PAPER 28

Design and Implementation of Advanced Automatic Control Strategy Based on Dynamic Models for High Capacity SAG Mill

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ABSTRACT

The Copper Concentrator Plant of Compañía Minera Doña Inés de Collahuasi (CMDIC) is composed of three grinding lines, the third one being the largest. Due to the capacity feature of the third line, specially its SAG mill, it is a priority that the advanced process control team of the Company deploys a supervisory control strategy that allows this unit to operate in an optimal way, in order to achieve the maximum productivity at minimum cost. It is in this kind of tasks where advanced control applications play a key role in obtaining the best economic profit of the process.

The advanced process control team, formed by people from Informatics, Automation and Operations of CMDIC have assumed the challenge of generating the transition from a manual SAG Mill 1011 operation (40 x 22 feet, the largest copper SAG mill of the world), to a fully automatic SAG Mill using a multivariable control strategy instead of a rule based on expert control system (widely used in industrial mining process control applications).

Therefore, CMDIC decided to work together with Honeywell APC Team implementing an advanced automatic control strategy for the SAG Mill 1011, using for this purpose a technology called Model Based Predictive Control (MPC), based on a variety of control methods that uses dynamical models of the process, obtained from input/output data, in order to print the process knowledge into a group of mathematical relationships that links the constraints (controlled variables) with available commands (manipulated variables) and measured disturbances.

The main objective of the advanced control strategy is to ensure process government, tending to throughput stability and optimization, by the execution of coordinated control actions, proactively avoiding measured disturbances effects and the SAG mill overloading.

The most important benefits of using a multivariable control strategy are: the automated operation of SAG mill 1011 (that was manually operated before the implementation of this application), a safer, more coordinated and more stable process operation, achieving through this an increase of throughput and a decrease of specific energy consumption, controlling the amount of oversize material production, power consumption, mill loading, noise and torque. In addition to the operational results, this challenge has consolidated a control team, with the participation of engineers and operators, diminishing the typical implementation time and achieving a greater use of the application in a short time.

INTRODUCTION

CMDIC is owned by subsidiaries of Anglo American PLC (44%), subsidiaries of Xstrata PLC (44%) and a consortium of Japanese companies led by Mitsui & Co. Ltd. (12%). It is located at 4,400 meters above the sea level, in the high plain (Altiplano) of the Tarapaca Region, Chile’s northern territory. The Concentrator Plant is fed at a rate of 130,000 tons per day with ore from Ujina and Rosario (open-pit mines). CMDIC operates with three SAG Mill lines and produces copper and molybdenum concentrate.

The mills are fed from a stockpile of coarse ore by 14 feeders and 3 conveyor belts, one for each
SAG line, being the third conveyor belt the biggest one, processing 80000 tons per day (60% of total concentrator plant production).

Nowadays this production line is composed by a SAG mill called SAG1011 that is driven by a gearless synchronic motor with a nominal power of 21 [MW] and two ball mills, each one of 26x38 feet and a nominal power of 7750 [KW]. Figure 1 shows the SAG1011 grinding-classification plant circuit.

**Figure 1: SAG Plant Process Overview of Grind Circuit 3.**

**Motivation**

The necessity of counting with automatic control tools capable of govern, stabilize, handle constraints and optimize the operation of the highest capacity SAG mill within the concentrator plant is one of the major management initiatives. Because of this, a multidisciplinary team was created to drive this technological and operational challenge. Three key tasks had to be developed by this team: search of advanced control solutions at the market, the choice of available alternatives and the formulation and implementation of advanced control strategies.

**METHODOLOGY**

**SAG Mill Control Challenge**

A high capacity SAG Mill implies a lot of new process and physical constraints compared to conventional SAG mills. The main restrictions for this plant are:

- The pebbles production can not be over 800 metric tons per hour, due to physical limitations
in the conveyor belt.
- A strictly mill’s noise array must be satisfied in order to ensure the “grindability” of the Mill. At the past, the mill’s noise has been used just like a high limit constraint (restriction) in order to preserve internal liners and lifters [Razzetto et al., 2007]. In this case a control range, with low and high limit, must be used due to the large amount of clay in the fresh ore.
- The SAG Mill’s electrical motor torque had to be introduced like an electromechanical constraint in order to preserve the continuous operation, avoiding activating the Mill’s protection system that decreases the rotation speed.

On the other hand there are some operational issues that should always be considered:
- Do not sacrifice tonnage unless is strictly necessary. This gives us some control priorities.
- To reduce the solids percentage ratio as much as possible.
- To preserve the measured mill’s weight (from load cells) between the range defined by the operation.

Control Strategy

Constraints are inherent to the process and must be considered in any control strategy, therefore measured and unmeasured disturbances transform this system into a highly complex multivariable control problem. A control strategy based on stability and focused in handling constraints and optimization has been designed using a successful control scheme called Model Based Predictive Control.

Model Based Predictive Control

Model based Predictive Control (MPC) has been reported in more than 2000 successful applications in the industry [Goodwin et al.; Qin et al.]. MPC does not designate a particular control strategy but a set of automatic control methods that uses explicit process models in order to calculate a control signal by minimizing an objective function [Camacho et al.]. MPC has some interesting advantages, like:
- It is particularly attractive because it concepts are very intuitive and it’s simple to tune.
- It can be used in a wide variety of processes, from the simple ones to processes with complex dynamics and large dead times, no-minimum phase, unstable or multivariable.
- Its predictive characteristics compensate intrinsically dead times and disturbances (feed forward).
- It allows handling the process constraints explicitly.

The methodology in a general MPC algorithm is as follows [A. Mathur et al.]:
- A model (generally, a dynamic interaction model identified off-line) of the process is run in parallel with the plant and subjected to the same plant inputs.
- The model is used to compute a predicted output trajectory over a certain number of future points or ‘horizon’ at each sample point.
- An optimization problem is then set up to minimize the deviation of this predicted output from a desired trajectory into the future. The decision variables are computed control moves.
The first control move is implemented on the plant and model, and the process is repeated.

Due to the dynamics of SAG mill and proven profits in grinding applications [Razzetto et al.; Mathur et al.; Cortes et al.; Gatica et al.; Nieto et al.] CMDIC has decided to use a MPC strategy to control its largest SAG mill, using the Honeywell’s MPC solution called Robust Multivariable Predictive Control Technology (RMPCT) or simply Profit Controller®.

Equation (1) shows the cost function used by RMPCT, which minimizes the weighted prediction error in order to compute the optimal trajectory of controlled variables, taking into account the process constraints and actuators limits.

\[ J = \min \| W (A \cdot x - y) \|^2 \]  

Subject to:

\[ cv_{\text{low}} \leq y \leq cv_{\text{high}} \]  
\[ mv_{\text{low}} \leq S \cdot y \leq mv_{\text{high}} \]  
\[ mv_{\text{low}} \leq x \leq mv_{\text{high}} \]

Where:
- \( y \): Optimal response trajectory.
- \( A \): Matrix of dynamic models.
- \( Ax \): Controlled variables predictions.
- \( cv_{\text{low}}, cv_{\text{high}} \): Controlled variables low and high limits.
- \( x \): Control solutions (manipulated variables movements).
- \( mv_{\text{low}}, mv_{\text{high}} \): Manipulated variables (actuation) low and high limits.
- \( \Delta mv_{\text{low}} \): actuation’s maximum down rate of change.
- \( \Delta mv_{\text{high}} \): actuation’s maximum raise rate of change.
- \( W \): Diagonal weighting matrix.
- \( S \): Accumulating sum matrix.

### Process Variables and Dynamic Models for Control Purposes

Taking into account the control challenge, the control variables shown in Table 1 have been chosen in order to accomplish the operational objectives and process constraints. From the linear systems point of view, manipulated variables and disturbance variables are “independent variables”, controlled variables are “dependent variables”. Measuring and modeling the disturbance variable effects allows the controller to avoid constraints violations and deviations from operational objectives ranges through the movement of the manipulated variables in a predictive way.
Table 1: Control Variables

<table>
<thead>
<tr>
<th>Controlled Variables (CVs)</th>
<th>Manipulated Variables (MVs)</th>
<th>Disturbance Variables (DV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N: Noise [%]</td>
<td>ω: Mill’s Rotation Speed [RPM]</td>
<td>Ffinp: Fine Ore Percentage [%]</td>
</tr>
<tr>
<td>J: Power [KW]</td>
<td>Sol%: Solids Percentage Rate [%]</td>
<td></td>
</tr>
<tr>
<td>Fpebb: Produced Pebbles [TPH]</td>
<td>τ: Torque [%]</td>
<td></td>
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</tbody>
</table>

A descriptive block diagram of the strategy is presented in Figure 1.

![Figure 1: Control Strategy Block Diagram](image)

The dynamic models used by the MPC controller have been identified mostly using historical data of manual operation. In some cases the historical data was not frequency rich enough; therefore some step testing was necessary.

The identification process has been done using conventional linear discrete modeling algorithms.

Figure 2 shows dynamic models identified for the SAG1011 advanced control application called ProfitSAG. The three first columns show the dynamic relations between MVs and CVs; the last two columns evidence the dynamic relations between DVs and CVs.
As was mentioned earlier, one control objective is to always give priority to fresh ore feeding, when enough degrees of freedom exist. This issue was resolved using a built-in Optimization Priority parameters feature.

**Implementation**

Deployment of this control scheme has been an interesting challenge mainly because of the integration tasks, involving OPC communications, C# function blocks programming and DCS sequential block programming.

**DCS Integration**

DCS integration was made through OPC connectivity between the ABB Aspect Server and the *Unified Real Time (URT)* platform, used by *ProfitSAG*.

Due to the advanced control layer requirements, in the form of some field data, a set of custom URT base level control (BLC) templates had to be built.

URT custom function blocks, programmed in C#, were made in order to build the integration layer between the control application and DCS, including a *Watchdog* signal.

The User interface was implemented using an URT client called *Operator Station*. 
RESULTS AND DISCUSSION

Evaluation Methodology

Evaluation has been done by following the criteria described below:

- To operate using ProfitSAG 12 hours per day (one shift a day), in an attempt to ensure the same ore quality in manual and automatic operation.
- To evaluate the performance only in normal operation conditions, this is:
  - Fresh ore feed rate over 2000 tons per hour.
  - SAG rotation speed over 7 rpm.
- The performance indicators considered for the evaluation are the Specific Energy Consumption, defined as \(\frac{\text{Energy Consumption}}{\text{Fresh Mineral Feed Rate}}\) and fresh ore feed rate statistical measurements.
- Performance with and without returned pebbles will be considered as an indicator of how the controller deals with low frequency disturbances and preserves the process in range.

Data must be filtered in order to ensure an evaluation only in normal operation conditions and generate useful information. Some statistical tools have been used, such as outlier rejection by using the two-sided version of Grubbs’s test [Grubbs; Barnet et al.] and the Lilliefors test of normality [Lilliefors]. Histograms have been used to plot results in order to show frequency of occurrence at each signal of interest.
Results

Following the above presented evaluation methodology, some results have been generated in order to estimate the controller’s performance (constraints handling and disturbances rejection). The major disturbance over the SAG mill normal operation is returned pebbles. Considering the stability and process performance the evaluation data has been processed considering two scenarios: with and without returned pebbles.

Figure 5 presents a first set of results, without the effect of returned pebbles. It can be seen that most of time ProfitSAG minimizes the solids percentage, giving better grind conditions to the process. Specific energy consumption average has been reduced by 2.2% and its standard deviation has been reduced by 4.8%. Mill noise average and standard deviation has been reduced as well. Fresh ore feed media has been incremented by 2.3% and its standard deviation has been reduced by 4%. As it can be seen, the minimum solids percentage is about 80% (recommended is about 65% [Magne et al.]), suggesting a critical lack of water.

The second set of results, presented in Figure 5, take into account the effect of returned pebbles. It can be seen that while ProfitSAG was operating the results were better. The histograms show that specific energy consumption has been reduced (average reduction of 4.5%) and fresh ore feed increased (average increment of 10%).

It can be seen from the graphs that fresh feed histograms shows several peaks. Those peaks are the common used limits and restrictions for this manipulated variable and highlight some restrictive scenarios.

Another result that it worth discussing is the operator acceptance of the controller. This can be seen from a high utilization of around 90%.
Figure 4: Results without returned pebbles

Figure 5: Results with returned pebbles
Future Possibilities

Some future possibilities for increase profits of this SAG plant:
- To deploy advanced control strategies over secondary grinding-classification circuits in order to control the product quality sent to rougher flotation.
- To integrate and coordinate the entire SAG plant by using some dynamic economic optimization control strategies.

CONCLUSIONS

When considering the implementation and performance results the following conclusions have been reached:
- Successful configuration of a multidisciplinary work team involving informatics, DCS, and process engineering from CMDIC and APC from Honeywell.
- Implementation was achieved in record time.
- High confidence of operators and supervision in the controller actions.
- ProfitSAG shows good disturbance rejection and handling of constraints.
- Advanced control applications have highlighted process constraints and offer an opportunity to take action based on the fundamentals.

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