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Supervisory Fuzzy Expert Controller for Sag Mill Grinding Circuits: Sungun Copper Concentrator

Mehdi Hadizadeh, Akbar Farzanegan, and Mohammad Noaparast
School of Mining, College of Engineering, University of Tehran, Tehran, Iran

ABSTRACT
Successful control of Semi-Autogenous Grinding (SAG) mill circuits has been the subject of many researches and main concern of plant operators for years. Distributed Control Systems (DCS) have had some degree of success in the mineral processing circuits, but maintaining operation of a SAG mill on the “edge” of its full capacity is not easily achievable by DCS. Advanced control systems, however, are a relatively new opportunity to successful control of mineral processing plants. This article presents the basis of a supervisory fuzzy expert controller for SAG mill circuits. Although leading companies in control and automation have their own commercial packages, this supervisory controller is coded in Matlab using Mamdani method and is able to connect to plant lower level control system. In the proposed controller, fuzzy system calculates optimum set point to the plant DCS control loops, enabling them to change the manipulating parameters to reach the new set points. This controller was installed, tested and verified in a copper grinding circuit. Results showed 1.8% increase in mill throughput, 3% decrease in power draw and more stable feeding regime at the same time.

1. Introduction
Efficient control of mineral grinding circuits has been the subject of many researches and main concern of operators for years. Most of the mineral processing plants have designed and implemented distributed control systems for their primary level of control, but these control systems are not able to stabilize, optimize and run the grinding circuit as designed. The problem is more evident when a SAG mill is included in the primary grinding circuit.

One of the drawbacks of the DCS systems is that, new set points should be calculated by “operators” and defined to the DCS “manually.” This will raise two issues: (a) which manipulating variable should be selected for applying necessary control action? (b) What should be the value of new set point for the selected manipulating variable? It is obvious that, different operators can make different decisions under the same situation which mainly depends on the level of their knowledge and experience. On the other hand, any delay or mistake in problem observation or calculation of the new set points can have negative effect on the operation of the grinding circuit or the downstream processes.

In order to overcome to these problems, a new Fuzzy Control System (FCS) has been designed and proposed to serve as a supervisory expert controller for plant lower level control system. This new control system has been installed, tested and verified in a copper grinding circuit which enhanced its throughput and decreased power draw at the same time.

Advanced control systems, brought the capability of stabilizing and optimization to the grinding circuits (Bartsch et al., 2008; Festa et al., 2009; Katom et al., 2003; Mccaffery et al., 2001; Strohmayr and Valery, 2001; van Drunick and Penny, 2005; Yutronic and Toro, 2010). There are different types of advanced control systems such as multivariable control (Chen et al., 2009; Craig and Macleod, 1995; Craighton et al., 1992; Duarte et al., 2002, 1999; Efe, 2003; Muller and Vaal, 2000), model based and model predictive control (Apelt and Thornhill, 2009a, 2009b, Chen et al., 2008, 2007; Galan et al., 2002; Herbst et al., 1992; Lestage et al., 2002; Niemi et al., 1997; Radhakrishnan, 1999; Ramasamy et al., 2005), adaptive control (Chen et al., 2009; Desbiens et al., 1997, 1994; Herbst et al., 1988; Najim et al., 1995; Tang et al., 2012) and artificial intelligence based control strategies such as fuzzy logic (Abou and Dao, 2009; Bartsch et al., 2008; Bouch et al., 2005; Cao et al., 2008; Chen et al., 2010, 2008; Costea et al., 2015; Farzanegan, 1998; Festa et al., 2009; Hales et al., 1988; Kandasamy et al., 2002; Strohmayr and Valery, 2001, 2001; Subbaraj and Anand, 2010; Takeuchi et al., 2010; van Drunick and Penny, 2005; Zhou et al., 2013), neural network (Chai et al., 2011; Conradie and Aldrich, 2001; Duarte et al., 2001; Flament et al., 1993; Ko and Shang, 2011; Stange, 1993; Topalov and Kaynak, 2004), genetic algorithm (Mitra and Gopinath, 2004) or combination of those (Karr et al., 2000; Katom et al., 2003; Mccaffery et al., 2001). It is noted that each of above-mentioned control strategies has its own benefits and drawbacks.

2. Theory
Distributed control systems with P, PI and PID controllers try to maintain the process values (PV) as closely as possible to the set points (SP) defined by the plant operators. It is obvious
that, these set points are not always optimum because the operators worry about the mill/circuit overload condition and so they keep the mill feed rate below design values which means a lower mill throughput. On the other hand, human sourced errors in choosing the correct manipulating variable and time delays cannot be ignored. The concept of the advance control system is to run the plant as much as possible close to the design values by calculating optimum set points, according to feed properties and mill operating condition. Calculated set points will then be delivered to DCS. Now this is the DCS which tunes corresponding manipulating variable to reach new defined set points. Therefore, the grinding circuit operation will be more stabilized while the maximum possible throughput is achieved.

3. Proposed advanced control system

The main goal of the new controller is maximizing mill throughput and decreasing energy consumption at the same time. In order to achieve this goal, a fuzzy control system has been developed. This controller uses a SAG mill power model as a soft sensor to predict the mill power draw and well-defined rules in fuzzy system to make the best decision as an expert operator under different situations. Combining these capabilities, allows for building a strong and reliable control system for grinding circuits to achieve predefined objectives. It is believed that, such a control system can minimize the need for full presence of operators in the control room. The objectives of this control system are:

- Stabilizing the grinding circuit
- Preventing the overload condition in the SAG mill;
- Increasing the SAG mill feed rate up to its designed capacity;
- Decreasing the specific energy consumption
- Preventing any damage to SAG mill liners and lifters.

3.1. FCS description

FCS comprises two main parts: a) SAG mill power model and b) fuzzy system. The schematic of this control strategy is depicted in Figure 1.

Data from PLC are collected every 30 seconds and the fuzzy system uses these data to ensure that all operating parameters are within optimum ranges and if any stabilizing/optimization/preventive action is needed.

The fuzzy system decides which set point should be changed and the calculated set points are enforced into DCS controllers (i.e. P, PI or PID). Now this is the DCS which tunes corresponding manipulating variable to reach new defined set points by the fuzzy system.

3.1.1. SAG mill power model

The aim of inclusion of a SAG mill power model is to use it as a soft sensor to predict mill power draw. The predicted mill power draw helps the operator to prevent SAG mill overloading and unnecessary production shut downs. The effect of any changes in the set point of a manipulating parameter will take 5-15 minutes to get stabilized in real operation,
which depends on the variable type and magnitude of change. Using mill power model as a soft sensor, the operators are able to see what will be the value of power draw as a result of increase in mill feed, just in seconds.

Selection of the best SAG mill power model among the three well known models (Austin, Morrell and Lovedy/Barrat) was done based on available literature. A comparison of the models was performed with real data for 25 different mineral grinding sites covering a wide operational conditions (Doll, 2013). The comparison showed that the Morrell C-Model can predict the mill power draw with a deviation of 1.4% with real plant data comparing with Austin (2.0%) and Lovedy/Barrat (9.2%). Hence, the Morrell-C formula was selected to be used. The formula can be written as below:

\[ \text{Gross Power} = \text{No_Load Power} + k \times (\text{Charge Motion Power}) \]  

(1)

Where \( k \) is a fitting parameter.

3.1.2. Fuzzy system

Although fuzzy control systems have already been used in other industries and have proved their practical value, they are relatively new to mineral processing plants, in spite of their high potential for improving plant control and operation.

To build up a rule-based controller for a specific application, it is necessary to understand the flow sheet, available instruments and capabilities of equipment. It is also necessary to know, which basic (or advanced) level of control is available in the plant. Accordingly, some critical questions should be answered to develop a supervisory control system such as:

- What kinds of control loops are available in the plant and where implemented?
- How the feed rate to the SAG mill is controlled (feeders’ speed, conveyor speed or both)?
- Is there any camera installed on the mill feed conveyor to estimate feed particle size distribution?
- SAG mill rotational speed is fixed or variable?
- Is there any sound analyser available for SAG mill?
- Is there any load cell installed for accurate mill load mass measurements?
- Is there any VFD available for cyclone feed pump?
- Is the vibration frequency of the screens fixed or variable?
- Which variables for cyclone circuit can be measured (e.g. feed flow rate, feed solid content, and cyclone pressure)?

Within the grinding circuit, SAG mill is the most complicated one due to nonlinear, interconnected parameters and delays. There are many factors affecting the operational condition of the SAG mill including:

- Feed properties: feed tonnage and specific gravity, particle size distribution, breakage properties
- Ball charge: total ball mass and size distribution, charging method
- Mill speed
- Mill load properties such as load shape, specific gravity and solid percent
- Mill design parameters: grating design and open area, liners shape and condition, discharge scheme.

On the other hand, individual control of the SAG mill will not yield to successful control of the whole grinding circuit as the SAG mill operating condition will affect downstream processes such as the vibrating screen, discharge sump, cyclone feed pumps and cyclones themselves. To have a better understanding of the issue, the schematic flow diagram of the Sungun copper grinding section is shown in Figure 2.

3.2. Effects of major process parameters on SAG mill performance

As stated earlier, to construct a series of fuzzy rules, it is necessary to understand the process behaviour. SAG mill as the most important equipment in the grinding circuit needs special attention. In the next sections, the effect of main parameters on SAG mill behaviour is described. These information have been incorporated in fuzzy rules.

3.2.1 Feed rate

Feed rate is one of the most important manipulating parameters in control strategies which can be changed in order to keep the power draw and bearing pressure within acceptable limits.

It is apparent that the charge volume and power draw parameters are related and both are affected by feed rate. Increase in feed rate will raise charge mass holdup inside the mill, and hence an increase in the power draw is accordingly expected. Thus, the power draw is not directly related to the feed rate and the power variations are due to variations in the mill charge (Valery and Morrell, 1995).

3.2.2. Feed size distribution

The effect of feed size distribution on SAG mill performance is highly dependent on the grinding circuit flow diagram (whether the SAG mill is in open circuit or in closed circuit with cyclones as well as inclusion of the pebble crusher). In cases in which SAG mill is operated in closed circuit with cyclones, the effect of feed size distribution is masked to some extent by the effect of recycle and accumulation of the slurry. The effect of feed size distribution is more relevant in open SAG mill circuits. In this case, a narrow feed size distribution means that majority of the feed remains in the intermediate size (normally 16-50 mm) which is very difficult to break. These particles are called critical sized particles which will start to be accumulated in the mill, and increasing the power draw. Using pebble ports on the discharge gratings can be one of the solutions which helps fast deploying of critical sized particles (Valery, 1997).

3.2.3. Pebble crusher effect

The effect of introduction of a pebble crusher can be described as a modification of the SAG mill feed size distribution. The main role of the pebble crusher is breaking down critical sized particles and reducing charge level in the mill (Valery and Morrell, 1995).
3.2.4. Ore hardness effect
Distinguishing the effect of ore hardness and ore particle size distribution on the SAG mill performance is relatively difficult as normally harder ores contribute to the larger sized particles. In SAG mill, the softer ore normally leads to higher throughputs as the ore will spend less time in the mill. On the other hand, the accumulation of the critical sized particles will be lower than harder ores. But, the product size distribution of SAG mills with softer ores, will be coarser than harder ores due to highlighted impact breakage action rather than abrasion breakage for this type of ore (Valery and Morrell, 1995).

3.2.5. Mill rotational speed
The clear effect of mill speed on mill performance is predominating impact breakage in higher speeds (which can increase mill throughput) and abrasion breakage in lower speeds. The rotational speed can be described as the frequency of impacts (breakage) as well as impact energy (due to change in drop weight). With increasing mill speed, it is expected to have coarser product from the mill. Therefore, mill speed manipulation can be a control strategy to compensate effects of feed hardness without decreasing the feed rate (which is not a favourite action of plant operators).

Mill speed also would affect the slurry hold up in the mill, as a sequence of change in the breakage regime. Increasing mill speed normally increases the slurry hold up as the cataracting breakage is promoting in this condition (Valery and Morrell, 1995).

3.2.6. Charge volume
Charge volume (water + ore + grinding balls) is the most important variable affecting mill performance. Unfortunately, it is very difficult to measure the charge volume and normally, the power draw and/or bearing pressure are used to infer the charge volume. Other methods such as power oscillation, vibration, conductivity, sound, impact and gauges have also been examined to estimate charge level (or mass) inside the mill.

It is obvious that, charge volume is not a very useful parameter if charge density is not considered. The same level of charge with different charge densities will lead to different charge mass, different breakage and mill performance. Thus, the best way to measure the charge mass is using load cells. Using soft sensing (models) is another solution to estimate the charge mass (Valery and Morrell, 1995).

Outotec has a method for determining the volumetric charge in a grinding mill based on the oscillation in the power draw of the driving motor. Movements of charge toe will lead the movement in the phase of the oscillation. These oscillation shifts are used to detect movement of the charge (Jarvinen, 2004).

A soft sensor based on the mill shell vibration signal in combination of Genetic Algorithm (GA) has been used to estimate the charge level of the wet ball mills (Zhao et al., 2010).

There are hard sensors which can be installed inside the mill to continuously measure the position of toe and shoulder of the charge. Raw data can be sent through a wireless link to the central unit where they are processed (Clermont and De Haas, 2010).

3.2.7. Ball charge effect
Grinding balls are very effective as grinding media (due to high kinetic energy) especially for large particles. Introduction of grinding balls into the mill, will break larger particles very
rapidly and so the contribution of the abrasion breakage will decrease, resulting in a coarser mill product. On the other hand, the steel balls are favourable in breakage of the critical sized particles. The disadvantage of using steel balls is destroying larger particles which could be a grinding media for finer particles. It is well known that, large particles are favoured by larger media, and finer particles need smaller balls to be broken efficiently. On the other hand, there are more small balls in the unit volume rather than larger balls. The large number of balls can provide more impact frequency but lower impact energy than larger balls. Therefore, there should be some kind of compensation between ball size and quantity (Valery and Morrell, 1995).

3.2.8. Water
Water addition could have a complicated effect on SAG mill performance. Operators normally use dilution water to empty the mill and decreasing power draw. In this way, they can prevent overloading the mill. The interesting issue is that, increasing water to the mill, will not increase charge mass as described in the next section.

Increasing water addition to the mill will deploy fine particles from the mill, leading to decreasing in solid percent and power draw. Adding more water to the mill will form a slurry pool in the mill, which can help more power drop (and decreasing impact energy of the balls).

By extracting fine particles from the charge, the interstitial voids will increase, leading in decrease of slurry level which will decrease discharge rate from the mill as well. This will in turn, increase fine particles accumulation, increase charge solid content and finally increasing power draw (Valery, 1997).

3.2.9. Slurry accumulation in the mill
In practice, the effect of a slurry pool is to reduce the power draw. This can manifest itself when closing an AG/SAG mill with hydrocyclones or spiral classifiers as an observed association between the amount of recycle and the power draw, which drops as the recycle increases (Valery, 1997).

4. Methodology
In order to develop the FCS, its verification, validation and final evaluation, the flow sheet of the Sungun phase 2 copper concentrating plant (Figure 2) has been considered. Process data and SAG mill operational condition information gathered for a period of 3 months. These data have been used to develop the SAG mill power draw model and fuzzy inference system.

4.1. Fuzzy system
The fuzzy controller has been coded in Matlab using its fuzzy toolbox. The fuzzy toolbox in Matlab is user friendly and can be exported to the Matlab workspace for any purpose.

4.1.1 Fuzzy inference system (FIS)
The fuzzy inference system has been developed using Mamdani method. In order to ease of programming, the grinding circuit was divided in two groups as presented in Figure 2. The first group is dedicated to SAG mill circuit, comprising stockpile feeders, SAG mill feed belt conveyor and SAG mill itself. The second group is for cyclone circuit comprising cyclone feed sump, sump (cyclone feed box), pumps and cyclones themselves. Tables 1 and 2 describe the manipulating and controlled variables for SAG mill and cyclone groups respectively.

Figure 3 shows the FIS for the SAG mill group with 4 input variables and 3 output variables.

4.1.2. Membership functions
One of the most important stages of any fuzzy system is development, is development of the membership functions. A membership function (MF) is a curve that defines degree of truth for linguistic expressions of an input variable. Each point in the input space is mapped into a membership value between 0 and 1.
using MFs. As an example, consider Figure 4 which shows MFs for SAG mill power draw as an input variable for fuzzy system. Five linguistic expressions (MFs) have been defined for this input variable: very low, low, good, high and very high. Any quantitative value for power draw, can be converted into a fuzzy value using these membership function. For example, a power draw with the value of 8000 kW, is interpreted by the fuzzy system as “high” with a degree of belief equal to 0.5 and “good” with a degree of belief equal to 0.9.

For this research, the operating data of the Sungun SAG mill grinding circuit (Phase 2) were monitored and collected for 3 months. After analysing these data as well as recommendations of the suppliers of equipment, the normal operating range and critical values for each variable were extracted. Table 3 shows information obtained for various desired variables.

According to these information, the membership functions for each variable were developed which then were subjected to more adjustments within offline tests and fine tuning during pre-commissioning with real plant control system.

### 4.1.3. Knowledge acquisition and fuzzy rules

Development of the fuzzy rules needs an insight understanding of the grinding process as well as a good experience of the plant operation. This knowledge should be subsequently translated into linguistic rules. In this research, the knowledge of the fuzzy system, has two sources. The first source is based on grinding theory and the behaviour of SAG mill which were described briefly in Section 3.2. The second source is the practical knowledge and expertise of Sungun plant operators who are well known as “expert” operators. During individual interviews with the plant operators in several sessions, the researchers have collected their preferred methods for interactions with different situations within the grinding circuit especially with the SAG mill. The questions asked were managed in such a way to cover all possible conditions and scenarios in a mineral grinding circuit and to understand their actions to prevent the mill from overload condition or to stabilize/optimize grinding circuit performance. The descriptive answers of the operators, were then formulated to build the knowledge base of the fuzzy system.

There are seven rules for SAG mill group and nineteen rules for cyclone group. It is believed that, these rules can cover all “expected” situations in the grinding circuit. The complete sets of rules are listed in Appendix 1. Figure 5 shows the relationship between mill feed rate, bearing pressure and power draw. As can be seen, there is a flat area, over which the values of bearing pressure and power draw are within “good” limits and so the feed rate can be at its designed value. An increase in power draw or bearing pressure will cause a decrease in mill feed rate as can be seen in Figure 5. The worst condition is an increase in both power draw and bearing pressure at the same time, which in this case, the feed rate will be reduced to its minimum defined value in order to accelerate reduction in charge level.

### 4.2. FCS connection with off-line central processing unit (CPU)

After evaluation of FCS with Sungun data, it was necessary to connect the program coded in Matlab with a real CPU.

As described earlier, there are four variables as input parameters to SAG mill fuzzy controller and three variables as the output parameters from fuzzy controller. Each of these variables has its own address in CPU which the fuzzy controller should read/write data. These addresses were used in the controller coded in Matlab.

#### 4.2.1 Hardware configuration

The following hardware were set up in laboratory and Sungun plant control logic downloaded onto the CPU.

1. Power supply, PS 407 10A
2. CPU, 416-5 H PN/DP
3. Communication processor, CP 443-1
4. RAM, MC SRAM, 16 MB
5. Communication cable.

---

**Table 3.** Operating values for control parameters in Sungun phase 2 copper grinding circuit.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trip</td>
<td>Trip</td>
</tr>
<tr>
<td>Fresh feed rate (t/h)</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Bearing pressure (MPa)</td>
<td>4.8</td>
<td>4.5</td>
</tr>
<tr>
<td>Power draw (kW)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cyclone feed sump level (%)</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Cyclone pressure (kPa)</td>
<td>80</td>
<td>60</td>
</tr>
</tbody>
</table>
4.2.2. Software requirements
To connect the controller with the CPU and get the necessary data, the following software was needed:

1. Simatic Manager, Step 7, V. 5.5
2. Simatic Net, V. 10
3. OPC Scout; V. 10.

5. Results and discussion
5.1. SAG mill power model
To provide a soft sensor to estimate SAG mill power draw, collected data from Sungun plant were employed.

Morrell equations have been applied to predict SAG mill power draw. Using Sungun data, fitting coefficients have been calculated by Excel Solver function making the square root of error in minimum. The second set of data has been used for verification of the model (Figure 6). Comparison of results with Sungun data showed that, the Morrell formula with calculated fitting coefficients can predict the SAG mill power draw accurately.

5.2. FCS off-Line test with sungun data
In order to evaluate the FCS, it was necessary to test the fuzzy rules and membership functions. To do this, data from Sungun plant was used to provide input data to fuzzy controller. Optimum set points for manipulating variables (SAG mill fresh feed, SAG mill rotational speed and SAG mill dilution water) which are calculated by fuzzy controller, compared with the operator set points.

5.2.1. SAG mill fresh feed
Figure 7 shows this comparison for SAG mill fresh feed. It is evident from Figure 7 that, the average of tonnage set points calculated by the fuzzy controller is 28 t/h more than the average of set points calculated by plant operators (754 t/h vs. 783 t/h). On the other hand, the oscillation of SAG mill feed set points calculated by the fuzzy controller is 17% lower than Sungun real data which means more stable feeding regime to the SAG mill by FCS.

5.2.2. SAG mill rotational speed
Figure 8 shows the comparison of mill speed set points calculated by fuzzy controller and Sungun plant operators. The plant data shows the rotational speed of SAG mill with the average of 70% (of critical speed) with a standard deviation of 4.5%. However, the fuzzy controller set points, shows 73% (of C.S.) with a standard deviation of 2.97%. This also shows reduction of oscillation in SAG mill rotational speed by 34%.
5.3. FCS online test

After offline evaluation of the FCS using Sungun data, it was connected to Sungun PLC using OPC Scout. In order to have the permission from plant control system to connect to an external high level controller, some modifications were made on the plant control logic blocks. FCS was successfully connected and integrated with existing control system and all data could be monitored online.

Online tests were carried out twice at Sungun Phase 2 plant. The first one was carried out on November 2, 2016 for one operating shift. The SAG mill liners had been renewed 3 months before the time of online test. The Second test was carried out on December 14, 2016 for 40 hours. It should be mentioned that, SAG mill liners were worn out more in compare with the time of first online test.

During online tests, the “write” command of the controller program, was activate, in order to enable the FCS to send calculated set points to the plant PLC.

In order to assess the results of the online application of the FCS, the plant operating data with the FCS have been compared with those when FCS was OFF, for the same duration before and after the online tests (when the FCS was ON). Also, in order to evaluate if the improvement in SAG mill operation with FCS-ON mode, was due to FCS functionality rather than variations in the feed properties, samples collected before, during and after the online test. This sampling carried out just for the second online test from SAG mill feed conveyor. Bond ball mill work index tests were done on the representative samples and the results will be described in the next sections.

5.3.1. SAG mill feed rate

Figures 9 and 10 show the feed rate (t/h) to the SAG mill for the first and second online tests, respectively. It is worth to mention that, the SAG mill maximum throughput for the time of the first test was 1035 t/h. This is due to the new set of liners installed to replace the worn set. So, this value considered as the target for the feed rate to the mill during first online test However, for the second test, SAG mill feed rate target value was 900 t/h due to worn liner condition.

From Figures 9 and 10, it is evident that the set points calculated by the FCS (marked as FCS-ON) is higher than those calculated by plant operators (marked as FCS-OFF). On the other hand, the fluctuations in the process values, has been decreased considerably during the online tests in compare with before and after of the tests. Tables 4 and 5, show the average feed rate and its variation during, before and after the tests.

It can be understood from both Figures 9 and 10 as well as Tables 4 and 5 that the feeding regime to the SAG mill was more stable during FCS-ON mode in compare with the sessions in which FCS was OFF.

![Figure 9. Set points and process values for SAG mill feed rate (first online test).](image-url)

![Figure 10. Set points and process values for SAG mill feed rate (second online test).](image-url)
5.3.2. SAG mill power draw

One of the advantages of the proposed control system is energy saving which is clearly persistent and observable in Figures 11 and 12. As can be seen, the average of Specific Energy Consumption (S.E.C.), is lower in FCS—ON mode, in compare with FCS—OFF mode for both tests. The results for both first and second online tests are compared in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Set Point (t/h)</th>
<th>Process value (t/h)</th>
<th>Standard deviation (t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before test</td>
<td>1012</td>
<td>1011</td>
<td>50</td>
</tr>
<tr>
<td>During test</td>
<td>1035</td>
<td>1029</td>
<td>37</td>
</tr>
<tr>
<td>After test</td>
<td>958</td>
<td>957</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 4. Fresh feed rate to the SAG mill (first online test).

Table 5. Fresh feed rate to the SAG mill (second online test).

<table>
<thead>
<tr>
<th></th>
<th>Set Point (t/h)</th>
<th>Process value (t/h)</th>
<th>Standard deviation (t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before test</td>
<td>856</td>
<td>855</td>
<td>43</td>
</tr>
<tr>
<td>During test</td>
<td>882</td>
<td>871</td>
<td>33</td>
</tr>
<tr>
<td>After test</td>
<td>853</td>
<td>836</td>
<td>39</td>
</tr>
</tbody>
</table>

5.3.3. SAG mill feed properties

In order to evaluate whether the improvement in SAG mill operation during online tests, was due to application of FCS or was a result of softer mill feed, samples were taken from SAG mill feed before, during and after the test. Bond ball mill work index tests have been conducted on those samples. It should be mentioned that, work index tests were performed only for samples collected for the second online test.

Results showed that there was no significant difference between the hardness of the samples, as indicated by their measured work indices. In other words, the ore breakage properties were the same before, during and after the test. Bond ball mill work index test results are shown in Table 7.

6. Conclusions

In order to overcome drawbacks of DCS in optimum control of SAG mill grinding circuit and to stabilize feeding regime to the mill, a fuzzy expert control system has been designed and proposed. Prior to online application of FCS, offline tests were conducted using Sungun grinding circuit data. Finally, online application of FCS at Sungun showed an increase of 1.8% in mill throughput and 3% decrease in specific energy consump-
Specific energy consumption (kWh/t) for both online tests.

<table>
<thead>
<tr>
<th></th>
<th>Before test</th>
<th>During test</th>
<th>After test</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>4.35</td>
<td>4.22</td>
<td>4.51</td>
</tr>
<tr>
<td>Second</td>
<td>6.04</td>
<td>5.81</td>
<td>6.37</td>
</tr>
</tbody>
</table>

Bond ball mill work index test results (second online test).

<table>
<thead>
<tr>
<th>Work Index (kWh/sh. t)</th>
<th>Before Enabling FCS Enabled</th>
<th>After Disabling FCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.120</td>
<td>14.261</td>
<td>14.803</td>
</tr>
</tbody>
</table>

Finally, online application and testing of the new control system at Sungun plant proved its ability to minimize the need for the "eyes" of the control room operators and would also be helpful for operator training purposes.

Acknowledgments

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ORCID

Akbar Farzanegan  http://orcid.org/0000-0002-5756-1699

References


Appendix 1: Sungun copper plant

Sungun copper mine is located at the north west of Iran. Two copper processing plants have been constructed. The first line is commissioned at 2006 and the second line (phase 2) is commissioned at 2015. The grinding circuits of both lines are the same (as shown in Figure 2), but the flotation sections are different. The SAG mills are equipped with variable speed drives and designed to grind 900 t/h fresh feed at the normal condition and 1035 t/h at Maximum. The feed rate to the SAG mills can be adjusted by variable speed feeders located under stockpile but the speed of mill feed conveyors is fixed. DCS is the control system of both lines and there is not any supervisory controller. Set points are calculated by operators in the control room. The fuzzy expert control system has been tested and verified at Sungun phase 2 SAG mill grinding circuit.

Appendix 2: Fuzzy rules

(A) SAG mill circuit

Rule 1
If (Bearing Pressure is NOT High) and (Power Draw is NOT High)
Then (Feed is INCREASE)

Rule 2
If (Bearing Pressure is High) and (Power Draw is High) and (Water in NOT Maximum)
Then (Water is INCREASE) and (Feed is DECREASE)

Rule 3
If (Bearing Pressure is High) and (Power Draw is High) and (Water is Maximum)
Then (Feed is DECREASE)

Rule 4
If (Bearing Pressure is NOT High) and (Power Draw is High) and
Then ((Speed is DECREASE)

Rule 5
If (Bearing Pressure is High) and (Power Draw is NOT High) and
(Speed is NOT Maximum)
Then (Speed is INCREASE)

Rule 6
If (Bearing Pressure is High) and (Power Draw is NOT High) and
(Water is NOT Maximum)
Then (Water is INCREASE)

Rule 7
If (Bearing Pressure is High) and (Power Draw is NOT High) and
(Water is Maximum) and (Speed is Maximum)
Then (Feed is DECREASE)

(B) Cyclone circuit

Rule 1
If (Sump Level is Low) and (Pump Speed is Low) and (Sump Water is Maximum)
Then (SAG Feed is INCREASE)

Rule 2
If (Sump Level is High) and (Pump Speed is High) and (Sump Water is Maximum)
Then (SAG Feed is INCREASE)

Rule 3
If (Cyclone Density is High) and (Pump Water is NOT Maximum)
Then (Pump Water is INCREASE)

Rule 4
If (Sump Level is NOT Low) and (Cyclone Density is NOT High) and (Pump Speed is NOT High) and (Pump Water is NOT Maximum)
Then (Pump Speed is INCREASE)

Rule 5
If (Sump Level is NOT High) and (Pump Speed is High) and (Pump Water is Maximum) and (Sump Water is NOT Maximum)
Then (Sump Water is INCREASE)

Rule 6
If (Cyclone Density is Low) and (Pump Water is NOT Minimum)
Then (Pump Water is DECREASE)
Rule 7
If (Sump Level is NOT High) and (Cyclone Density is Low) and (Pump Speed is NOT Low) and (Pump Water is Minimum)
Then (Pump Speed is DECREASE)

Rule 8
If (Sump Level is NOT Low) and (Cyclone Density is Low) and (Pump Speed is Low) and (Pump Water is Minimum) and (Sump Water is NOT Minimum)
Then (Sump Water is DECREASE)

Rule 9
If (Cyclone Pressure is High) and (Number of cyclones is NOT Maximum)
Then (Number of cyclones is INCREASE)

Rule 10
If (Cyclone Pressure is High) and (Number of cyclones is Maximum) and (Pump Speed is NOT Low)
Then (Pump Speed is DECREASE)

Rule 11
If (Cyclone Pressure is Low) and (Number of cyclones is NOT Minimum)
Then (Number of cyclones is DECREASE)

Rule 12
If (Cyclone Pressure is Low) and (Number of cyclones is Minimum) and (Pump Speed is NOT High)
Then (Pump Speed is INCREASE)

Rule 13
If (Cyclone Flow is Low) and (Pump Speed is NOT High)
Then (Pump Speed is INCREASE)

Rule 14
If (Cyclone Flow is High) and (Pump Speed is NOT Low)
Then (Pump Speed is DECREASE)

Rule 15
If (Sump Level is High) and (Pump Speed is NOT High)
Then (Pump Speed is INCREASE)

Rule 16
If (Sump Level is High) and (Pump Speed is High) and (Sump Water is NOT Minimum)
Then (Sump Water is DECREASE)

Rule 17
If (Sump Level is Low) and (Pump Speed is NOT Low)
Then (Pump Speed is DECREASE)

Rule 18
If (Sump Level is Low) and (Pump Speed is Low) and (Sump Water is NOT Minimum)
Then (Sump Water is INCREASE)

Rule 19
If (Sump Level is High) and (Cyclone Density is High) and (Pump Speed is High) and (Pump Water is Maximum)
Then (SAG Feed is DECREASE)