MINTEK'S ADVANCED OPTIMISATION CONTROL STRATEGIES IN MILLING, FLOTATION AND SMELTING

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Abstract: Mintek, specialists in mineral and metallurgical technology, have developed advanced optimisation control strategies in milling, flotation and smelting. The strategies address process specific problems namely downstream flow disturbances in flotation circuits from open milling circuits, fluctuating grade and recovery of flotation circuits and furnace fault conditions including power trips and electrode breakages. PlantStar is Mintek's plant-wide control platform used to implement the customised optimisation and control software modules to solve the aforementioned difficulties. These modules are the MillStar™ Mill Feed Controller, the FloatStar™ Grade-Recovery Optimiser and the Minstral™ Electrode Hoist Controller. The commercial results of implementations demonstrate the success thereof.

Keywords: process control, optimisation, software, plantwide, flotation, comminution, milling, grinding, furnace, smelting.

1. INTRODUCTION

Mintek, South Africa, are specialists in the research and development of mineral and metallurgical technology. Mintek's Measurement and Control Division has garnered process specific control optimisation experience in the areas of milling, flotation and smelting for many years. Expertise in each process has led to the development of customised, advanced control optimisation solutions. Examples of such solutions are 1) the MillStar™ Mill Feed Controller in milling, 2) the FloatStar™ Grade-Recovery Optimiser in flotation control, and 3) the Minstral™ Electrode Hoist Controller in smelting. Each of the custom modules above has been designed to solve process specific problems experienced in the minerals processing industry. The problem experienced, the technique used to solve the problem and the industrial results of each respective module will be described.

2. MINTEK'S SOFTWARE PLATFORM

Mintek uses its own plant wide software platform to implement control systems and optimisation strategies such as MillStar™, FloatStar™ and Minstral™. This platform is PlantStar. PlantStar integrates with existing plant infrastructure by communicating with the plant PLC, DCS or SCADA systems. Direct control of the plant is thus achieved with loop execution times of 100ms in the case of furnace control and 1-3s in milling and flotation control.

PlantStar allows the control engineer to:

- define process variable measurements and actuators, including filters and alarms,
- define controllers with interlinked or cascaded connections,
- automatically tune the above controllers, and
- log plant data.

Key qualities of the system are its robustness, flexibility and scalability. It's robustness is derived from a client – server architecture, with the core operations being performed by the server. Its flexibility is due to the manner in which control algorithms and strategies can quickly be created and deployed using libraries containing both simple PI and advanced process control techniques. It is scaleable as an easy to use interface exists with many rapid development wizards to help control engineers design solutions.

PlantStar fulfils the role of both the stabilisation and optimisation layer of plant control (Houseman, *et al*, 2000). It also includes a management information system called mInfoStar which can log all process variables and control actions.

User profiles allow for different hierarchies of users, from plant operators through to plant managers, thus allowing separate control of different aspects of the system.

3. MINTEK'S CONTROL OPTIMISATION SOLUTIONS

Mintek has invested significant resources into the stabilisation of mineral processing plants. Three specific industrial control problems are presented in each of Mintek's core focus areas. Custom tools and techniques used to solve these problems are described. These problems constitute only a minor selection of difficulties faced in the mineral processing industry. Emphasis is placed on the utilisation of such tools to optimise the overall operation of the respective processing plants.

Problem Statements

The list below describes specific problems possibly experienced by plant operators and metallurgists in the minerals processing industry:

1) Changing ore size or hardness affects the mill load and grinding efficiency and eventually downstream operations.
2) Fluctuating grade and recovery of flotation circuits.
3) Furnace fault conditions including power trips and electrode breakages.

The methods to overcome the above difficulties form part of Mintek's total control solution suite in milling, flotation and furnace control. These process improvements lead to a greater degree of plant optimisation.

3.1 The MillStar™ Mill Feed Controller

Comminution is the single most expensive operation in mineral processing, consuming roughly 50% of the energy required for mineral extraction (Agar, 1976). Maintaining milling circuits at their optimum design point therefore has economic benefits. Flotation circuits downstream from milling circuits are adversely affected by disturbances to the comminution circuit such as ore hardness and feed particle size variations. Ensuring milling circuit stability therefore represents overall grade and recovery improvements in the flotation circuit.

An open SAG milling circuit with segregated ore supply and multiple feeders is considered. Good control of the mill load is critical to efficient mill operation and energy utilisation. The circuit does not have a mill product feedback loop which results in disturbances being transferred forward to the flotation circuit. A recycle loop would have a desensitising effect on the mill operation's influence on the flotation circuit. The flow and particle size disturbances passed onto downstream flotation circuits must be minimised.

Characteristics of a Milling Circuit

The system to be controlled is a multivariable interactive one. The manipulated variables are the feed rate and feed coarseness. The feed coarseness is determined by specifying the ratio contribution which each feeder makes towards the total solids feed.

The measured process variable is the mill load determined by the weight or bearing pressure depending on the instrumentation available.

Stabilisation Control Objective

The primary objective is to ensure that the mill is grinding efficiently by controlling the mill load to setpoint.

The MillStar™ Mill Feed Controller demonstrates excellent control of the mill load to setpoint. This is achieved by effectively handling large conveyor transport lags in the solids feed. These time delays make the system inherently difficult to control.

Using traditional Smith Predictor controllers to overcome time lags cannot be implemented successfully. Drifting process models induce model errors in the predictor. Controllers then have to be severely detuned to remain robust and stable. This results in poor controller response similar to normal plant control as shown in Figure 2 below.

An advanced algorithm using time delay compensation techniques has been developed to accommodate for these delays. The improved setpoint tracking capability (reduced standard deviation) of the model is shown below in Figure 3. It shows a reduction in rise time from 5 minutes to 1 minute.

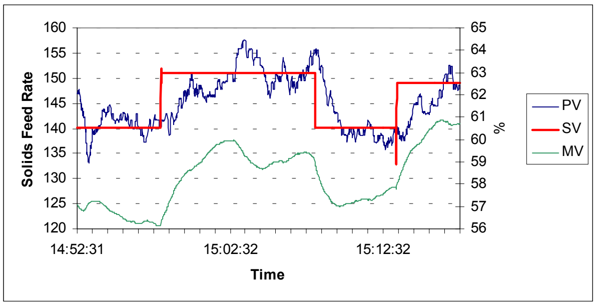

Fig. 2: Solids feed control using normal plant control

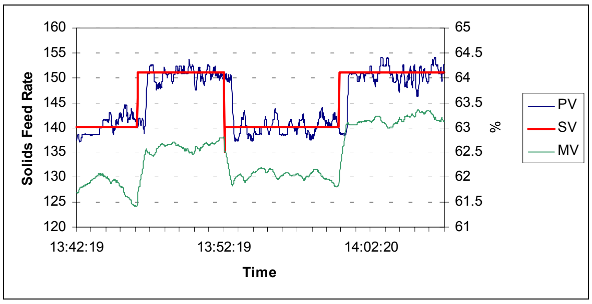

Fig. 3: Solids feed control using delay compensator

Once the mill has achieved steady state it is desirable not to affect the solids feed rate or the mill inlet water, as the change in mass feed will cause a large disturbance downstream. Any subsequent change to the solids feed rate causes a large disturbance in the product particle size which has a large dead time as the disturbance propagates through the entire milling circuit. Therefore minimising input disturbances is imperative on open circuit mills.

Optimisation Control Objective

Disturbances do exist however in the form of varying ore hardness and feed particle size. For segregated ore supply and multiple feeder arrangements an optimisation controller can be designed to compensate for this by utilising another degree of freedom: the relative feeder speeds.

The Mill Feed Controller includes a feed coarseness controller which calculates the overall coarseness of the feed and uses this 'process variable' in feedback to control the feeder size, by manipulating the fine and coarse feeder speeds relative to each other. This is a multivariable interactive system subject to system constraints, such as maximum feeder speeds or higher priority controller's resistance to change the overall solids feed rate.

System constraints are handled by constraint handlers an example of which is switching automatic feeders on and off when a required coarseness cannot be reached by purely changing the required feeder speeds.

Only when changing feeder speeds cannot bring the mill load to setpoint are feeders turned on and off. Only when switching feeders on and off cannot return the system to setpoint is the total solids feed rate changed as a last recourse. This is achieved by a constraint handler which ensures smooth switching between control modes.

Results from a Mexican silver plant

An open SAG circuit with three segregated feed controllers ran out of coarse ore. The mill load drifted far from setpoint resulting in a drop in mill power. The time series of mill load, mill power, solids feed rate, feeder ratios and feeder speeds appear in Figure 4. The maximum possible coarseness had been reached with the fine (feeder 1) and medium (feeder 2) coarseness feeders available as is evident by the flat ratio trends at their limits. No further feeders could be switched in or out and no control could be exhibited by manipulating feed ratios.

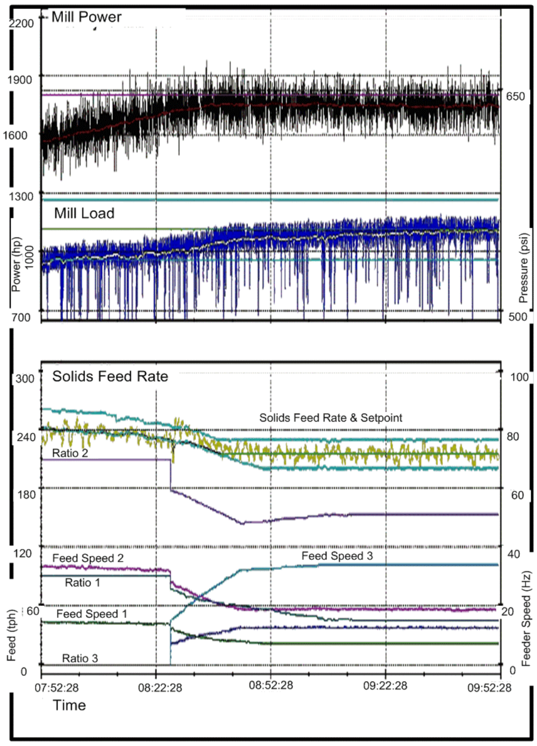

Fig. 4 Time series of Mill Feed Controller behaviour

The result was that the constraint handler on the mill load caused the overall solids feed rate to increase, with the mill power and load increasing as expected.

The time series shows the solids feed rate returning slowly to setpoint after some corrective action in the past. At 08:30 the coarse feeder (feeder 3) becomes available and is manually switched on. Two new trends show the coarse feeder's speed (feeder speed 3) and respective feed ratio (ratio 3), and the resultant effect on the other feeders' speeds and relative ratios.

With new scope for control due to the third feeder being introduced, the constraint handler is no longer necessary to manipulate the solids feed rate. The smooth transition to normal control is evident. A quicker mill load and power response is achieved by increasing the coarseness, whilst still allowing the solids feed rate to return to setpoint, along with the mill load and mill power.

In comparison to conventional operational practice the introduction of a new feeder would call for drastic control actions and subsequent associated disturbances. Such excessive dynamics and disturbances do not occur in the case of the MillStar™ Mill Feed Controller.

Benefits

Minimising disturbances propagating from varying input disturbances through the plant results in improved throughput and product size control.

3.2 The FloatStar™ Grade Recovery Optimiser

Recovery rates on a flotation plant are typically around 90 % and often lower, making flotation one of the least efficient processes in the concentration path. (Singh and Schubert, 2000). Due to the physical configuration of a typical flotation separation plant the system is highly interactive. Initially these interactions led to disturbances propagating throughout the plant and subsequently eroding base layer stabilisation control.

Mintek, with the development of FloatStar™ Level Stabiliser has solved this interactive problem and allowed plant operators to tightly control their levels to setpoint and minimise disturbances introduced into the system. One of Mintek's techniques to subsequently optimise the flotation circuit relies on this stabilisation control, and is employed in cascade to FloatStar™ Level Stabiliser. The FloatStar™ Grade-Recovery Optimiser demonstrates excellent results of improved grade vs. recovery performance for a flotation circuit in South America.

Characteristics of a Flotation Circuit

A flotation circuit is used to separate valuable minerals from waste material. Valuable material is collected in a concentrate stream whilst gangue material exits the system through tails streams.

Process control handles are pulp level setpoints (or froth depth), aeration rates and reagent addition. Reagent control, due to its long time delay, is not considered. The relationship between level setpoints and grade is fundamental to the optimisation technique. Grade is increased by decreasing pulp level setpoints (or increasing the froth depth).

The process variables are the grade and recovery of the circuit. Downstream smelting processes require a product with a certain grade to perform economically, whilst the separation process must seek to recover as much valuable material as possible.

Stabilisation Control Objective

The stabilisation control objective of the flotation circuit is to ensure optimal level setpoint tracking, which ensures froth stability.

Once good stabilisation control has been achieved, optimisation control can be attempted. (Singh, et al, 2000)

Optimisation Control Objective

The trade off commonly accepted in flotation control is that to increase recovery, good product grade must be sacrificed, and vice versa. Mintek's optimisation objective is to maximise recovery whilst maintaining a minimum required product grade. Figure 5 below demonstrates the concept.

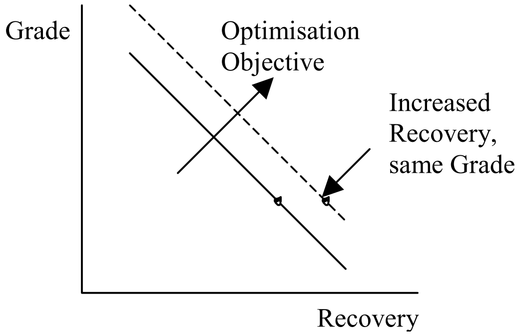

Fig. 5. Optimisation Control Objective

The minimum permissible grade and recovery would be set by the metalurgist. This optimisation allows one to 'push' the plant into new areas of operation.

Constraint Handler

Both the grade and recovery of the circuit are subject to the following constraint: should the recovery drop below the permissible value, the grade is sacrificed to re-obtain the required recovery. When the recovery returns to above the minimum level, grade control can resume. Hence recovery is prioritised.

Multiple Input – Multiple Output Controller

The Grade-Recovery optimiser has as inputs the grade of the feed, the grade of the concentrate stream and the grade of the tailings stream. The recovery is determined or can also be an input to the system.

The optimiser manipulates the levels and the aeration rates of the plant to effect control.

Figure 6 shows an example of the controller on a rougher for two sections. The grade is above setpoint in section 1. In section 2 the optimising controller increases the level setpoints to decrease grades as shown. Simultaneous to the grade decreasing to setpoint, the recovery is being maximized and increases. Thus if the grade is above its setpoint the optimizing controller will attempt to increase the level setpoints to decrease grade to setpoint, thus maximizing recovery.

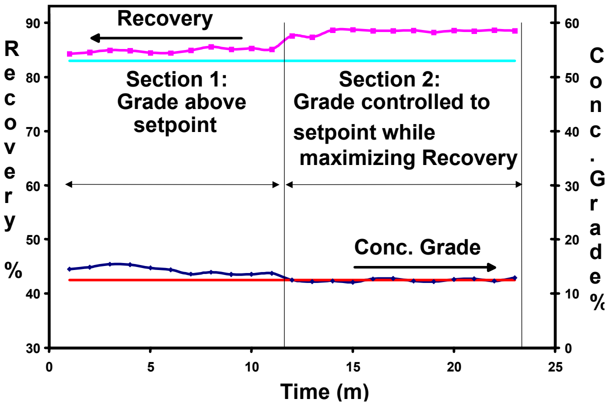

Fig. 6. Recovery Maximisation.

The grade setpoint is chosen to be the maximum grade that can be achieved for the ore being processed. The recovery is chosen as the minimum desired recovery for the ore being processed. The controller ensures recovery at or above the minimum desired recovery, thus maximizing recovery, while producing a consistent product.

The optimising algorithm aims to maximise recovery from the various sections of the flotation circuit while maintaining product quality (concentrate grade). The controller aims to achieve these objectives by manipulating the level setpoints and / or the aeration rates.

Results from a South American copper plant

Figure 7 below is a plot of data logged from an implementation of the Grade-Recovery optimiser on a South American copper plant. The data compares the grade plotted vs the recovery in the cases of the optimiser being on and off. The dark points represent 2 weeks of data with the optimiser being off, whilst the light points represent 2 weeks of data with the optimiser on. The graph shows an initial response of the circuit, with sustained results expected over a longer time period. It is important to note, that simultaneous to the optimiser being activated, the ore characteristics changed. The ore processed with no optimiser displayed good floatability characteristics: namely a normal pH, density and hardness. The ore processed with the optimiser enabled was oxidised, had a high lead content and had an varying pH. All these factors combined would conventionally cause a decrease in circuit performance. However, as was commented by plant metallurgists, the optimiser allowed the circuit to

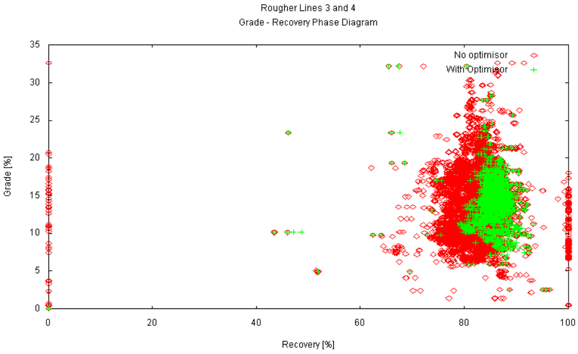

Fig. 7 – Grade vs Recovery for Rougher Lines 3 & 4

maintain final grade control, whilst maximising recovery. This can be validated in the clustering of data further along the recovery x-axis, whilst reducing the variation of grade in the y-axis.

3.3 The Minstral™ Electrode Hoist Controller

Furnace dynamics change frequently and unpredictably. The type of control required to keep the furnace operating in its optimum condition is influenced by the vagaries of the furnace dynamics. Examples of different conditions experienced in furnace control are electrical asymmetry, product tapping and electrode baking. Each condition requires different control. PlantStar, due to its modular nature, allows for a custom control module to be integrated into the overall furnace control strategy. The Minstral™ takes account of these different conditions in the form of its Electrode Hoist Controller. Before the specific solution is presented the whole system is considered briefly, the control objectives are discussed and the dynamics which the Electrode Hoist Controller manages are elaborated upon.

Characteristics of a Furnace

Submerged arc furnaces are used for ferro-alloy production. Typically these furnaces use three phase alternating-current power supplied to the burden trough three triangulated Søderberg electrodes. Self-baking, large diameter Søderberg electrodes are usually used due to economic constraints of graphite or pre-baked electrodes as well as to satisfy large current demands.

In the reduction of the ferro-alloy it is necessary to optimise the power delivered to the system. The power P_E delivered per electrode is described by:

$$P_E = I^2 \times R \, .$$

The resistance R and the current I are both process variables which need to be controlled to operate the furnace economically.

Control of a Furnace

For this system to represent a control problem there must be two competing physical phenomena. The trade-off can be simply stated: The lower an electrode's tip is in the burden, the lower the resistive component and hence less power supplied to the furnace. If the electrode is raised higher, the resistance will increase and hence the power supplied too. However, the higher the electrode's tip the greater the possibility of the process becoming destabilised: inadequate heat concentration resulting in the cooling off of the metal and inter-electrode conduction causing slag boils.

Two distinct control techniques exist in the field of submerged-arc furnaces namely: regulation of electrode penetration (controlling R) and the manipulation of the transformer tap positions (controlling I). These are the system's manipulated variables.

Mintek's Minstral™ makes use of an advanced differential tapping algorithm to ensure that the highest power input into the furnace within the electrical limits of the circuit is achieved. This technique is well documented.

Mintek's Minstral™ also regulates the electrode penetration of the furnace to a given desired resistance setpoint by means of manipulating the electrode hoist controller.

Stabilisation Control Objective

The base layer of the control hierarchy is to maintain balanced electrical conditions in the circuit, such that more power can be delivered to the furnace without jeopardising normal operations.

Optimisation Control Objective

The optimisation objective of the furnace's operation is two fold: the power input in *MWh* must be maximised whilst the specific energy consumption *MWh/t* must be minimised.

The power factor seen by the electricity supply is a directly proportional function of the size of the furnace and can be corrected by the installation of capacitor banks.

Process Disturbances

Disturbances to normal operating conditions are costly. Examples of such fault conditions are electrode breakages, electrical trips and tap hole blockages. These are often induced by problems associated with electrode management and if their occurrence can be minimised, so too can the furnace's operation be maximised.

Electrode breakages result from inadequate baking or temperature related stresses.

Electrical trips can result from circuit imbalances called asymmetry. Asymmetrical conditions are also visible to the supply grid which can result in imposed fines on furnace operators as this can cause general power failures. Asymmetry is caused by:

1) one electrode being shorter than others, possibly as a result of a break, or
2) metallurgical fluctuations in the burden under one electrode, possibly as a result of a large quantity of fines being added, or
3) poor electrode length management.

Electrode management is difficult due to:

1) the physical size of the electrodes coupled with poor weight to strength ratios, which limits the velocity, displacement and frequency of movement.
2) the susceptibility of electrodes to thermal shock, and
3) large uncertainties in electrode lengths.

Furnace Dynamics

Operational practice of a furnace requires specific procedures to be followed according to conditions present. Examples of such procedures are product tapping and electrode baking.

Probably the greatest challenge for the operator of a ferro-alloy furnace with Søderberg electrodes is to balance the baking-slipping rates of the electrodes, as required to maintain electrode lengths. (Barcza, et al, 2002).

Furnace operators hence require assistance with the following furnace conditions: 1) General conditions – a) Balanced circuit or 2) Special conditions - a) Warm up, b) Cool down c) Product tapping, d) Electrode baking and e) Asymmetry correction

Control Sets

The Minstral™ Electrode Hoist Controller is able to improve control of a submerged-arc furnace by being able to control the behaviour of the hoist to match the prevailing furnace conditions. This is achieved by defining different control sets which describe the required hoist controller behaviour during these specific periods. As noted above the furnace can operate in General or Special modes, each with their own collection of profiles. General conditions are indicated by the operator whilst special conditions are dynamically identified and immediately managed. The inputs into the Minstral™ Electrode Hoist Controller are a tapping flag, a baking flag and the percentage system asymmetry. These inputs allow for the detection of the matching conditions and the dynamic loading of the special sets for tapping, baking and asymmetry correction respectively.

The required behaviour for the specific conditions above are described below.

1a) In a **balanced circuit** the electrodes are all controlled to their respective resistance setpoints. An electrically balanced circuit allows for power optimisation and hence maximum efficiency is reached.

2a) During **warm up** the current in the electrode is slowly ramped up to prevent thermal shock and the possible resultant breakage.

2b) While **cooling down** the electrode is also susceptible to thermal shock for many hours after shutdown.

2c) **Product tapping** occurs frequently: for example 30 minutes every 3 hours is not unusual during normal operation. Depending on the nature of the process and the furnace operator's preferences different hoist control is required for the electrode closest to the tap hole. The first option can be to move the electrode in quickly as the bath and slag level drops during tapping. This strategy will prevent electrode pieces from blocking the tap hole. It also maintains the temperature in the area which assists with tapping as less lancing is necessary. A second strategy could be to move the electrode slowly or keep it stationary so as to minimise the risk of the electrode breaking. Implementing the full range of strategies is possible.

2d) Due to continuous electrode tip consumption **electrode baking** to is a continuous process and requires regular slipping. Electrode paste manufacturers supply baking schedules according to slip lengths, which specify the maximum amount of slip permissible and the frequency of slipping. Such baking schedules can easily be included into the Minstral™ ensuring adherence thereto. Only small electrode movements are permissible during a long baking period and only in a downward direction. This reduces the risk of further breakages.

2e) **Asymmetry corrections** are necessary after either an electrode breaks or if fine feed material unbalances the load. The Electrode Hoist Controller accommodates for asymmetry by automatically adjusting resistance setpoints of all the electrodes to reduce the imbalance whilst also adjusting the electrode controller response times to allow for quicker responses from the system.

Benefits

The ability of the Minstral™ control module to dynamically control the furnace according to prevailing conditions provides for improved control of the furnace. The result is improved electrode management, reduced risk of electrode breakages and fewer circuit trips. These improvements contribute directly to increased product yield with lower energy consumption.

4. CONCLUSIONS

Mintek's ability to develop custom control modules for specific process related problems has been demonstrated in the areas of milling, flotation and furnace control. Process control improvements in the form of advanced control strategies lead to the general optimisation of plant operational practices. Minerals processing is an industry where small process control improvements in already controlled environments yield significant savings. Customers benefit from improved process optimisation and direct cost savings.

5. ACKNOWLEDGEMENTS

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