A Holistic Approach to Control and Optimisation of an Industrial Crushing Circuit

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Abstract: Anglo Platinum's control schema for crusher circuits follows a layered approach that includes basic control (regulatory, interlock and sequence control), fuzzy logic, rule-based and model predictive control. This allows for a robust approach to circuit optimization. This paper outlines a typical control schema for a crushing plant, and discusses the benefits that have been achieved over a wide range of fluctuating feed conditions and different equipment availabilities at two industrial installations.

Keywords: Crushing Circuit, Model Predictive Control, Constraints, Control Layers.

1. INTRODUCTION

Crushing plants are an integral part of most conventional comminution circuits. At Anglo Platinum the main objective of the crushing plant is the effective utilization of energy in reducing either the top size (typical for secondary crushing plants) or the fraction of critically sized material (typical for in-circuit crushing (ICC) plants) in order to optimize and balance the overall comminution capability between the crushing and grinding circuit operations. Sustainable control of yield and quality of crusher product requires the use of automated control strategies (Hultén and Evertsson, 2008). Anglo Platinum's crusher circuit control schema employs a layered approach that includes both basic control (interlocks, sequences and regulatory control) and supervisory control consisting of fuzzy logic rule-based and model predictive control (MPC). This layered approach to the control schema provides a robust and holistic approach to optimization.

Each layer of the control schema contributes in a unique manner to the overall control performance, each with its own associated benefits. The control schema is made up of hierarchical control layers and the effective functioning of each layer is dependent on the performance of the layer that feeds into it. The complexity of the control strategy is reflected in the complexity of the final schema, which is a function of the process complexity, the number of process variables considered, the disturbance rejection capabilities of the process equipment, and the process dynamics.

This paper reviews Anglo Platinum's control schema for a typical crushing plant and discusses the process benefits that have been achieved at two industrial installations with varying feed properties and different equipment availabilities.

2. PROCESS DESCRIPTION

A process flow diagram for a typical secondary crushing circuit is shown in Figure 1. A primary crusher (not shown) receives ROM ore from the mine, and delivers sized product to the conical stockpile. The stockpile forms a buffer between the primary and secondary crushing operations. Several variable speed feeders then withdraw ore from the conical stockpile and deliver it to a vibrating grizzly screen for size classification.

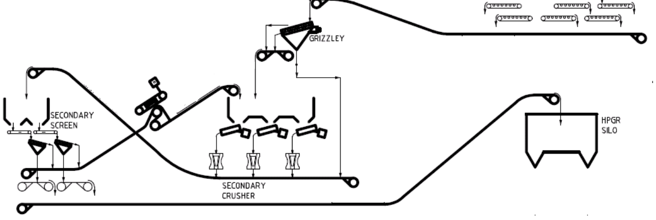

Figure 1: A typical Anglo Platinum secondary crusher circuit process flow diagram (PFD).

The grizzly oversize material is transferred to the secondary crusher feed bin by belt conveyor. Several secondary crushers might be fed from this bin, depending on the duty. In Figure 1, three secondary crusher feeders operate independently, feeding each secondary cone crusher at a controlled rate. The feeders are usually variable speed units controlling the feed to the crushers in order to maintain the crusher cavity level. The secondary crusher product together with the vibrating grizzly screen undersize, is conveyed to the secondary screen feed bin.

Typically variable speed feeders are used to feed the secondary classification screens. In Figure 1 two variable speed belt feeders transfer crushed ore from the bin to each of two vibrating screens. The oversize material is recycled back to the secondary crusher feed bin by belt conveyor. The screen undersize reports to a tertiary crusher / High Pressure Grinding Roller (HPGR) Feed bin via a dedicated conveyor.

It is evident from Figure 1 that several classification screens exist. The continuous and efficient (no overload) operation of these screens is critical to circuit performance. Inefficient screening can easily lead to a high circulating load, burdening the circuit with misplaced material and degrading its energy efficiency and throughput capability.

3. BASIC CONTROL

The basic layer of the control schema is implemented within a programmable logic controller (PLC) using interlocks, sequences and feedback control loops (PID algorithms). The primary objective of the basic control layer is to ensure safe operation with adequate equipment protection, while stabilizing important process variables such as the fresh feed rate and storage bin levels. The basic control layer handles processing upset conditions, equipment failures and implements operator actions. This control layer is a pre-requisite for the advanced process control (APC) layer.

Implementing control on a crushing circuit such as that depicted in Figure 1 (using a basic control schema that primarily consists of feedback type controllers (PID controllers only), often results in several difficulties which manifest because of the limitations of the control schema to deal effectively with the various interactions between the processing units. These limitations include the following:

- Stand alone control on a specific process unit to a fixed setpoint (SP), usually set by the process operator, with
- little or no feed-forward control inputs from its upstream or downstream process units that minimizes the potential to cater for possible constraints in these units.
- Due to the control horizon typically represented by the basic control layer, it is difficult to predict constraints that develop over longer time periods and across the various process units where multiple interactions may exist. This limits the ability of the basic control layer to effectively feed-forward the required control actions to the relevant feedback controllers in time to alleviate these circuit constraints, which if achieved will allow the whole circuit to perform optimally.
- Additionally, unmeasured disturbances such as changes in the ore feed size distribution (FSD) and/or ore hardness, can have a significant impact on the performance and ability of the basic control schema to handle and reject process disturbances resulting from these changing characteristics.

Given the limitations listed above, it is evident that a more advanced control strategy is required to optimize the crushing circuit under consideration.

4. SUPERVISORY CONTROL

Anglo Platinum has a well developed supervisory control layer (APC layer) that is tightly integrated into the basic control schema. By combining the best-of-breed features found in various technologies, Anglo Platinum has derived an integrated APC suite that provides all the tools required to design, deploy and support an ever growing APC footprint. The suite is centered on a G2 based Expert System and is known as the Anglo Platinum Expert Toolkit (APET). A standard interface module has been developed in the basic control layer that provides a single point of write access from APET to the PLC layer. This interface, in combination with the regulatory and interlocking schemes ensures tight integration between the APC and PLC layer resulting in good overall system performance.

The supervisory control layer (APC layer) consists of a fuzzy logic, rule-based expert system with both model based and model predictive control (MPC) capability for optimization. The fuzzy logic and rules allows a robust and non-linear control algorithm to be implemented, which delivers improved stability by de-coupling highly non-linear and interactive process variables.

The control variables are "fuzzified" and expressed in linguistic terms such as high and decreasing instead of 85% and -2%/min. This means that an exact match between rules and process is not required for control purposes (Moshgbar et. al. 1994). Mamdami-type fuzzy controllers are utilized by the Fuzzy Inference System (FIS) module within APET. In Figure 2, for example, the bin level of 70% results in an 80% belief for the HIGH bin level fuzzy member. It also results in a 20% belief for the OK bin level fuzzy member.

The screen bin level expert controller uses a combination of rules that weighs the fuzzy outputs of the screen bin level fuzzy set, the screen motor current draw fuzzy set and the downstream conveyor belt motor current draw fuzzy set. All logically possible rule permutations with the above fuzzy set memberships are included in the rule set. This results in a rule set of 75 different rules.

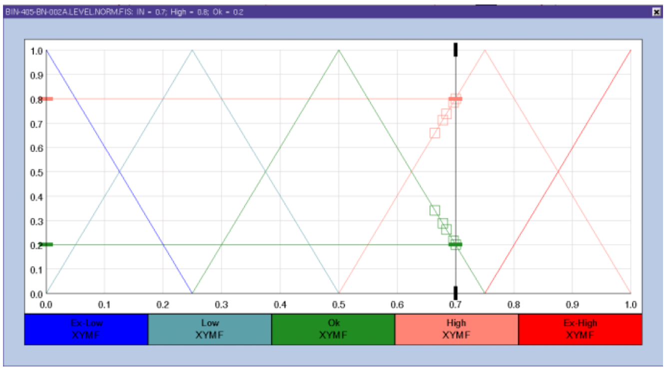

Figure 2: Fuzzy membership functions showing the functions, overlaid with recent data, used to fuzzify the bin level.

Several controller templates have been developed and refined over many years. The lessons learnt from various instance implementations of the same template on different sites have been back engineered into the template to continuously improve its control performance. The template approach ensures that a new controller can be deployed within a matter of hours. Once loaded, these templates will auto configure based on the existing relationships found in the APET schematic as shown in Figure 3 and Figure 4. During a controller setup, all of its trends, additional required calculation blocks, message queue and relationships are automatically created and/or configured. This ensures properly standardized controllers that are easy to maintain. The templates also make it possible to reuse predefined structures and modules. This assists with rapid development while enforcing standards.

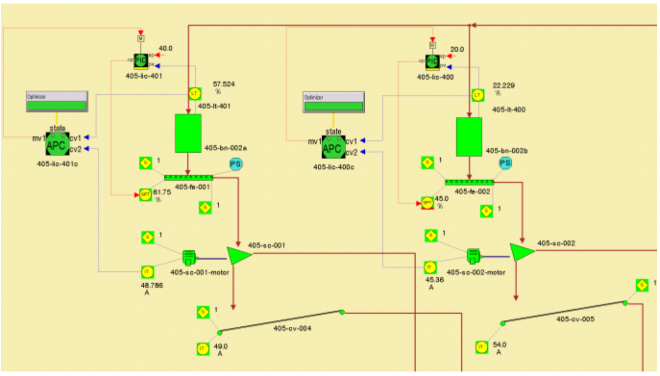

Figure 3: Example of a screen bin APC in APET that manipulates the screen feeder speed to control the bin level and prevent a screen overload.

For the crushing circuit under consideration, optimization was implemented using QPrime, an MPC platform developed by Randburg Control Solutions (RCS), a local South African company. By design, the APET platform integrates easily with almost any 3rd party control software, which allows Anglo Platinum to evaluate and select appropriate control technology from various suppliers in the industry to achieve the goal of optimal plant performance.

Various process states are derived and prioritized and used to influence the controller actions to best deal with the current process upset condition/state. Depending on the active process state, the frequency and/or magnitude of the control actions are adjusted, or an alternative control algorithm (MPC) is implemented.

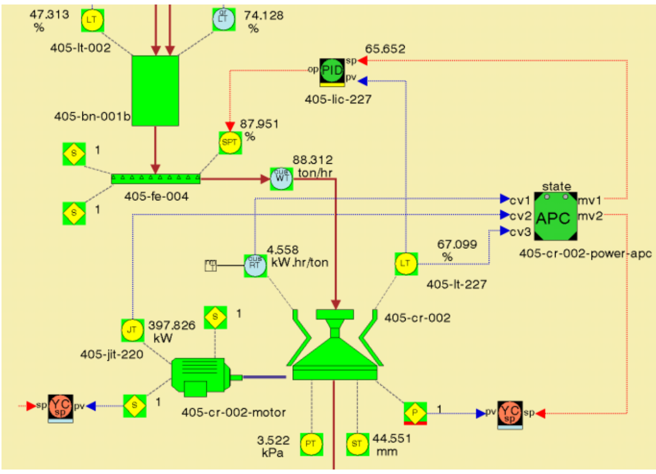

Figure 4: Example of a cone crusher APC in APET that manipulates the crusher cavity level PID SP and crusher closed side setting (ASRi controller) to control the crusher power draw.

The APC layer also implements an operational objective in the form of a set process recipe. The most basic form of process recipe setting is achieved by setting ranges (process limits) for the critical CVs and MVs used by the APC. In addition to the set recipe, state control is also included within the supervisory control layer. When calculating the required SP values for the various manipulated variables (these MV's are typically the PID controller SP values), the supervisory control layer takes into account the different process states, and the set process recipe - this allows the controller to drive process stability and optimization at the same time.

Several APC controllers were deployed in the crushing circuit's supervisory layer in order to achieve the set objectives. One of these APC controllers targeted stabilization of the secondary screen feed bin levels. Acceptable level stability in these bins could not be achieved with conventional feedback control algorithms (PID) in the basic control layer. After APC implementation, the bin levels were kept within an optimum range, while taking constraints (such as screen and conveyor belt overloading) into account. A significant stability and throughput benefit was achieved with APC alone in the form of increased equipment run time (bin feeders and conveyors) through the elimination of high and low bin level interlock control activating when the bin levels reached extremes.

In order to drive maximum throughput, a "push-pull" control philosophy was introduced within the supervisory control layer. The "push" effect is achieved by introducing as much fresh feed into the circuit as the process states and limits allow by controlling the feed to the circuit. The "pull" effect is achieved by controlling the various feeder speeds withdrawing material out of various bins within the circuit, again subject to the process states and limits imposed by the equipment. It is critical to implement the correct process "recipe" on both the crusher feed bin and secondary screen feed bin by setting appropriate high and low bin level limits (CVs used by the APC). These bin levels must be maintained and balanced at optimum values and this is critical to the operation of this circuit. Upstream equipment will be automatically stopped (interlock control in the basic control layer) if the bin levels go to extreme high values to prevent material overflowing from the bin. Similarly downstream equipment will be automatically stopped (interlocked in the basic control layer) if the bin levels go to extreme low values to prevent equipment damage from ore impacting directly onto the feeders.

Setting the optimal ranges for the various bin levels is not straight forward and many factors need to be considered. For example, depending on the bin design, withdrawing material from its base can result in funnel flow. Funnel-flow is characterized by material sloughing off the top surface and flowing down the central flow channel which forms above the feeder as depicted in Figure 5. In the case of the secondary screen feed bin, the level above one of the feeders has to be maintained at a higher value than the other to ensure overflow of material to the "opposite side" of the bin. This is because of the "dead volume" of material which forms inside the bin between the feeders as a result of the funnel-flow pattern. For optimal operation, it is vital that both feeders contribute towards the throughput (share the load) and that neither operates in a stop/start fashion.

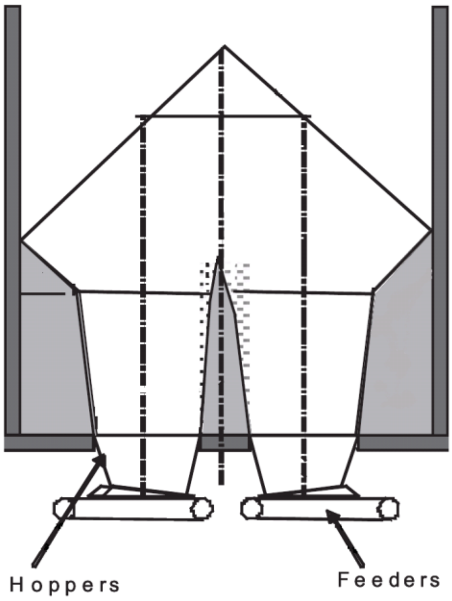

Figure 5: Funnel flow of material build up inside the secondary screen feed bin

5. OPTIMIZATION CONTROL

The supervisory control layer includes model based and model predictive control capability for optimization purposes. In this case, the MPC calculates the various set point values for many of the basic control layer PID controllers, and sets limits for some of the supervisory fuzzy logic rule-based controllers based on the economic objective function. The objective function is geared to maximize the production of crushed material, while at the same time ensuring that the various bin levels, mechanical, process and safety constraints are not exceeded.

Examples of these constraints are:

- Physical constraints on bin levels (not overflowing nor running empty),
- Conveyor belt capacity constraints (e.g. volume fill and/or installed motor power constraints),
- Screening capacity constraints (e.g. remaining within the installed motor power limit),
- Equipment duty cycles (e.g. limiting the number of starts on equipment to prolong service life)

Significant process and transport (introduced by conveyor) lags exacerbate the effect of process disturbances on the overall circuit stability and throughput. Together with the recycle stream, these result in a highly dynamic and non-linear response to disturbances, which is further complicated by the various equipment constraints. The MPC algorithm that has been deployed is capable of dealing with the complexity that results from the modest residence times in the crusher and screen bins, the process lags, the transport lags stemming from long conveyor runs, and variability introduced by feed fragmentation, ore characteristics and internal recycle. This would not be possible using only basic PLC layer control.

The energy efficiency of the crusher circuit can be defined by the specific energy consumption (the total electrical energy consumed in producing one unit of crushed product), expressed in (kWh/tonne). One of the MPC objectives is to minimize this specific power consumption, subject to achieving the required production rate (minimum required threshold). Factors that may influence the specific energy consumption include:

- Particle size distribution of the feed,
- Ore hardness,
- Crusher (and screen) performance (equipment wear, etc.),
- Unwanted equipment stoppages,
- Other external factors (e.g. wet feedstock material due to rain).

The development of a successful control strategy requires a good understanding of the process dynamics and equipment characteristics, a broad knowledge of control principles and a well designed control schema. Tight integration between the basic control layer and the supervisory control layer is required in order for the optimization techniques to work well, and most importantly, it is imperative that the process control deliverables are articulated in a clearly defined objective function in order to achieve optimal crusher circuit performance.

6. RESULTS AND DISCUSSION

The plant production personnel have embraced the control solution to deal with the multivariate nature of the process optimization in real time. Analysis of the operating data before and after the commissioning of the supervisory control layer indicates a significant decrease in the number of equipment stoppages and equipment constraint violations.

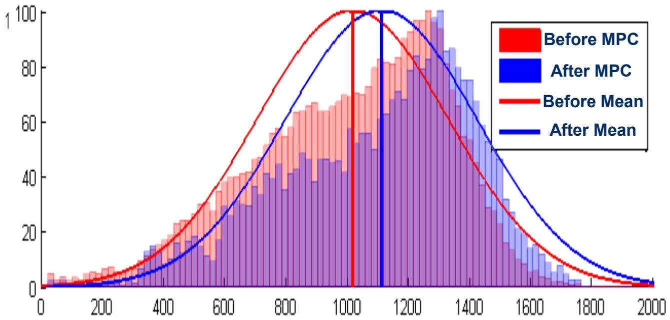

Figure 6: Secondary crusher circuit throughput increase data.

Furthermore, the supervisory (MPC) control has resulted in a 9% increase in crusher throughput (as shown by Figure 6), while simultaneously maintaining the circuit's efficiency.

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