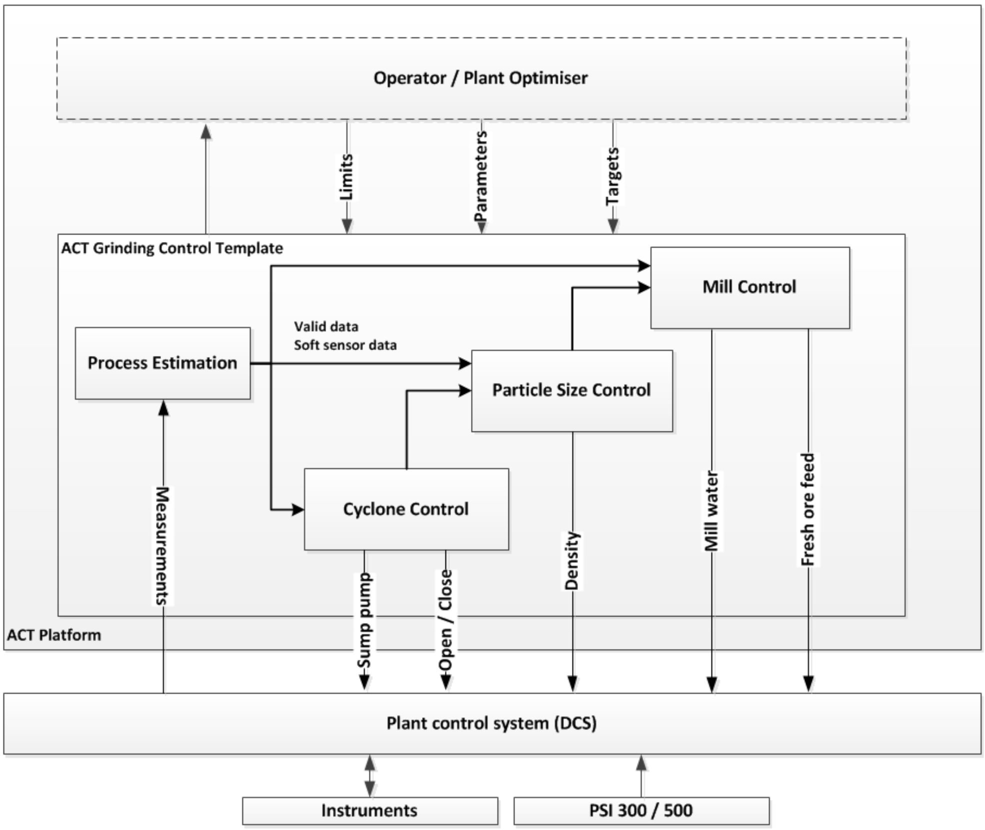


Figure 2 – Modular template for advanced grinding circuit control.

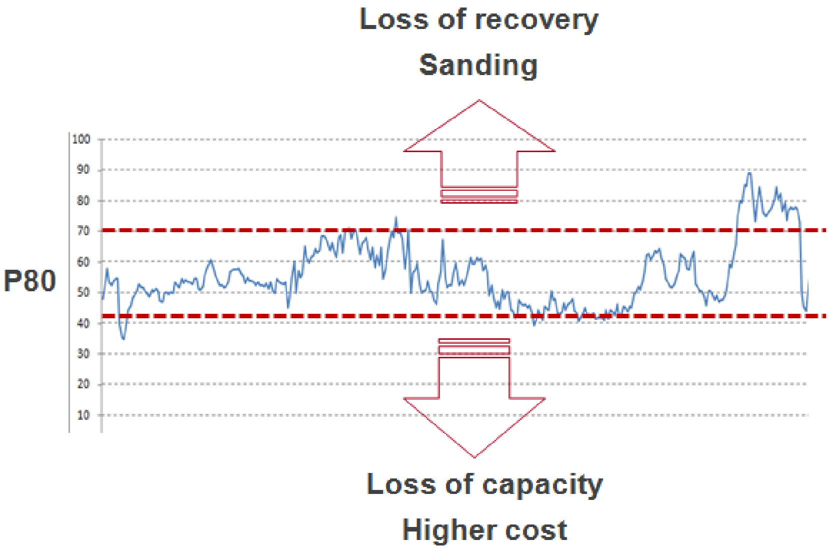


Figure 3 – Typical effects of too fine or coarse particle size (P80, µm).

The mill control module stabilizes the mill operation and attempts to increase primary mill throughput whenever the circuit is stable and within the safe operating limits. Depending on the available instruments additional limits can be generated for instance to operate at certain mill charge and close to maximum or optimum mill power. Another very important function is to react to feed ore changes and delays in order to maintain optimum grinding condition inside the mill. Due to the inherent objective of continuous pushing of the circuit capacity, appropriate reaction and recovery of violating the critical constraints are included in order to avoid unexpected mill shut downs.

CASE STUDY 1: THROUGHPUT AND STABILITY IMPROVEMENT

An advanced process control (APC) strategy was applied to a traditional medium capacity grinding circuit consisting of a primary SAG mill and secondary closed circuit ball mill. Highly variable fresh feed ore hardness creates the main challenge for the plant operators in reaching the target throughput, high availability and stable feed with optimal particle size to downstream processes for high recovery of valuable minerals. Therefore the main goal of the implement APC control strategy was set to improve the stability of the circuit while maintaining the optimal particle size distribution at the cyclone overflow. Before the implementation the performance of the existing base level PID controllers were evaluated, and as a result, all of the loops were tuned.

The implemented APC strategy was based on the template modules presented in the Figure 2 above that were customized to fit the circuit in question. The APC strategy is mainly based on rule based reasoning and advanced PID control with delay compensation. Controls and operator interfaces were implemented with Outotec's ACT advanced process control software platform that interacts with the plant process control system for measurements and set-point changes with standard OPC interface.

The APC strategy consists of three main control modules: mill control, cyclone control and particle size control utilizing Outotec's PSI analyser. In addition, an evaluation module is used for continuous assessment of the validity and integrity of the measurement data and executing the implemented soft sensor for SAG mill charge level. Charge level was estimated with the existing microphone installed to mill's proximity, which provided some additional support for the mill power control in adjusting the feed to mill. Additional improvement for the indirect charge estimation was tested by adding the mill bearing pressure information to the model but it was soon discovered to be affected by too many external disturbances for reliable information.

Results

The benefits of the implemented APC control strategy were evaluated with the paired t-testing method by running the grinding circuit with APC control for a certain period and then revert back to manual control for an equal period of time (Napier-Munn 2010). Here the manual control means operating the process with recently tuned base level PID controllers and set-points provided by the operators. Ten on and ten off periods were included in the test plan. Duration of each on or off period was twenty four hours in order to allow alternating ore hardness to affect both periods. Also the longish overall test period of twenty days minimised the possible bias between the operator shifts (each shift had five APC on and five APC off periods). The first two hours of every twenty four hour period were removed to compensate for the potential disturbances caused by the switching from manual to APC mode and vice versa. 30 minute average values were used as sample points in the analysis.

Results

SAG mill feed (t/h), SAG power (kW), particle size at cyclone overflow (% -200 mesh) and cyclone feed density (%) were chosen as key performance indicators for comparison. In addition cyclone feed flow (m^3/h) and pump sump level (%) were evaluated for interest. Table 1 shows results between APC on and off periods. Absolute numbers are unfortunately not available for the public domain but it can clearly be seen that compared to manual operation, APC strategy provided 1.2 % increased throughput and a significantly more stable circuit operation. The scale of improvement in monetary terms compares to one million US dollars annually. Improved stability is expressed as decreased standard deviation for all of the evaluated key parameters. T-test p-values close to zero indicate that the differences between the averages are not caused by chance.

Table 1 – Improvement of the APC control strategy to case study grinding circuit key variables.

	Improvement	Standard deviation	t-test (p)
SAG Feed (t/h)	+ 1.2 %	- 44.5 %	< 0.005
Particle Size (% -200 mesh) Process value deviation to target (P80: 80%)	- 83.7 %	- 62.3%	< 0.005
SAG Power (kW)	- 8.3 %	- 42.6 %	< 0.005
Cyclone Feed Density (%)	+ 3.8 %	- 61.2 %	< 0.005
Cyclone Feed Flow (m^3/h)	- 2.5 %	- 11.6 %	< 0.005
Pump Box Level (%)	+ 33.2 %	- 85.6 %	< 0.005

The higher ore feed and smaller mill power draw (smaller kW/t) is most likely caused by the more efficient charge position, seen in Figure 4 earlier. This charge position is achieved by the APC control that prevents the situations where the mill is run overloaded or too empty. The result was also supported by the SAG noise measurement that had 25.6% smaller standard deviation during the APC control. More stable charge level prevents also liner damage in the longer run for instance.

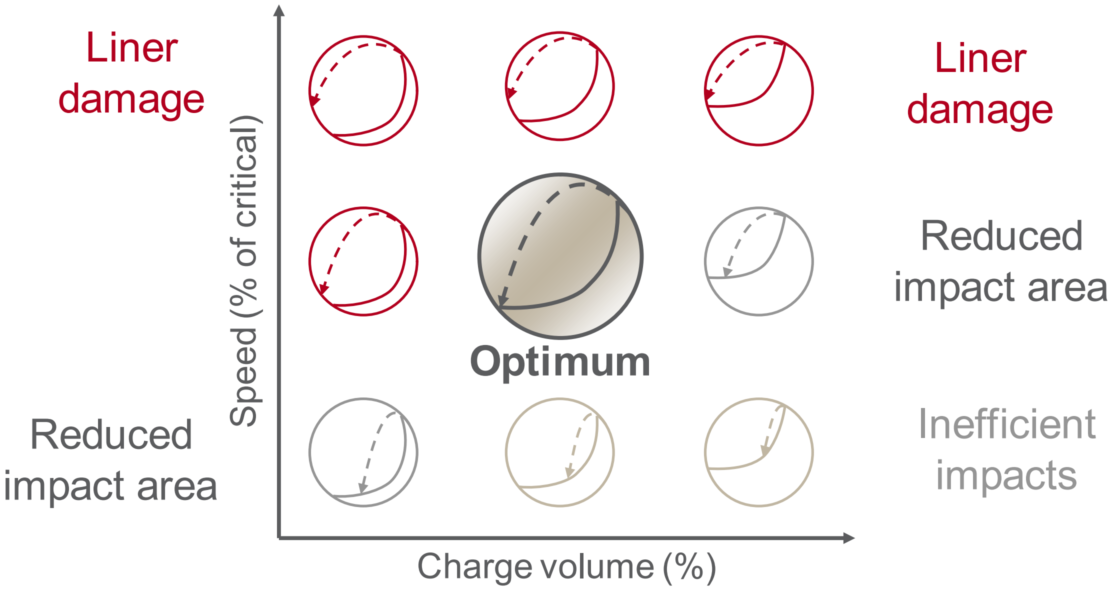


Figure 4 – Impact grinding efficiency with different mill conditions.

The average cyclone overflow particle size was over 80 % closer to the target value of 80 % -200 mesh under APC control. This is achieved by continuous monitoring of the particle size and making adjustments to cyclone feed density and if necessary to fresh ore feed. The smaller standard deviation means that the particle size variation to downstream processes was closer to optimum.

The average cyclone feed flow was lower and more stable in APC mode. The grinding circuit had also smaller circulating load, cyclone battery operation was more stable and therefore less chance of slurry spilling over from the launders, which occasionally happens when operators are pushing the throughput. APC control was also able to provide higher average cyclone feed density which means that less water addition is needed to pump sump. More stable feed density benefits also the management of the particle size distribution.

In practice the throughput improvement was probably larger than 1.2 % due to regular slurry spillage to the plant floor from an overly high circulation load during the manual periods. Trends in Figure 5 provide an example. The APC control logic contained a limit for cyclone feed flow in order to prevent spillages. In case the limit was exceeded the actions such as decreasing fresh ore feed were taken. One can clearly see that the ore feed decreases are caused by the cyclone feed flow exceeding the high limit during APC control. The limit violations were most often happening due to rapid changes in ore hardness. During manual control operators have tried to push the circuit resulting short unexpected feed belt stops, excessive circulation load and spillages at the cyclones and pump sumps. The high circulation load has also resulted coarser particle size for the flotation feed which will have significant negative effect to the final recovery at this plant.

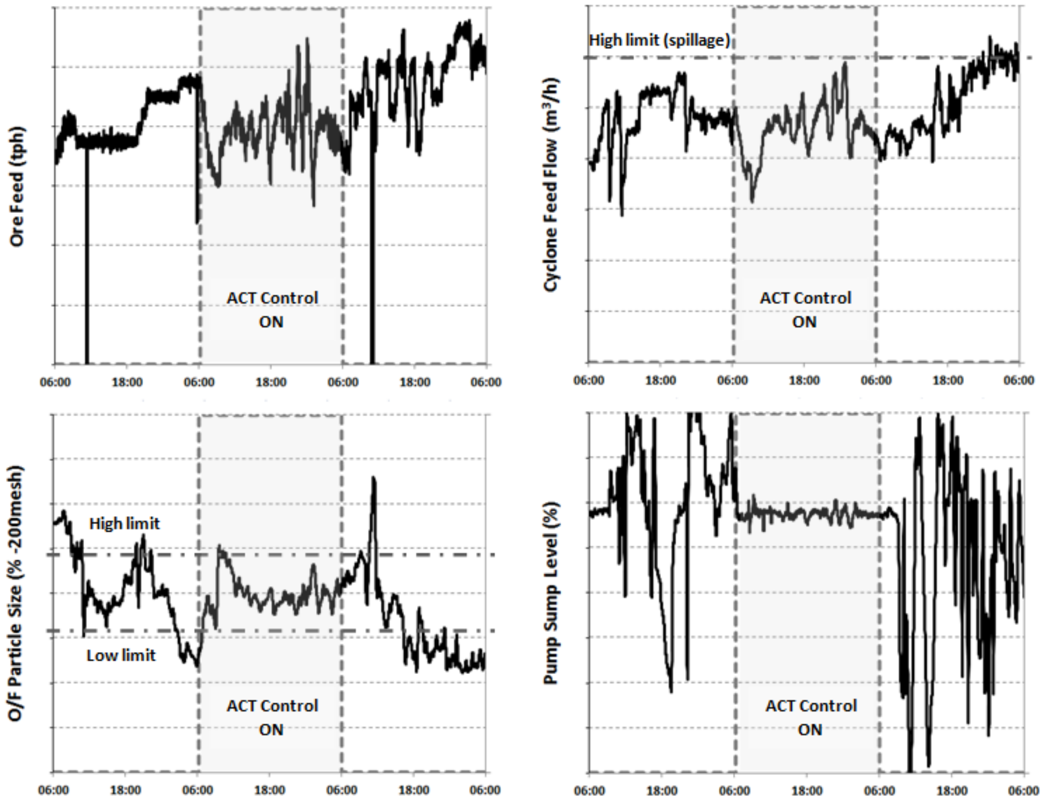


Figure 5 – APC control effect compared to manual circuit operation.

Another example of the benefit of APC control on circuit stability is presented in Figure 6. During that time the ore had been harder, making the SAG mill the bottleneck of the circuit. In these kinds of process conditions, APC control proves very useful in efficiently controlling the SAG mill charge. It is clear that running the mill with a constant charge will result in a better overall throughput than filling the mill and stopping the feed several times during the day of manual control. These stops can cause significant losses at an annual level. APC control was able to maintain circuit stable and push the maximum possible through the harder ore periods. Often the harder ore type had also higher grade. Therefore the improved performance under these conditions is especially important for the profitability of the total process.

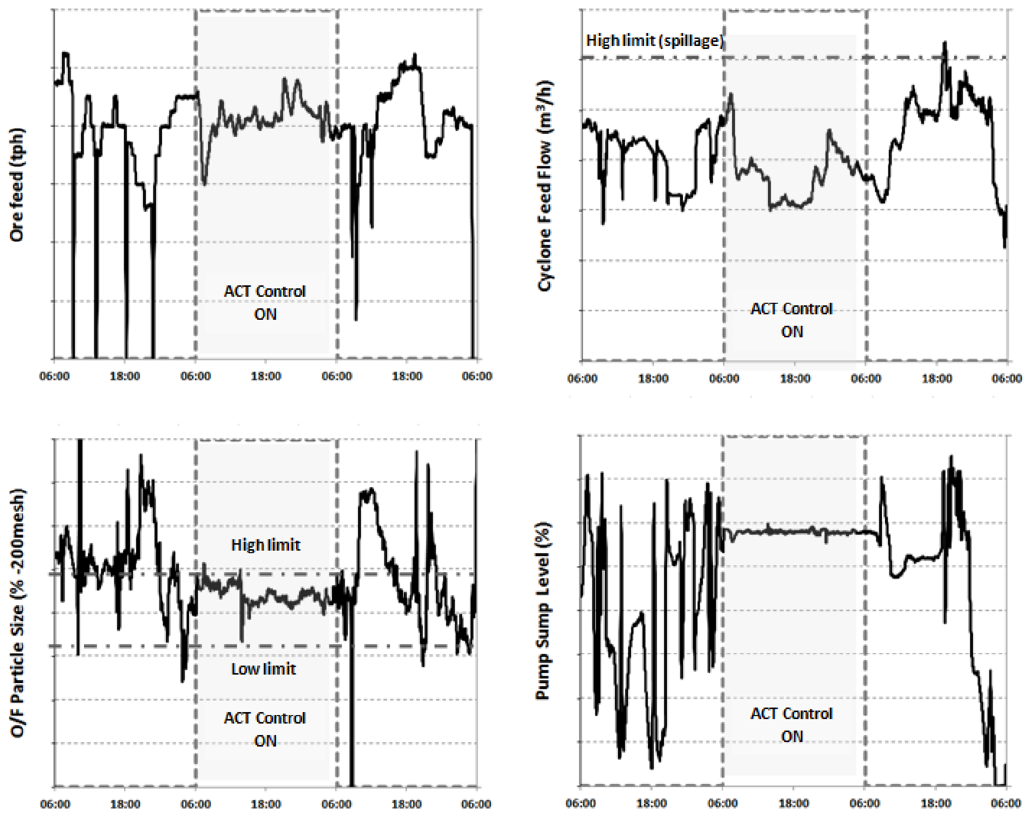


Figure 6 – APC control effect compared to manual circuit operation during harder ore feed period.

CASE STUDY 2: APC EFFECT TO THROUGHPUT

The performance of the mill control module was tested also in another grinding circuit with a high level of instrumentation and base level control with two parallel closed loop AG mills with equal split feed combined with a closed loop pebble mill circuit, shown in Figure 7. At this plant the characteristics of the fresh ore feed are also varying but not to the degree of the first case study. On the other hand low head grade emphasizes the significance of high grinding availability and throughput.

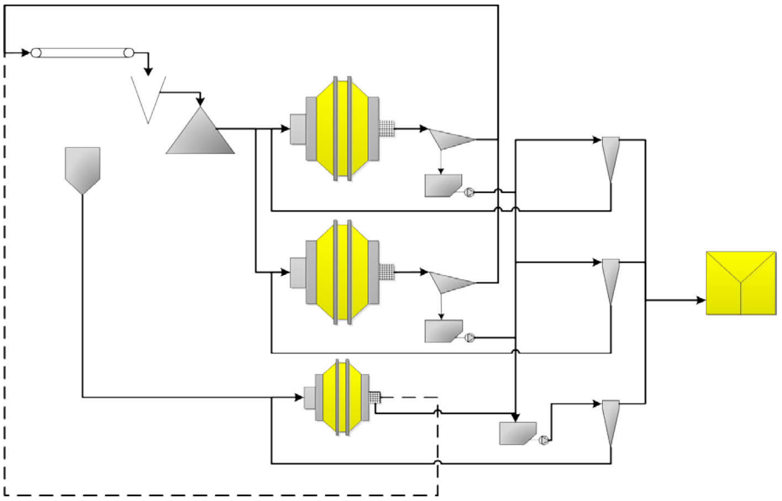


Figure 7 – Schematic flow sheet of the second case study grinding circuit.

A mill control module has been designed for the circuit using Outotec's ACT system. The performance of the milling circuit was compared in on/off tests where the mill control module of both AG mills was concurrently either enabled or disabled. Other implemented APC modules were off-line during the tests because the objective was to evaluate mill control effect to key variables. In this evaluation dry feed tons to flotation was the main key variable (t/h), and other variables of interest were SAG mill feed (t/h), SAG power (kW) and cyclone overflow particle size (% -75 µm).

Results

Six consecutive periods of six hours were recorded, and one hour in the beginning of each period was omitted to eliminate the disturbance caused by the control change. Each collected data point represented a 30 min long average of data. Some data had to be removed due to a short shutdown of the grinding circuit, resulting in a data set with 20 samples where the APC control was disabled, and 36 samples where the APC control was enabled. Figure 8 shows the data collected during the APC power control performance tests.

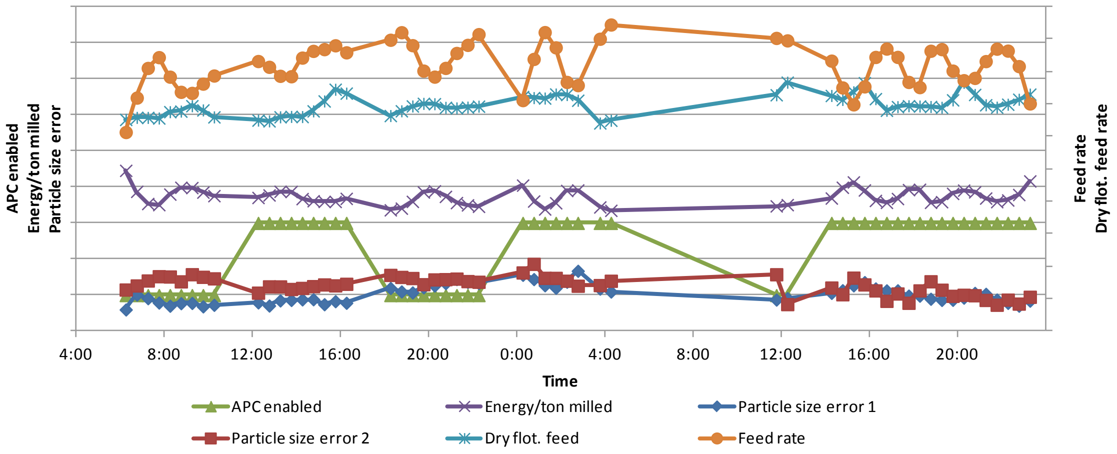


Figure 8 – Data collected from the second grinding circuit case.

Table 2 summarizes the results of the tests. The main improvement was achieved in the throughput of the circuit: The dry feed to the flotation circuit was 2.0 % higher when the APC control was used instead of the manual control by the operators. This difference is also statistically significant. At the same time, there were no significant difference in the milling energy or the tons fed to the circuit. The deviation of the mill product particle size compared to the target value remained at the same level in the first mill, but significantly improved in the second mill. The stabilizing effect of the automatic controller is demonstrated by the reduced variation of the feed rate and energy consumption.

Table 2 – Improvement of the APC power control strategy to second case study variables.

	Improvement	**Standard deviation**	**t-test (p)**
Flotation dry feed (t/h)	+ 2.0 %	+ 19 %	0.04
Grinding circuit feed (t/h)	+ 0.3 %	- 24.3 %	0.86*
AG Energy/ton milled (kW/t)	+ 1.3 %	- 26.3 %	0.58*
Particle size (% -75 µm), Mill 1 Process value deviation from target (75 %)	+ 5 %	- 7.6 %	0.68*
Particle size (% -75 µm), Mill 2 Process value deviation from target (75 %)	- 55 %	+ 34 %	< 0.005

*Not statistically significant

CASE STUDY 3: MILL CHARGE ANALYSIS

Changes in ore properties affect the impact breakage efficiency and therefore the efficiency of the whole grinding process. As a result, the efficiency and optimal operating parameters constantly change in the mill. Although the effectiveness of grinding is affected by many factors that are difficult to measure, most are linked to the charge behavior and its properties. Therefore, as shown schematically in Figure 4 before, being able to on-line measure mill charge and position in the mill in order to manage it continuously to optimum area benefits throughput, availability and liner life.

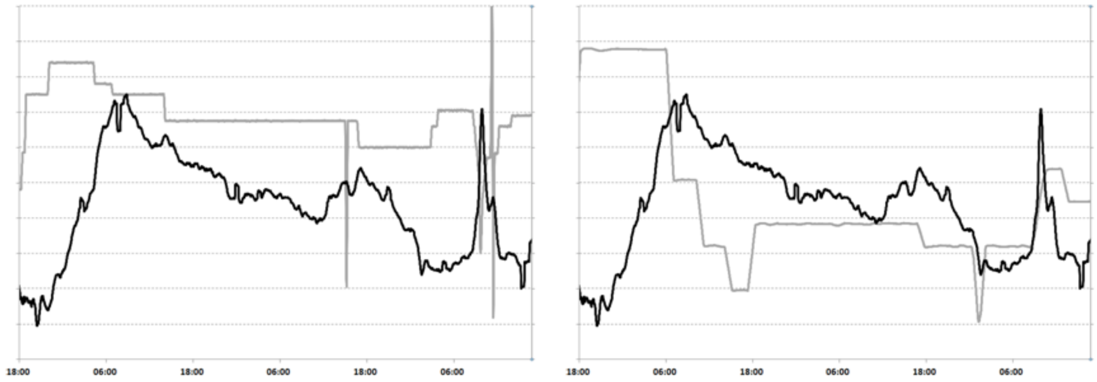
There are many ways to estimate the mill charge with their pros and cons. Very conventional methods include using mill power draw, load cells or bearing pressure, as they typically are available in many circuits. Unfortunately these are also known to be very prone to other variables' influence, non-linearities, liner wear and changing parameters making at least direct correlation with the mill charge impossible. Acoustic measurements are also common with single or arrays of microphones (Pax et. al., 2014). In addition to estimating toe position they provide additional information regarding charge and grinding media behavior, but often require rather extensive signal analysis and interpretation or frequent validation or calibration due to indirect measurement principle.

Over the years there have been lot developments around on-mill-shell type of measurement devices. There are systems that are based on acoustic sensor on the mill shell, strain gauges embedded to a lifter of the mill or vibration sensors on the mill for example. The benefit of these on the shell type sensors is that they have much better opportunity for more direct, accurate and even absolute measurement of the charge position. On the other hand the main challenges have been the reliability of the measurement in terms of powering and very limited access for maintenance during the operation.

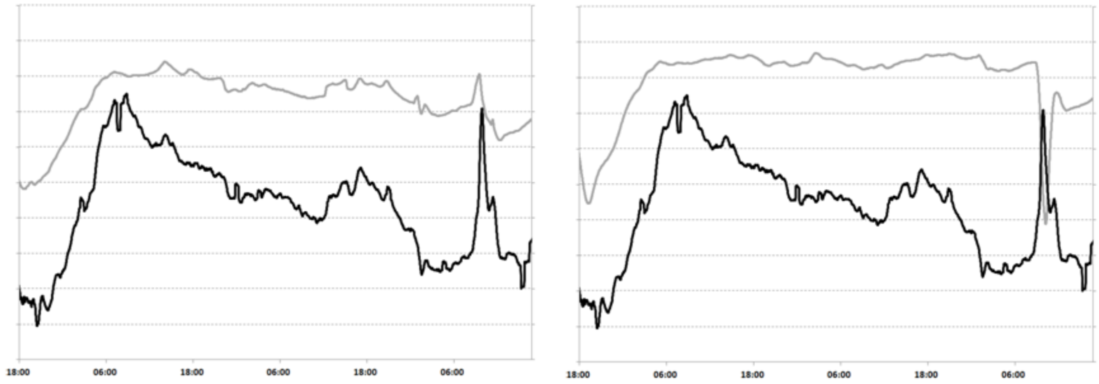
Recognizing the benefit of reliable on-line mill charge measurement for increasing the availability, robustness and performance of grinding, Outotec has been developing a new generation measurement based on a standard strain gauge installed to a liner bolt on the mill shell. The measurement has then simple, absolute and direct nature to capture the exact toe position and accurate estimate of the charge volume. The reliability of the sensor powering is solved by using inductive transfer of energy outside the mill during each mill revolution. Measurement data is transferred wirelessly out from the mill shell. The new measurement system has been tested at different mills over several liner cycles with good reliability and promising results.

Figure 9 shows over two day trend of measured mill charge of a closed loop pebble mill and its correlations with mill power, load, pebble feed and mill water. Clear responses to changes in pebble feed and mill water can be observed in the mill charge. Despite of the high correlation between variables, reliable indication about the absolute mill charge is difficult with other variables alone. For instance mill power responses to the increase of pebble feed but settles down to the level even when the pebble feed is decreased afterwards.

Another example for a primary AG mill of another plant is presented in Figure 10, where fresh ore feed (tph) is compared with the mill charge measurement. Good response of primary feed rate change to mill charge can be seen and also measurement system's capability to measure the mill charge until the mill is stopped before the scheduled maintenance shut down shown in the last part of the trend.



Mill charge (black) (%) and pebble feed (grey) (tph) **Mill charge (black) (%) and water feed (grey) (m^3/h)**



Mill charge (black) (%) and load (grey) (psi) **Mill charge (black) (%) and mill power (grey) (kW)**

Figure 9 – Correlation of the mill charge with key mill variables. Absolute variance between minimum and maximum charge was 6 % during the period.

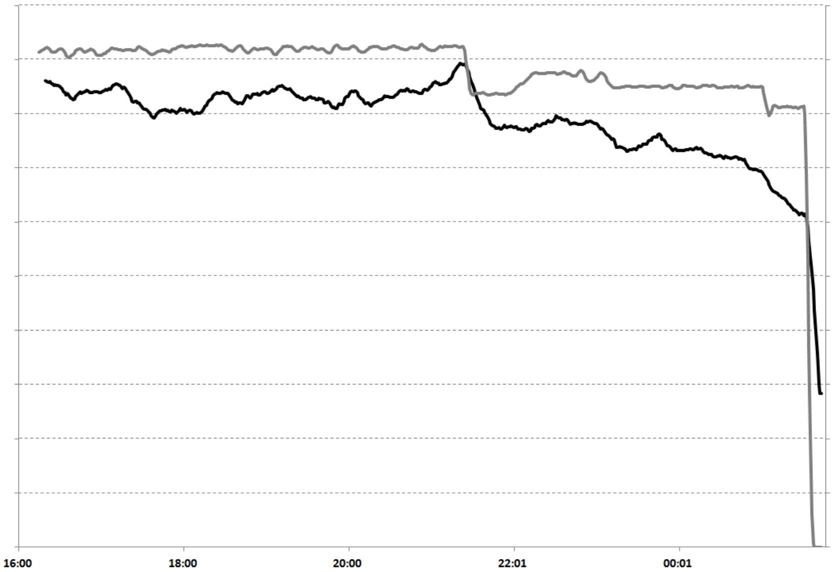


Figure 10 – Correlation of an AG mill charge (black) with mill feed (grey) before mill maintenance shut down.

CONCLUSIONS

The grinding circuit's capability to manage variable ore feed can be improved by ensuring an adequate level of instrumentation, tuned base level controls and modulated advanced process control strategy that is customized to specific targets of a circuit. For long term benefits it is essential that all of these layers exist and are performing properly, as demonstrated by three case studies of the paper.

In addition to a significantly more stable and consistently operating grinding circuit and 1 – 2% increases in throughput, the advanced process control implementation based on Outotec's ACT system allowed other unforseen benefits such as a decreased number of unexpected mill shut downs or increased operator time to focus on improving plant's overall efficiency.

Being able to measure accurately the mill charge provides additional benefits for increasing grinding circuit's robustness towards alternating feed characteristics and therefore the efficiency of the mills. A novel measurement system based on an induction powered strain gauge that is installed to a liner bolt provides absolute, repeatable and reliable measurement of the mill charge and toe position of a mill. Initial results obtained in long term tests conducted at industrial grinding mills are encouraging towards beneficial utilization of the system to further increase grinding circuits' robustness for changing ore characteristics.

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