Increasing Productivity Without Capital Expenditure

Grinding Circuit Advanced Control Provides Quick Payback at Gold Mine Operations

Abstract

3.8 kilometres long, 1.35km wide and going down more than 500m, the Super Pit (Kalgoorlie's best known landmark) provides enough ore to sustain an annual production of approximately 850,000 ounces of gold, making it the biggest open pit mine in Australia.

Honeywell was engaged to provide a complete grinding circuit control, optimization and monitoring solution for the mills supplied from the Super Pit. The objective of the supervisory control and optimization is to maximize the circuit throughputs whilst respecting cyclone overflow constraints. Project scope included:

- full on-line closed-loop grinding circuit supervisory control and optimization,
- operator decision support,
- key parameter estimation,
- automated controller monitoring and performance assessment.

This paper outlines a robust and methodical approach to implementation of grinding circuit optimization: focusing on variability reduction, improving circuit stability, and model-based optimization. The implementation of the supervisory control system has resulted in reduced operator workload, process variability, and a more consistent day-to-day operation of the circuit.

Introduction

It is well known that improving process stability for grinding circuits can result in numerous improvements: improved grinding efficiency resulting in increased throughput or reduced energy consumption, reduced downtime and equipment wear, a more stable feed to later stages of processing, etc. However, input disturbances (feed particle size distribution and ore hardness), unmeasured key variables, process non-linearities, time variance, data scatter and the multivariable nature of the process make grinding circuit control a difficult problem: especially for a human operator.

The goal of this project was to implement a supervisory control system across the circuit outlined in figure 1, thus reducing the workload of the operator and also improving circuit performance by reducing the dependency of operations on the minute-to-minute intervention of the operator. The major components of the circuit are the feeders, the semi-autogenous grinding (SAG) mill, the recycle pebble crusher, two ball mills, and the cyclones.

Figure 1 – Grinding Circuit
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Architecture

Due to the fore mentioned difficulties associated with grinding circuits, supervisory control has typically been developed as “a model of the operator” (i.e. a rules-based approach). This rules-based approach is successful in providing a consistent operation of the process, but fails to address the optimization of the throughput. Subsequently, Matrikon’s experience in grinding circuit control has resulted in the development of a control solution based around model-based advanced regulatory control, rules-based supervisory control, model-based optimization, and coupled with key parameter estimation (soft sensing).

![Diagram](image)

**Figure 2 - Grinding Circuit Supervisory Control System**

The supervisory control system is a robust and maintainable solution, addressing all layers of control from the regulatory through to the optimization. The strategy recognizes the importance of reducing single loop variability, providing a stable circuit operation before tackling the optimization problem, and finally monitoring and maintaining these benefits. As shown in figure 2, the control system consists of a number of components including: (a) enhanced SAG mill load control, (b) rules-based supervisory control, (c) model-based optimizer, and (d) soft sensors for SAG mill charge/volume, cyclone transfer densities, cyclone over-flow and under-flow cut size, etc.

Regulatory Control

As a first stage in the grinding circuit control optimization, a regulatory control performance monitoring and assessment stage was completed. This stage ensures a sound foundation for the subsequent advanced control implementation. Closed-loop data was used to evaluate control performance against a variety of indicators, including: (a) saturation and service factor, (b) loop oscillation, (c) standard deviation, (d) closed loop impulse and frequency responses, and (e) minimum variance control. Minimum variance control represents the best achievable control for the process, given the process dead time. Implementing a minimum variance controller can be dangerous due to poor robustness [9], however the comparison of current performance to the minimum variance allows the engineer to rapidly identify loops with “room for improvement”.

Loops flagged as poor performers were retuned, and in the case of the SAG mill load controller, the existing controller was replaced with a more enhanced controller that was developed and implemented as a part of the supervisory control system.

![Plot](image)

**Figure 3 - Results of the SAG mill load controller**

The enhanced controller displays a greater than 30% reduction in the variability of the load compared to the traditional cascade strategy.

Rules-Based Supervisory Control and Optimization

Previously grinding circuit advanced control systems have been limited by the available implementation platform technology. Plant owners could select expert system approaches or model based approaches but due to technology limitations could not combine the two. More recently, a number of platforms allow the combination of different control techniques in the same system, allowing the best solution for a particular problem to be implemented.

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1 The Supervisory Control System was fully implemented in Matrikon™ Control Performance Optimizer. Matrikon™ Control Performance Optimizer is a complete solution for the design, development, simulation and implementation of enhanced and advanced process control strategies. Matrikon™ Control Performance Optimizer contains functionality that allow the control engineer to: (a) improve regulatory control, (b) drive the regulatory control layer with supervisory control and optimizers, (c) implement advanced real-time soft sensors, and (d) develop simulators to design and test control strategies or PLC/HMIs offline.
The collaborative approach to the design and development of a hybrid rule and model based system results in very high operator acceptance and utilization. Since implementation the system has been active for approximately 90% of the time and has required little operator intervention.

The rules-based is a crisp logic implementation (a series of IF, THEN, ELSE statements). The rules-based consists of three separate rules sets that can be run individually or together.

1. Feed system or coarse ore stockpile rules – increase or decrease coarse feed.
2. SAG mill rules – evaluate the SAG mill and ball mills weights and power draws and adjust accordingly.
3. Ball mill rules – increase or decrease feeds based on weights and power draws.

Effectively the rules base acts as an envelope around the model-based optimizer. It acts as a check on outputs before they are written to the final control elements and is able to take fast action in abnormal operating situations.

SAG mill throughput and energy consumption are non-linear functions of the mill volumetric charge. At any given time the mill throughput can be maximized, but as the weight for the SAG mill varies over time (due to the liner wear) the optimization must be repeated. A model-based optimizer has been implemented to adjust the mill load set point as to maintain the throughput and reduce energy consumption.

**Soft Sensing**

There are a number of parameters within grinding circuits that are not measured continuously because sensors are unreliable, unavailable or too expensive to install. These parameters include mill total charge, mill ball charge, cyclone overflow size and even SAG mill discharge slurry flow rates and densities. The implementation of soft sensors to estimate these variables can provide additional information to aid circuit optimization as well as increasing advanced control system availability.

The SAG mill charge estimator combines the SAG mill mass balance, Morrel’s C model for power draw, and a nonlinear liner wear function as to calculate the power and weight, the total charge/volume, the ball/charge, and the shoulder/toe angles for the mill. The SAG mass balance is based upon Epstein’s Population Balance Model, and water and ball holdup models.

**Feed In + Breakage In = Product Out + Breakage Out**

The water and ball holdups within the mill have been described with first order models, and the SAG Power Model uses Morrel’s C Model. The primary power equation is below, for a complete derivation and set of equations refer to Morrell’s 1996 paper.

\[
P = \left( \frac{V_t}{L \rho_c} \right) \left( \frac{\sin \theta_s - \sin \theta_r}{\frac{V^2 L \rho_c}{2}} \right) \frac{r}{g}
\]

Where:
- \( P \) is the power draw (kW)
- \( V_t \) is the tangential velocity at \( r \)
- \( L \) is the mill length (m)
- \( \rho_c \) is the charge density (ton/m³)
- \( r \) is the radial position
- \( g \) is gravity (m/s²)
- \( \theta_s \) is the charge shoulder angle (rad)
- \( \theta_r \) is the charge toe angle (rad)

A Kalman filter is used to correct the charge/volume estimation, using feedback from the measured mill power and mill weight. The estimated mill charge is very sensitive to changes in the breakage and appearance parameters. If the parameters are incorrectly estimated, there can be an offset from the real value. Hence the charge/volume estimator uses dynamic model parameter estimation to minimize this error.

**Grinding Circuit Dynamic Simulation**

An additional outcome of the model based control design process is a dynamic simulator. The simulator can be used to further enhance process understanding, test scenarios, controller design and prototyping as well as investigation of various possible optimization strategies.
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 simulator implements models for the conveyors, SAG and ball mills hold-up and power draw, recycle crusher, cyclones and their feed pumps, and the control system. The results from the dynamic simulator are presented below.

Automated Advanced Control Monitoring 2

Honeywell's experience is that the performance of many advanced control solutions deteriorates over time due to a lack of maintenance and support. Honeywell's solution to this issue has been to develop tools for automated monitoring and assessment of advanced control systems as well as offering open solutions that can be easily supported and maintained by site personnel. The performance of the supervisory controller is evaluated on a day-to-day basis with indicators for: (a) key measured variables (density, power, weight), (b) estimated variables (SAG total charge, SAG ball charge, transfer density and flow, cyclone overflow), (c) rules base and optimizer, (d) constraints.

Control Performance Monitor is a monitoring platform with standard functions for regulatory and advanced control loop performance monitoring. The control loop performance monitoring functions are designed to use plant historical data to automatically assist engineers and technicians in the assessment of loop performance, the identification of regulatory loop problems, guidance in the rectification of regulatory loop problems and the on-going monitoring for sustained performance.
Conclusion
The acid test for any supervisory control system is the operator acceptance test. Grinding circuits are typically controlled by operators, and supervisory controllers need to demonstrate a high level of performance and robustness (and maintain these) to be globally accepted. The supervisory control system implemented by Honeywell has demonstrated a 90% uptime since inception, a 30% reduction in SAG mill load variability, and a more stable and consistent circuit operation. Financial benefits from the implementation are yet to be qualified.

References