Optimizing Grinding Circuits

Abstract

This paper outlines the development and implementation of a grinding circuit simulator for BHP Billiton’s Cannington facility. Steady-state first principles models have been used in conjunction with dynamic process modeling; giving rise to a hybrid model simulator that is valid across a much larger operating range than a simulator developed from black box modeling.

As mill overload had been a major cause of plant downtime for the three months prior to the project initiation, the objective of this project was help Cannington personnel develop a more profound understanding of their grinding circuit; from mill feed through to the flotation circuits. In addition to the simulator, an AG mill charge-volume estimator was developed to provide real-time feedback to the operators on the state of the mill.

The simulator was developed within the framework of Control Performance Optimizer, Honeywell’s advanced control and simulation software and interfaced to the site HMI. When the simulator is off-line, it can track the plant state and when initiated it displays (in “real-time”) the effect of various changes on the plant. The simulator is, therefore, an excellent operator training station. Furthermore, as the simulator models both the process dynamics and the control system, engineers can evaluate various optimization strategies within Control Performance Optimizer (e.g. rules base, fuzzy logic, model-based controllers) before implementing these on the process.

Control Performance Optimizer is Powered by Matrikon, which represents vendor neutrality. This product works with third-party control systems and applications.

Executive Summary

BHP Billiton’s Cannington facility is a mining and minerals processing plant near Mt. Isa in Central Queensland, Australia, producing silver, lead and zinc. Mine ore is processed in a concentrator, which consists of grinding, flotation, thickening and filtration. Grinding is carried out in a fully autogenous (AG) mill. The mill operates in closed circuit with a pebble crusher. Throughput is approximately 380 tph. Cyclone overflow from the grinding circuit is fed into a flotation circuit for the recovery of lead, zinc and silver. Two concentrates are produced (lead and zinc), which are then thickened and filtered. The filtered concentrate is transported by road to a rail receiving station. From here the concentrate is railed to port in Townsville for shipment to the smelter.

Honeywell and Engineers at BHP Billiton’s Canning Mine have used Control Performance Optimizer to develop a flexible, nonlinear dynamic simulator for the grinding circuit to further enhance process understanding, as well to investigate various optimization strategies. An online charge volume estimator was also developed for the AG mill to aid in the understanding of overload conditions, which for the previous three months had been the primary contributor to downtime.

The models were developed using a combination of first-principles modeling along with input/output dynamic responses. Examples of models used include: Morrell “C” model for power and charge shoulder/toe angle prediction; Whiten’s mixing model for breakage and hold-up; Nageswararao cyclone model for predicting cut size; slurry recovery and water recovery. The composite model simulates system dynamics starting from the stockpile reclaim system and finishing at the feed for the flotation process.

The objective was to provide a tool that assisted Cannington in understanding their Grinding Circuit and allowed them to develop and evaluate circuit optimization strategies.
Honeywell has subsequently applied this model-based approach to the development and implementation of a full circuit optimizer for a large Australian gold mine. On/off testing has been performed to evaluate the performance of the system and the preliminary results suggest that the increases in throughput are worth >3 million AUD per year.

**Introduction**

To understand the process is the mantra for all Process Control Engineers and the precursor for a successful (regulatory through to advanced) control strategy implementation. The development of a dynamic simulator, based on first-principle models, provides an opportunity for comprehensive investigations of a system.

**Grinding Circuit Simulator**

The Grinding Circuit Simulator at Cannington has enabled further process understanding, controller design and prototyping, as well as investigation of various optimization strategies. The key ideas in using a simulator are it can be used to:

- test and clarify ideas before committing to final implementation
- explore situations that could be potentially hazardous or difficult

Further, any control or optimization concepts prototyped in the Control Performance Optimizer system can also readily be tested out on the actual process using the existing Control Performance Optimizer runtime system (reducing commissioning time). It is simply a matter of replacing the Grinding Circuit Simulation with appropriate I/O tags, adding variable checking, and implementing glue logic in the PLC to allow Control Performance Optimizer to take control of the desired loops.

**Control Performance Monitor**

Control Performance Optimizer is Honeywell’s advanced control and simulation software and provides a complete environment for modeling, simulation, design, prototyping and implementation of conventional through to advanced control strategies. Control Performance Optimizer provides seamless connectivity with PLC, DCS and HMI systems and the object-oriented user interface allows for a rapid prototyping and final implementation.

Control Performance Optimizer supports the development and implementation of Advanced Process Control (APC) strategies, where APC is the pragmatic mix of conventional and advanced control technologies applied within a systematic design methodology and making direct use of quantitative process knowledge. In light of this, the environment contains a wide range of control technologies and algorithms ranging from PID controllers through to model predictive controllers, fuzzy logic controllers, and model based soft-sensors and linear or non-linear Kalman filters.

The control solution is introduced through a methodical approach - in order to select the simplest technology possible to meet the required system performance and stability, thus ensuring sustainability of the application: both in long-term maintenance and ease-of-understanding for non-control personnel.

**Designing the Simulator**

**Developing System Models**

There are three general types of dynamic models that can be obtained:

- **First-principle models** – typically based on mass and energy balances plus descriptions of other relevant physical and/or chemical phenomena. They are generally non-linear and have the ability to accurately describe process dynamic behavior over a wide range of operating conditions.

- **Black-box models (or input-output models)** – typically involve breaking down the overall dynamics into fundamental dynamic elements such as transport delays, lags and other higher order dynamics, along with multi-variable interactions and external non-linearities such as actuator saturation. They are typically linear and describe the behavior in a relatively narrow region of operation.

- **Hybrid models** – are a combination of these two models. These models blend static information from the first-principles approach (usually simple mass and energy balance equations) combined with dynamic information from the black-box approach (lags, dead-times, gains, integrators, etc).
The use of first-principle models facilitates systematic control
system design. These models are simply sets of equations that
capture the effect of certain system variables on other system
variables. This approach results in enhanced process
understanding and a physical insight into the process.
Furthermore, first-principle model-based development also allows
the logical incorporation of process and circuit changes, giving a
more maintainable solution. The Grinding Circuit Simulator
combines both first-principle and input-output models into a
hybrid model.

Grinding Circuit System Models
The Grinding Circuit Simulator has been split into components
based largely upon the physical plant (figure 1).

Figure 1 - Grinding Circuit at Cannington

This results in ten blocks (listed below), with each of these blocks
containing one or more of the system models (both physical and
control).

1. **Reclaim Feeders** – this block takes the input size
   fraction information and determines rock and critical size
   feed quantities.
2. **Feed Conveyor** – calculation of final feed fractions to
   the AG Mill taking into account Pebble Recycle and
   Cyclone Underflow Streams.
3. **Recycle Conveyor** – this block consists of a series of
   conveyor models.
4. **Ore Blend** – the ore blend system allows the
   proportions of the three different ore types to be
   entered. The block then calculates ore hardness
   (kWh/t), ore impact breakage parameter (Ab), and ore
   abrasion breakage parameter (Ta).
5. **AG Mill (Solids) Holdup** – contains the breakage
   models used to determine the raw mill mass, as well as
   the solid product flows.
6. **AG Water Holdup** – contains the first order water
   model as well as the feed water controller.
7. **AG Filling (Weight)** – determines the total mill mass
   based upon the mass of liquid and solids present.
8. **AG Power Model** – determines the mill power draw as
   well as the charge toe and shoulder angles.
9. **Discharge Hopper** – this block is split into three
   components describing cyclone pressure, hopper level,
   and cyclone feed.
10. **Cyclone Model** – contains the modified Nageswararao
    model as well as calculations to determine the
    overflow/underflow split.

The Grinding Circuit Simulator at Cannington has been
developed as a hybrid model, and hence uses a combination of
first-principles modeling along with input-output dynamic
behavior. The components of the simulator, listed above, consist
of models for: (a) Conveyors, (b) Mill Holdup and Power Draw,
(c) Feed Pumps, (d) Cyclone Model, (e) Control System.

Conveyors
The conveyors have been modeled as simple delays. Plug flow
has been assumed and chutes have been considered as
extensions to the conveyor where material continues at the same
velocity.

AG Mill Solids and Water Holdup
The AG Mill Holdup System contains the breakage models used
to determine a raw mill mass, as well as the solid product flows.
A series of factors such as ore hardness, feed water addition, mill
filling and cyclone underflow rate alter the breakage parameters
of the different feed components.

The AG Mill Holdup model is based upon Epstein's Population
Balance Model (Napier-Munn et al 1996) as follows:
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\[ \text{Feed In} + \text{Breakage In} = \text{Product Out} + \text{Breakage Out} \]  \hspace{1cm} (1)

Breakage is described as a function of the mill contents:

\[ \text{Breakage}_i = k_i m_i \]  \hspace{1cm} (2)

Where:

- \( k_i \) is a lumped parameter describing the rate of breakage of size fraction \( i \).
- \( m_i \) is the mass of material in the mill of size fraction \( i \).

The inclusion of an appearance function describes that fact that breakage can result in a number of different size ranges, not simply size fraction \( i \).

\[ \text{Formation}_i = a_{ij} k_j m_j \]  \hspace{1cm} (3)

Where:

- \( a_{ij} \) is the appearance function, describing the fraction of material breaking from size \( j \) to size \( i \).

This results in the following relationship.

\[ f_i + \sum_{j 
eq i} a_{ij} k_j m_j = p_i + k_i m_i \]  \hspace{1cm} (4)

Where:

- \( f_i \) is the feed flow of material of size fraction \( i \).
- \( p_i \) is the discharge flow of material of size fraction \( i \).

A further simplification can be made through the assumption of perfect mixing. The product out term can now be related to a discharge function and the mill contents.

\[ p_i = d_i m_i \]  \hspace{1cm} (5)

Where:

- \( d_i \) is the discharge rate of material of size fraction \( i \).

This results in Whiten’s Perfect Mixing Model.
\[ f_i + \sum_{j=1}^{i-1} a_j k_j m_j = d_i m_i + k_i m_i \]  \quad (6)

For the Grinding Circuit Simulator, three size fractions have been chosen: (i) Rock, (ii) Critical Size (Pebbles) and (iii) Fines. These sizes were chosen, as their flows can be determined from existing plant instrumentation without the need for survey data. This simplification is appropriate for the simulator and for further control system development (Hales, Vanderbeek, Herbst 1988). As a further simplification the breakage and appearance functions have been combined. For the fines model, the discharge and breakage/appearance functions have also been combined and the equations modified to include dynamics. This results in the following system:

**Rock**

\[ f_r = k_r m_r + \frac{dm_r}{dt} \]  \quad (7)

**Critical (Pebbles)**

\[ f_c + k_c m_c = d_c m_c + k_c m_c + \frac{dm_c}{dt} \]  \quad (8)

**Fines**

\[ f_f + k_f m_f = d_f m_f + \frac{dm_f}{dt} \]  \quad (9)

**AG Water Holdup**

Water holdup within the mill has also been described with a first order model (Hales, Vanderbeek, Herbst 1988).

\[ f_w = P_w + \frac{dm_w}{dt} \]  \quad (10)

**AG Mill Power**

The AG Power Model uses Morrell’s C Model (Morrell 1996). The primary power equation is below. For a complete derivation and set of equations refer to Morrell’s 1996 paper.

\[ P_i = \frac{\pi}{6} \left[ V_r L \rho_c r g (\sin \theta_s - \sin \theta_r) + \frac{V_r^2 L \rho_c}{2} \right] dr \]  \quad (11)

Where:
- \( P_i \) is the power draw (kW)
- \( V_r \) is the tangential velocity at \( r \)
- \( L \) is the mill length (m)
- \( \rho_c \) is the charge density (t/m³)
- \( r \) is the radial position
- \( g \) is gravity
- \( \theta_s \) is the charge shoulder angle (rad)
- \( \theta_r \) is the charge toe angle (rad)
Cyclone Feed Pump
The cyclone feed pump model uses components of the Nageswararao Cyclone Model (Nageswararao 1995) and the Warman 12/10 AH Pump curve solved simultaneously to determine pressure.

Cyclone Model
The cyclone model is based upon the Nageswararao Cyclone Model (Nageswararao 1995). This model relies upon cyclone dimensions and parameters determined from surveys to calculate cyclone throughput cut size, slurry recovery and water recovery. The primary equations are as follows:

\[
Q = K_Q D_c^2 \left( \frac{P}{\rho_p} \right)^{0.5} \left( \frac{D_o}{D_c} \right)^{0.58}
\]  

(12)

\[
d_{50C} = K_{D2} \left( \frac{D_o}{D_c} \right)^{0.32} \left( \frac{D_u}{D_c} \right)^{-0.47} \left( \frac{P}{\rho_p g D_c} \right)^{-0.22}
\]  

(13)

\[
R_f = K_{w2} \left( \frac{D_o}{D_c} \right)^{-1.19} \left( \frac{D_u}{D_c} \right)^{2.40} \left( \frac{P}{\rho_p g D_c} \right)^{-0.27}
\]  

(14)

\[
R_v = K_{v2} \left( \frac{D_o}{D_c} \right)^{-0.94} \left( \frac{D_u}{D_c} \right)^{1.83} \left( \frac{P}{\rho_p g D_c} \right)^{-0.21}
\]  

(15)

Where:

\[
\dot{\lambda} = \frac{10^{18.2C}}{8.05(1.0 - C_v)^2}
\]  

(16)

\(Q\) throughput (m³/h)
\(d_{50C}\) size of a particle in the cyclone feed with an equal probability of going to underflow or overflow (mm).
\(R_f\) recovery of water to the underflow (%) 
\(R_v\) volumetric recovery of feed pulp to underflow (%) 
\(P\) pressure (kPa)
\(\rho_p\) feed slurry density (t/m³)
\(D_o\) diameter of cyclone vortex finder (m)
\(D_c\) cyclone diameter (m)
\(D_s\) diameter of cyclone spigot (m)
\(K_Q\) a constant in cyclone pressure throughput relationship
\(K_{D2}\) a constant in cyclone classification size relationship
\(K_{w2}\) a constant in cyclone water recovery relationship
\(K_{v2}\) a constant in cyclone volume pulp recovery relationship
\(C_v\) volumetric fraction of solids in feed slurry
Charge Volume Estimator
Like the AG Power Model the charge volume estimator is based upon the Morrell C Model. The model is used to determine the power curve for a particular set of conditions. The curve is then interpreted to give the charge volume in terms of a mill fractional filling. The model also outputs the charge toe and shoulder angles.

Operation of the Grinding Circuit Simulator
The simulator has been designed for use through the HMI. The interface is similar to the normal plant operation graphics. With this interface, the user can enter operating parameters and view simulation results. The following settings can be altered from the HMI graphic: (a) feed set point, (b) ore feed blend, (c) feed water set point, (d) discharge hopper level set point, (e) cyclone pressure set point, (f) number of cyclones operating.

Each of the controllers can be operated in auto or manual through the normal HMI pop-ups. Similarly tuning parameters can also be entered for each of the controllers.

In addition to the normal operation of the simulator for operator training or evaluating “what-if” scenarios, the simulator can be used to evaluate different control and optimization strategies offline. As Control Performance Optimizer includes a wide range of control technologies (from basic PID through to model predictive controllers), the engineers can test and within Control Performance Optimizer the anticipated effect of various closed loop control strategies. Honeywell uses this approach to all control strategy development: modeling, process simulation, controller design, testing against the simulation, and subsequently implementation. This approach provides the lowest risk implementation (less “ad hoc” online tuning is required), and the resulting controller is more robust and out performs those developed from non-model based approaches.
Figure 3 shows the results of the simulation for the cyclone feed flow, density, pump speed and water addition to a step change in the cyclone pressure set point. The simulation shows good agreement with the plant response during the period of the disturbance.

**Conclusion**

In conjunction with BHP Billiton Cannington Mine, a dynamic Grinding Circuit Simulator has been developed. The simulator, implementing both first-principles and input-output models, predicts eighteen outputs including mill weight, power, volume filling, cyclone overflow sizes and flow rates. Plant data was collected and the model validated across a range of operating conditions.

The simulator showed good correspondence with the real system during the validation stage, and can be relied upon to provide a sound base for future control strategy simulation and development. Additional work towards the refinement of the breakage/discharge functions should be performed as more data becomes available to further enhance the performance of the model.
References


For more information:
For more information about Control Performance Optimizer, visit our website www.honeywell.com/ps or contact your Honeywell account manager.
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