Model Predictive Control for SAG Milling in Minerals Processing

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Introduction

SAG and ball mills are generally accepted as the largest power consumers in a mining and mineral processing operation and can be 80% of total electrical energy consumed at a specific power consumption of around 20kWh/ton.

Their function is to effect size reduction of rock in order to liberate the target metal compound or compounds trapped in the mined ore, so that these can be further concentrated e.g. through flotation and eventually refined to the metallic state.

Correct operation of this section is vital to reduce overgrinding and its effect not only on power consumption but on the performance of the downstream beneficiation and recovery process.

Different configurations of SAG, ball and rod mill occur but in general a SAG mill can be considered an intermediate stage in breaking down rock from the crushing plant, and feeding to ball or rod mills for further size reduction.

Types of Mill

Different types of mill are in operation e.g. rod or ball mills, so called depending on the steel based media placed internally to assist the grinding process. If no media is used i.e. the tumbling ore itself causes breakdown then the mill is called Autogenous Grinding or AG. A combination of autogenous and media assisted grinding is known as a Semi-Autogenous Grinding or SAG mill.

Development of ever larger SAG units has helped in the processing of lower grade ores and the simplification of the crushing section - elimination of secondary and tertiary crushing – and of the milling section - in terms of the numbers of ball and rod mills used previously.

Principle of Operation

The mill operates as a wet circuit - ore suspended in water - as opposed to the air swept grinding used in some minerals industries. This is for transport of the mill product to the downstream hydrometallurgical processes.
Ore from primary crushers is combined with water in the mill where rotation causes the grinding media and the ore to be drawn upwards with the mill liners and tumble, causing fracturing in the first instance, followed by further grinding.

Mills can be open or closed circuit. In open circuit, the ore passes through the mill once and on to a classifier which separates fine and oversize material, the former going to a product stream and the latter to a secondary mill. In a closed circuit the discharge flows from the mill to a sump and is pumped to hydrocyclones. These effect the separation of acceptable product size from oversize material which then flows back to the mill for another pass.

Challenges and Objectives of Operation

Mineral processes are difficult to control since the raw material is naturally occurring and therefore variable in chemical and physical characteristics. The cause and effect between multiple process variables and ore mineralogy is difficult to identify even from offline data and over time and such measurements are certainly not available for use on a real time basis for control purposes.

The behavior of the SAG mill circuit is multivariable i.e. exhibit complex interactions and non-linear behavior between the process variables. It is also dynamic i.e. delay times between variables within the process need to be considered before control actions are executed.

Given these challenges, the objectives for acceptable SAG mill operation are:

- maintain a stable process at high throughput – for power efficiency
- grind to a target size specification and distribution – for downstream recovery efficiency
Operator control is influenced by the degree of experience and attentiveness of personnel, who may be overseeing multiple stages of a process. This results in operation which naturally varies across personnel and shifts. Layered onto this are the inherent variability in the process itself:

- Ore composition – hardness, size distribution
- Different ore types causing large variations in tonnage, accentuating non-linear behavior
- Equipment changes (wear on mill liners and pump internals, screen integrity, feed weigher drift)
- Slurry rheology – viscosity changes

**Operation and Control**

In general, as ore is fed to the mill, water is added to assist with solids transport along the mill.

The weight of the ore and water needs to be controlled within the accepted operating range – too high and the mill becomes inefficient, too low and the autogenous effect is not used properly.

Water addition is an important variable for control of mill power draw. This has to be considered along with ore feed rate to safeguard the maximum power constraint of the mill and to maintain constant slurry density at the mill discharge, since this signifies stable operation but also safeguards mill and pump liners from excessive wear or damage.

Mill rotational speed may be variable, in which case increasing speed increases grinding capacity, since this increases the rise and subsequent fall of ore and media – provided the mill is not run up to critical speed. Mill speed variation has a large gain effect in terms of control and is important to compensate for variations in ore hardness. This is an unmeasured disturbance to the process and it is important that the control solution deployed be effective in dealing with such an effect. Softer ore would require mill speed decrease to maintain a satisfactory ore bed and grinding conditions, while protecting the mill liners from direct impact. Conversely for hard ore, mill speed is increased to input more energy to the process and improve the tumbling action to deliver the required grind.

The following variables may be measured in SAG mill circuits and used for control purposes:

- Ore feed rate
- Image analysis (particle size) on feed ore
- Water volumetric flow rate
- Mill rotational speed
- Mill weight/Discharge end bearing oil pressure
- Power consumption
- Hydrocyclone pressure
- Solid percentage and size distribution at the hydrocyclones
- Slurry flow and density to hydrocyclones
- Mill pump feed sump level
- Recycle flow
- Noise
Expert Systems in SAG Mill Control

Expert Systems allow hand coding of operator control actions such that these can be automated as a type of auto-pilot for a process. They are explicit, non-optimal systems tracking the process and executing control action by referring to a rule base.

Only relationships between variables that are easily understood and coded are included in the rule base hence the system is not considered an accurate model of the process, but a mechanism to determine control actions to be taken with actual operators as the model.

Control actions are taken only when required to correct a trend or to bring the process back to the stable operating region i.e. regulatory control is not taken on a fixed frequency, consequently several minutes can elapse without any control action, even in circumstances where the mill has temporary capacity to process more feed.

These have drawbacks in the case of complex variable interactions and process dynamics and especially where process drift is a major disturbance, all of which are prevalent in milling circuits dealing with mined natural materials. It is therefore expected that such systems do not deliver long term robustness i.e. sustained performance over and above that achieved by manual control and with an acceptable tuning or maintenance resource loading.

Since the aim is to imitate operator behavior and introduce stability, there is no objective to introduce real time optimization such as is possible using other techniques such as Model Predictive Control, which drive the process to higher levels of performance and for much longer sustained periods.

Model Predictive Control for SAG and Ball Mill Control

Real Time Optimization based on a model predictive controller is considered a better approach to SAG and ball mill control.

Model Predictive Control is specifically designed to drive multiple outputs (targets and limits) using available multiple inputs, and to solve for the best set of control actions on a fixed cycle – typically less than one minute.

The controller is typically constructed from “pulse” tests on the process during which the response to a step move in important variables is recorded until the new steady state is attained. Delay times, time constants (rise times) and final gains are captured and input to a matrix style controller which is then deployed on line.

The model looks at the current state of the process and the set point changes that need to be executed over a specified time horizon e.g. the next 30 minutes, to drive the grinding circuit to a higher level of performance. This is based on the optimization objectives selected – increased throughput, particle size spread, reduced specific energy consumption.

The predictive controller looks at where the process is now – current set points, then at the operational objectives – process state, and calculates the new set points to reach the new desired state.

So, instead of a static Expert System an adaptive controller that deals with ore and equipment variations is an improved solution which will drive significant operational value at very reasonable cost for the value chain.
Model Predictive Control on a SAG Mill and Ball Mills

The solution for the SAG Mill is an adaptive controller which controls mill load using direct mill weight measurement or indirectly from bearing oil pressure.

The solution automatically controls ore master feed rate and water addition to increase throughput, while keeping mill load within high and low constraints – with a high hard limit - AND while controlling slurry specific gravity.

This promotes the correct ore bed and grinding conditions for the mill and for effective hydrocyclone classification.

The solution uses mill rotational speed concurrently as part of the multivariable solution to maintain ore throughput, increasing speed as ore becomes harder to grind to add energy to the process for the additional grinding work and then decreasing as the ore becomes easier to grind.

Hydrocyclone parameters and mill sump level are used as constraints in the solution to allow for additional degrees of freedom in adjusting to mill condition, while keeping the process stable.

Ball mills present in the milling configuration can be included in the control solution.

The density of the slurry feed should be as high as possible but still allow for easy flow through the mill. This ensures that the balls are covered with a layer of ore solids since dilute slurry increases metal on metal contact between the balls, causing increased wear of the grinding media and reduced grinding efficiency.

The ball mill optimizer will use sump water, cyclone underflow water, cyclone pressure and pump speed to process the material from the SAG mill and control the final grind.

Mill Controller Matrix Example

<table>
<thead>
<tr>
<th>Ore Feed</th>
<th>Water Feed</th>
<th>Mill Speed</th>
<th>Feed Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Slurry Density</td>
<td>✓ Mill Power</td>
<td>✓ Mill Sump Level</td>
<td>✓ Hydro Cyclone Pressure</td>
</tr>
<tr>
<td>✓ Ore Feed</td>
<td>✓ Water Feed</td>
<td>✓ Mill Speed</td>
<td>✓ Feed Size</td>
</tr>
</tbody>
</table>

Positive correlation between variables

Negative correlation between variables
Estimated Benefits

- Improvements are expected as follows:
- Throughput increase 2 - 5%
- Specific Energy Consumption decrease 2 – 5 %
- Particle Size Distribution variation decrease 20 -30 %

This should also improve overall operation and downstream beneficiation through
- Reduced carbon footprint from energy use
- Reduced water consumption in mill circuit
- Increase downstream yield 0.5 % - 1.0 %
- Improved downstream grade and grade consistency
- Reduced flotation reagents
- More stable operation reducing processing cost per ton of concentrate
- Increased profit margin
- Increased sellable tonnage

Model Predictive Control On a Process Line

Implementation of MPC solutions on sequential units in a processing plant delivers overall optimization in addition to the control and optimization of individual units.

Consider the example of a milling and flotation plant where the individual units would be optimized as follows:

SAG mill – maximum tonnage
Ball mill – target grind size
Flotation Rougher – maximum recovery
Flotation Cleaner – target concentrate grade
Flotation Scavenger – maximum recovery

Interconnection of solutions leads not only to independent optimization of each unit operation to the specific unit goals, but also allows interaction with e.g. the upstream unit to relieve constraints.

e.g. a SAG mill automatically adjusts to more attrition grinding work if the ball mill is fully loaded and needs to protect the grind target, having maximized or minimized the available variables.