A plant-scale validated MATLAB-based fuzzy expert system to control SAG mill circuits

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ABSTRACT

This article presents the basis of a supervisory fuzzy expert controller for semi-autogenous grinding mill circuits. Stable feeding regimen to the mill, enhanced throughput, energy saving and human operator training are the most important objectives of this advanced control system. The fuzzy system calculates optimum set points for plant distributed control loops, causing them to tune semi-autogenous grinding mill performance to new operating set points. Although leading companies have their own commercial control packages, this supervisory controller is coded in MATLAB® and is able to connect to plant lower level controller. The controller has been tested and verified in Sungun copper concentrator semi-autogenous grinding circuit. Results proved the ability of proposed supervisory control system to increase the throughput of the mill by 3.26% and decrease the specific energy consumption by 6.29% at the same time. On the other hand, smooth set points calculated by the fuzzy control system, decrease the fluctuations in mill operation which finally results in a more stable operation of the grinding circuit.

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1. Introduction

Most of the mineral processing plants have Distributed Control Systems (DCS) for their primary level of control, but these control systems need to be operated by skilled and knowledgeable operators to run the grinding circuit under designed parameters. SAG mill control, delivers more challenges to the control room operators due to its nonlinear and complex behaviour. In order to cope with operating problems or to stabilize/optimize the circuit, operators should answer the following questions for each control action:

- Which manipulating variable should be changed?
- What should be the value of the new set point?
- When the operator should change a set point?

The following problems also will occur when the set points are calculated and inserted to DCS by operators manually:

- The set points defined by the operators are not necessarily optimum because the operators are always worried about mill/circuit overload condition. So, they keep the mill feed rate below design value.
- As the changes in the set points are stepwise (not smooth continuous values), the fluctuations in the process values will be inevitable.
- Human-sourced errors in choosing the right manipulating variable and time delays in response time of operators cannot be ignored.
- According to level of knowledge and experience of different operators, they can control the grinding circuit in different ways, even under the same situation.

1.1. Background

Automatic calculations of set points by advanced control systems, could rectify the problems of traditional DCS systems in manual calculations and selection of manipulating variables. There are different types of advanced control systems such as multivariable control, model based and model predictive control, adaptive control and artificial intelligence (AI) based control strategies such as fuzzy logic, neural network, genetic algorithm or combination of those.

In the case of non-linear behaviours and lack of process models to cover all changes in physical properties of material (such as variable characteristics of ore bodies) fuzzy control schemes can be used instead of model-based control strategies. Fuzzy logic control systems can deal with situations where the sources of information are inaccurate, uncertain or subjectively interpreted [1]. These
systems, are very easy to understood and implemented. Operators are able to see the rule base and discover the relations between input and output parameters of the controller. In fact, after the commissioning of an initial fuzzy logic controller at a plant, it will be easy and practical to enhance rule base via addition of rules and membership functions according to plant condition (e.g. at the time of installation of more instruments on the circuit such as load cell, camera or impact meter). On the other hand, model-based approaches need more calibration and correction factors with changes in mill feed characteristics. The model itself maybe too difficult to be understood by plant operators and they will work with a black box. In the case of addition of instruments to the circuit or variations of the ore body, the model should be reconstructed or recalibrated and this will be time consuming and complicated.

The behaviour of SAG mill itself is very complicated due to time delays and variations in ore characteristics. There are interactions between SAG mill operating parameters (bearing pressure, mill load weight, power draw and motor torque). The characteristics of the ore cannot be measured online and this will make MPC approaches difficult to calibrate. These characteristics include: feed size distribution, hardness, breakage properties, micro-cracks, specific gravity, moisture content, etc.

There are several publications related to knowledge-based strategies and fuzzy logic control systems for mineral grinding applications. But there are actually a few publications in the field of fuzzy control systems for SAG mill circuits. Some of them are the results of application of an industrial advanced control package (e.g. Metso OCS) with a little information about functionality, rules and membership functions. Remaining ones are theoretical proposed fuzzy controllers which are not verified in the industry. In this section, papers in the field of fuzzy control systems for mineral grinding circuits are discussed.

Farzaneh introduced offline optimization of grinding circuits using knowledge-based systems [2]. Radhakrishnan developed a model-based controller for ball mill and hydrocyclone circuit to serve as a supervisory optimizing controller on the regulatory PID loops. The proposed supervisory controller has not been verified industrially but tested in simulation environment [3]. Kandasamy et al. introduced a fuzzy expert system to control the separator speed in grinding circuit of cement industries [4]. Ramasamy et al. proposed a model predictive controller for ball mill grinding circuit to handle interactions between input and output variables. Performance of the controller has been studied in the laboratory [5]. Ruel described application of a fuzzy controller to a SAG mill for a nickel mine. Proposed controller has five input variables (bearing pressure, ore size, recirculation, power draw and density) and three output variables (mill feed flow rate, water flow rate and mill speed). Paper presents increase of mill feed by 81/h and decrease in power consumption by 8% [6]. The main difference of the fuzzy control system in the present study with the fuzzy control system built by Ruel is the structure of the controller in terms of input variables as well as the rule base. The other difference is the method of implementation. Ruel used the abilities of the plant PLC to code the fuzzy rules, but in the present study, MATLAB software is used on a separate computer for programming and the MATLAB and plant PLC has been connected via OPC server. van Drunick and Penny as well as Bouch et al. described application of the Optimizing Control System (OCS) at the AngloGold Ashanti Gold plants [7,8]. OCS is an advanced control package for grinding circuit developed by Metso. Cao et al. described a fuzzy control system as an advisory controller for a ball mill in Cement industries [9]. Bartsch et al. introduced a fuzzy controller for Xstrata Nickel Raglan operation. Their fuzzy system, had three variables (power draw, bearing pressure and feed size) as input to the fuzzy controller and three variables (feed rate, water rate and crusher gap) as output [10]. Festa et al. described installation of expert control systems in two mines of Mexico. Those expert control system have been developed by Penoles mining companies and Advanced Systems Group of SGS (Minnovex). However, there is not enough information about the rules and membership functions in that publication [11]. Advanced Systems Group of SGS has been involved in another expert control system for SAG mill in Barrick North Mara mine in Tanzania. This expert control system is created with SGS’s MET expert console and is running on Gensym’s G2 real time interface software. Controlled variables were power draw, mill load, discharge sump level, cyclone feed density and pebble recycle rate. However, manipulated variables were mill feed, mill discharge density and feeder ratio. Mill feed increase by 14.6% has been reported. Although power draw has not been decreased with expert system, fluctuations of power draw has been decreased [12]. Subbaraj and Anand used Genetic Algorithms for optimization of fuzzy controller parameters in MATLAB Simulink [13]. Takeuchi et al. developed a novel particle size control system for hammer milling using fuzzy logic [14]. Chen et al. proposed a theoretical improved strategy for energy saving and pollution reduction in ball mill grinding circuits [15]. Chai et al. developed an intelligent decoupling method to control a coal-pulverizing ball mill. Nonlinearities has been managed by a neural network approach. Proposed controller has been tested in China on a 200 MW ball mill [16]. Zhou et al. proposed an optimized control system based on artificial intelligence for ball mill grinding circuits which is tested in China [17]. Costea et al. described a theoretical control system architecture for cement finish grinding. Proposed control system, adjusts fresh feed based on four input variables to the fuzzy controller [18]. Hadizadeh et al. described application of a fuzzy control system to the SAG mill grinding circuits. Proposed advanced control system tested in a copper grinding circuit [19]. Their proposed control system has two input variables (power draw and bearing pressure) while the current study considers two more input variables (motor torque and motor current). Another difference is the rule base of the controller which is described in detail in Section 2.4.

2. Proposed fuzzy expert control system

Proposed Fuzzy Expert Control System (FECS) is coded in MATLAB® using its embedded fuzzy toolbox and installed and verified in Sungun copper grinding circuit in Iran. The controller is very user friendly and operators can see the results by means of graphs for better understanding of the ‘decisions’ made by the FECS. On the other hand, it is possible to expand the functionality of FECS by adding new rules to its knowledge base upon request of operators.

The main goal of the fuzzy expert control system is running the plant as much as possible close to the design values via calculating optimum set points, according to feed properties and mill operating condition.

The most advantages of the FECS over human-based control strategies are:

(1) The FECS is able to monitor several parameters simultaneously, analyse them and calculate SPs for all manipulating variables, while control room operator is unable to monitor several parameters in such a short time and to handle manipulating variables simultaneously.

(2) The FECS calculates SPs every two seconds according to mill operating data (input variables to the controller). So, the SPs are very close together and finally grinding circuit will have a smooth curve for each output (manipulating) variable (i.e. feed rate, water addition rate and mill speed). However, human operators normally change the SPs when they think it is necessary to do so. That is why we observe a stepwise SPs manipulation from human operators. These fluctuations will make the process unstable.
(3) FECS maintains the mill performance very close to its design values (in terms of throughput) by online monitoring of its operating condition. But human operators always are worried about mill overloading condition so that they normally operate the mill below its optimal design values.

(4) Human operators are prone to human-related errors. They have different skills and experiences, they may show slow or delayed reactions to disturbances in the process and are unable to keep looking at HMI for the whole time (they may be tired, sleeping at night shifts, etc.), but the FECS solves such type of issues.

(5) Online monitoring of the SAG mill operating condition will prevent damage to the mill liners because the FECS prevents the mill to be operated at a very low charge level or with a very high mill speed at which steel balls impact on liners occurs. On the other hand, the particle size distribution of the mill product will be improved as the fluctuations of feeding regime and mill speed (as illustrated in Fig. 8 and Table 4) can be decreased using proposed FECS.

2.1. Fuzzy expert control system

The schematic of the proposed FECS is depicted in Fig. 1. Data from plant PLC are collected every 2s by the FECS (which is adjustable according to fluctuations in mill operating condition) and the fuzzy system uses these data to evaluate operating condition of the mill and if any control action is needed.

The fuzzy rules are used to decide which set point should be changed and membership functions define the change values. The calculated set points are enforced into the DCS controllers. Consequently, the DCS tunes corresponding manipulating variables to reach new defined set points. Therefore, the SAG mill will be running under more stabilized condition while maintaining maximum throughput. The main goals of the FECS are: stabilization of SAG mill operation, maximize mill throughput, decreasing specific energy consumption, adjusting the feed solid content to the desired interval, training of the control room operators and to avoid the human-sourced errors from control strategies to ensure that the best decision will be made on time.

2.2. Fuzzy inference system (FIS)

In this research, "Mamdani" method [20] has been used to develop the fuzzy inference system. This method is embedded in MATLAB fuzzy toolbox, compatible with control applications and found to be simple and easy to use. It is necessary to define input and output variables for the fuzzy inference system. At this stage, manipulating variables should be selected among available variables (automatic valves, variable speed drives, etc.) and the main objective(s) of the advance control system should be clearly defined.

Table 1 shows the manipulating and controlled variables for defined scope of control for Sungun SAG mill circuit (as shown in Fig. 2).

The FECS calculates the SPs for manipulating variables (FIS outputs) according to values of controlled variables (FIS inputs).

The proposed FECS has been constructed according to the available instruments in Sungun SAG mill circuit. As there are no impact meter, load cell and camera available on Sungun SAG mill grinding circuit, the sensory information from these instruments were excluded from inputs of the FECS. Otherwise, those variables could have been included as additional controlled variables in FECS which may lead to a better control of the mill. However, in the absence of load cell, bearing pressure can be used to represent the charge weight of the mill and in combination with power draw and motor torque, gives a good sense to the human operators. The relationships among these variables and the way that FECS should act, are implemented in fuzzy rules.

The grind size is one of the main target variables to control in any comminution plant. In reality, SAG mill product size cannot be measured online in most mineral processing plants (including Sungun copper grinding circuit) due to arrangement, accessibility, massive flow rate and lack of appropriate instruments issues. The product of the SAG mill circuit is actually an intermediate stream and its size, so called Transfer size or T80, is set according to plant steady-state design. On the other hand, the final product of the grinding circuit (i.e., P80 of ball mill circuit product or hydrocyclone overflow) designed to be the target grind size. Hydrocyclone overflow particle size distribution can be measured online using an on-line particle size analyzer (OPSA) which is the final product of the whole com-
minimization plant. It should be noted that the control philosophy in SAG/Ball mill comminution plants is maximize throughput through SAG mill circuit (primary grinding) and achieving optimal grind size through ball mill circuit (secondary grinding). For the above-mentioned reasons, the SAG mill product particle size distribution was not considered as a controlled parameter in this research.

Normally under steady-state condition, it can be assumed that the flow rate of the mill product is equal to flow rate of the mill feed. This assumption is correct if the charge level inside the mill is stable. On the other hand, the flow rate of the SAG mill product, cannot be measured online. Therefore, the flow rate of the SAG mill product was excluded from controlled variables of the FECS but the flow rate of the SAG mill feed is considered as a manipulating variable.

The flow rate of pebbles can be measured online in most grinding circuits (including Sungun plant). As the pebbles are sent back to the SAG mill feed, the effect of recycling can be seen on SAG mill operating condition as well (i.e. bearing pressure, power draw, motor torque and motor current). Therefore, it was decided to exclude flow rate of recycled pebbles from controlled variables.

### 2.3. Membership functions

One of the most important parts of any fuzzy system is developing the Membership Functions (MF). MFs should be developed both for controlled and manipulating variables. Accordingly, there will be seven MF groups for proposed FECS. In order to develop MFs for FIS variables, it is necessary to identify critical values (i.e. Low, Very Low, Normal, High and Very High) for each variable. Next step is to establish suitable curves for each variable according to defined critical values to represent the degree of truth for each variable (fuzzification). The MFs for each input and output variables of the FECS have been selected from the predefined types of MFs in MATLAB Fuzzy toolbox. Table 2 shows the types of MFs for each variable of the proposed controller.

As the main objective of the proposed FECS is to maximize SAG mill feed rate according to mill operating condition (i.e. values of controlled variables), the target value for feed rate choose to be 900–1035 t/h as the plant is designed to process 900 t/h in normal condition and 1035 t/h in maximum. It is obvious that, the SAG mill feed rate can be lower than 900 t/h if the values of controlled variables (e.g. bearing pressure) go higher than its normal values. If the values of the controlled variables indicate a drift from normal operating range, the FECS will make a decision to change set points for manipulating variables in order to keep the values of controlled variables within normal operating range.

For this research, the operating data of the Sungun SAG mill circuit for the desired variables have been monitored and collected for three months. According to those data as well as recommendations of the suppliers of equipment and plant operators, the normal operating range and critical values for each variable have been extracted. Table 3 presents the values of the MFs for Sungun SAG mill.

### 2.4. Knowledge acquisition and fuzzy rules

Development of the fuzzy rules needs insights into the grinding process and a good experience of the plant operation. This knowledge should be subsequently translated to linguistic rules. In this research, the fuzzy system was built based on two main knowledge sources. The first knowledge acquisition source was the literature available regarding theory and practice of grinding process and in particular the behaviour of SAG mill circuits. The second source was the experiential knowledge of Sungun plant operators who are considered as expert in the field. During individual interviews with the plant operators, the authors have collected their preferred methods for interactions with different situations within the grinding circuit especially with the SAG mill. Descriptive answers of the operators, have been formulated to construct the knowledge base of the fuzzy system.

The proposed FECS includes 13 rules for SAG mill circuit. It is believed that these rules cover almost all expected scenarios observed during the SAG mill circuit operation. On the other hand, these rules actually embody the practical knowledge of plant human operators to control the SAG mill circuit under expected scenarios. The current state of the rule data base is explained below:

The following abbreviations have been used inside the LHS (Left Hand Side) and RHS (Right Hand Side) of rules:

- **BP**: Bearing Pressure;
- **PD**: Power Draw;
- **MT**: Motor Torque
- **MC**: Motor Current
- **WR**: Water Flow Rate;
- **FR**: Feed Flow Rate;
- **S**: Mill Speed;

Three rules were defined based on bearing pressure, power draw, motor torque and motor current to insert the facts regarding feed flow rate and mill speed:

**Rule 1**

If (BP is NOT High) and (PD is NOT High) and (MT is NOT High) and (MC is NOT High) Then (FR is INCREASE).

**Rule 2**

If (BP is NOT High) and (PD is High) Then (S is DECREASE).

**Rule 3**

If (MC is High) or (MT is High) Then (FR is DECREASE)

Rule 1 checks the status of all input variables. If all of them are not High, it means that the SAG mill feed rate can be increased. As the result, Rule 1 fires and mill feed will be increased.

On the other hand, if bearing pressure is not high (mill is not full) and power draw is High (i.e. the situation for Rule 2), SAG mill speed should be decreased in order to decrease the power draw (As the mill speed and power draw have direct relationship). This rule is responsible for energy saving which will be described in Section 3.4.2.

Motor current and motor torque can give the operator a good scene of mill charge. If one of these variables is High, it means that the mill is full. In order to decrease the mill load, mill speed should
be increased or mill feed should be decreased. In this situation, mill speed cannot be increased because the motor current or the motor torque is High. The correct action would be decreasing the mill feed (Rule 3).

Two rules were defined based on bearing pressure, power draw and water flow rate to decide assertion of the facts related to water flow rate and feed flow rate:

**Rule 4**

If (BP is High) and (PD is High) and (WR is NOT Maximum) and (FR is DECREASE)

**Rule 5**

If (BP is High) and (PD is High) and (WR is Maximum) and (FR is DECREASE)

Rule 4, checks the status of bearing pressure, power draw and water flow rate. If both of bearing pressure and power draw are High, increasing the water flow rate can increase the discharge rate from mill and finally decrease the bearing pressure and power draw. But this action can be done if water flow rate is not Maximum. As both of bearing pressure and power draw are High, this is a very critical situation. So, in addition to increasing water flow rate, mill feed has to be decreased in order to overcome to this critical situation. If the water flow rate is Maximum (i.e. the situation for Rule 5), then water flow rate cannot be increased and remaining solution will be decrease in mill feed.

One rule considers BP, PD and S:

**Rule 6**

If (BP is High) and (PD is NOT High) and (S is NOT Maximum) and (S is INCREASE)

This rule is responsible for increasing discharge rate from mill by increasing mill speed, in order to decrease the bearing pressure. But increasing mill speed will increase the power draw and can be done only if the speed is lower than Maximum. So, if the power draw is not High and speed is Not Maximum, mill speed will be increased to decrease the mill weight and this way, bearing pressure will be decreased.

Two rules are based on considering four parameters on their LHS:

**Rule 7**

If (BP is High) and (PD is NOT High) and (WR is NOT Maximum) and (S is Maximum) Then (WR is INCREASE)

**Rule 8**

If (BP is High) and (PD is NOT High) and (WR is Maximum) and (S is Maximum) Then (FR is DECREASE)

In order to decrease the water consumption per tonne of mill feed, in case of high values of bearing pressure or power draw, it is preferred to increase SAG mill speed as the first priority rather than increasing water flow rate. Rule 7, is considered for the situation where BP is High (i.e. mill is full) and speed cannot be increased (because it is Maximum). So, water flow rate will be increased in order to increase discharge rate from mill. On the other hand, if both of mill speed and water rate are at their Maximum values, mill feed has to be decreased as the final solution (Rule 8).

Five different rules were defined just based on feed flow rate to adjust feed solid percent inside the mill:

**Rule 9**

If (FR is Very Low) Then (WR is Very Low)

**Rule 10**

If (FR is Low) Then (WR is Low)

**Rule 11**

If (FR is Normal) Then (WR is Normal)

**Rule 12**

If (FR is High) Then (WR is High)

**Rule 13**

If (FR is Very High) Then (WR is Very High)

In order to keep the solid percentage of the mill content at its desired range, the mill feed is divided into five groups (i.e. Very Low, Low, Normal, High and Very High). For each of these groups, the rate of water flow will be tuned according to Rules 9–13.

### 3. Time delays and its effect on FECS

The delays in SAG mill circuit depend on the general arrangement of the circuit (e.g. distance between feeders, belt scales and the mill), PID controller settings and speed of belt conveyors. As can be seen in Fig. 2, distance between stockpile feeders to the first belt scale, is 51 m (equivalent to 34 s, considering belt conveyer speed of 1.5 m/s) and the distance between secondary belt scale to the SAG mill is 79 m (equivalent to 52 s). This means that, any change in mill fresh feed will show itself after 34 s on the first belt scale and will affect the mill operating condition after 151 s (distance between feeder and the mill is 226 m). On the other hand, any change in pebbles tonnage will show itself after 5 s on secondary belt scale and after 57 s on SAG mill operating condition. Considering the fact that even a change in pebbles tonnage will affect the SAG mill after at least 57 s, setting the scan time to 2 s for the FECS seems quite adequate.

In order to cope with time delays imposed by distance between belt scales and the mill itself, the differences between exact values of feed (which enters into the mill) and data from belt scales (which are sent to FECS as input variable) should be minimized. The FECS approach is to minimize that difference by decreasing the fluctuations of process values (PVs) of mill feed via minimizing the differences between consecutive SPs for the mill feed. This is also necessary to ensure that rules 9–13, in which FR is antecedent, get the correct MFs. This goal achieved by considering a small value (i.e. 2 s) as scan time. With decrease in variations of the SPs, the fluctuations of the PVs will be reduced. Consequently, fluctuations of the controlled variables (PD, BP, MT and MC) will be reduced leading the mill to run at a more stable condition. Higher scan times, would cause in big differences in consecutive SPs which results in fluctuations in PVs and increase the difference between mill feed exact values and data from belt scale.

### 4. Four-step verification of the FECS

The functionality of the FECS was evaluated in four-step verification tests before online application to the real industrial SAG mill circuit at Sungun copper plant.

#### 4.1. FECS functionality test (off-line)

The objectives of this test were to ensure that there are no missing rules and the existing rules are covering all expected situations in a SAG mill circuit, to evaluate the FECS controller actions against disturbances in input variables and to detect any possible contradictions between the rules.

Proposed FECS comprises four input (controlled) variables (PD, BP, MT and MC) and three output (manipulating) variables (FR, WR and S). During this test, the effect of variations in input variables on the output variables of the FECS was evaluated in offline mode. Three types of hypothetical disturbances in input variables were considered: sinusoidal, step change and impulse change. This evaluation was separately carried out for all input variables (i.e., changing one variable at each stage while keeping the others unchanged). Figs. 3–5 represent the actions of the controller against the above-mentioned types of hypothetical variations in bearing pressure, as an input variable, on all output variables.

Fig. 3 represents the response of the FECS controller to a sinusoidal disturbance in SAG mill bearing pressure. It can be seen that, the controller shows a reasonable response for all output variables (FR, WR and S).
Decreasing the bearing pressure resulted in decreasing the mill speed with the purpose of energy saving. During this time, mill feed and water addition had no change. Increasing the bearing pressure, led to increase the mill speed in order to increase breakage and discharge rate. After some time, as the bearing pressure was increasing continuously, mill feed rate decreased and water flow rate adjusts itself with the feed rate in order to keep SAG mill load solid percent within acceptable limits. It is worth to mention that, in order
to stabilize the circuit, responses of FECS have been started before bearing pressure reaching the “Hi” limit.

At the time of 50 h, a step change in bearing pressure was intentionally introduced. Fig. 4 shows that mill speed increased to the maximum in order to increase discharge rate from the mill but as the increase in bearing pressure is continued, feed rate decreased and water flow rate also decreased to maintain the mill content percent solid at the desired level. Fig. 5 represents the action of the controller against an impulse disturbance in BP on output variables.

It is obvious that this type of sharp and short time disturbance in SAG mill bearing pressure is unlikely in a real operation, but this test demonstrates the accuracy of the controller reaction and behaviour of the output variables.

4.2. Calibration of the FECS (off-line)

In order to calibrate membership functions, SAG mill operating data for Sungun copper grinding circuit was used. At this stage (off line mode), operating data for a period of 3 months, collected and formatted as an input matrix to the FECS controller. The set points defined by operators were compared with the set points (output) of the FECS. Fig. 6 shows the comparison of the operator and FECS SPs for SAG mill feed rate. As the consequences of the FECS SPs were not applied to the process, the comparison should be done for each individual time spot. As can be seen, at the end of comparison, the standard deviation of the FECS SPs (37 t/h) is lower than standard deviation of the operator SPs (54 t/h).

4.3. FECS test in open loop

For the third step, the FECS was connected to Sungun control system and data acquisition from Sungun PLC was conducted online. However, the set points of the FECS were not written on to the plant PLC because the ‘write’ command of the controller program had been deactivated.

Fig. 7 shows the comparison of operator SPs and FECS SPs for the mill feed. FECS SPs are smooth and reduced fluctuations (SD = 68 t/h), however, operator SPs are step wise which resulted in more fluctuations (SD = 171 t/h). This type of verification is called “reading mode”.

4.4. FECS online test (pre-commissioning)

As the final test, the FECS was connected to Sungun control system and data acquisition from Sungun PLC was conducted online. FECS calculated set points, also were written on to the plant PLC online. All required data was collected one operating shift “before” the test, “during” and one operating shift “after” the test. Data recording intervals was 2 min during “before” and “after” test and 2 s during the test. The test has been continued for more than 6 h during evening shift of the plant. Results of this test is discussed in the following sections.

4.4.1. SAG mill feed rate

Fig. 8 shows the feed rate to the SAG mill for the time period in which comparison has been made. It is worth to mention that, the SAG mill maximum throughput (design value) for the time of the tests was 1035 t/h. This is due to the new set of liners installed to place the worn set.

From Fig. 8, it is clearly evident that the set points calculated by the FECS is very close to the target value during the test (marked as FECS—ON). On the other hand, the fluctuations in the process values, has been decreased considerably during the test in comparison with “before” and “after” of the test (marked as FECS—OFF).

Spikes in Fig. 8 are excluded from calculations. Feeding regimen to the SAG mill was more stable during the test in comparison to the periods which FECS was OFF (standard deviations shown on Fig. 8).

As can be seen in Fig. 8, the PVs of the feed rate are fluctuating. There are two reasons why such situation is observed: the step changes of control room operators in feed SPs caused fluctuations in PVs of the feed rate (which is more evident in the first part of Fig. 8). The other reason is the problems with vibrating feeders (under the stockpile) which was due to high moisture content of the ore. This is more present in the third part of Fig. 8. At the middle part of that figure, since the SPs of FECS were constant, the fluctuations in FR decreased considerably (but still exist).

4.4.2. SAG mill power draw

One of the advantages of the proposed control system is energy saving which is established well in Fig. 9. As can be seen, the average of power draw before, during and after the test are 4403, 4289 and 4348 kW, respectively. Considering accumulated mill feed for those periods as well as time durations, the specific energy consumptions (S.E.C.) can be calculated accordingly (Shown in Fig. 9).

The peak in power draw (Fig. 9) during the test is an intentional enforced value into the plant PLC to evaluate the response of the FECS to high values of power draw. In other words, that peak (i.e. 7500 kW) is not a real process value but is a virtual value inserted by the engineering station operator from HMI to see how the FECS stabilizes the mill under new condition. The response of the FECS to this step change is described in Section 5.
5. Response of the FECS to the impulse changes in power draw and bearing pressure (online)

In order to evaluate the performance of the FECS in different conditions, it was decided to simulate the condition in which high power draw or bearing pressure occurs (Events 1–3 in Figs. 10 and 11). The responses of the FECS to those changes (Responses 1–4 in Figs. 12 and 13), are described in the following sections.

At the time of 525 min, the bearing pressure have been set to be 7.5 MPa (Event 1 at Fig. 10). As can be seen in Fig. 12, in order to overcome high bearing pressure, FECS increased mill speed from 78% to 84% (% of critical speed) with the aim of increase the breakage rate and lighten the mill charge (Response 1 in Fig. 12). Set point for mill feed rate also have been decreased by the FECS at the same time to cope with high values of bearing pressure (Response 3 in Fig. 13).
Table 4

<table>
<thead>
<tr>
<th>Feed (t/h)</th>
<th>Increase in feed (%)</th>
<th>SD (SP)</th>
<th>Decrease in fluctuations (%)</th>
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<tbody>
<tr>
<td>Before test</td>
<td>856</td>
<td>3.05</td>
<td>43</td>
</tr>
<tr>
<td>During test</td>
<td>882</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>After test</td>
<td>853</td>
<td>3.48</td>
<td>32</td>
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</table>

Table 5

<table>
<thead>
<tr>
<th>Total feed (t)</th>
<th>Avg. power (kW)</th>
<th>S.E.C. (kWh/t)</th>
<th>Decrease in S.E.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before test</td>
<td>34,186</td>
<td>5,166</td>
<td>6.04</td>
</tr>
<tr>
<td>During test</td>
<td>34,831</td>
<td>5,060</td>
<td>5.81</td>
</tr>
<tr>
<td>After test</td>
<td>34,442</td>
<td>5,322</td>
<td>6.37</td>
</tr>
</tbody>
</table>

Table 6

<table>
<thead>
<tr>
<th>Total water (m3)</th>
<th>Water consumption (l/t)</th>
<th>Decrease in water consumption (%)</th>
<th>Mill solid content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before test</td>
<td>15,307</td>
<td>448</td>
<td>1.37</td>
</tr>
<tr>
<td>During test</td>
<td>15,382</td>
<td>442</td>
<td>-</td>
</tr>
<tr>
<td>After test</td>
<td>15,328</td>
<td>458</td>
<td>3.65</td>
</tr>
</tbody>
</table>

6.1. Mill feed and power draw

Fig. 14 shows the results of the online application of the FECS at Sungun SAG mill circuit for comparison time of 120 h in terms of mill feed and power draw. Target value for mill feed during this application decreased to be 950 t/h due to worn liners comparing with the time of previous online test as well as other constraints in downstream.

Table 4 represents the average feed rate and its variation during, before and after the test. As can be seen, FECS increased the feed rate by 3.05% and 3.48% (average = 3.26%) in comparison with “before” and “after” the test respectively. On the other hand, fluctuations in feed regimen decreased by 37.53% and 14.49% (average = 26.01%) at the same time.

Table 5 represents the average values of mill power draw and specific energy consumption for the same time of comparison. It can be seen that, although total mill feed for the period which FECS was ON is more than periods which FECS was OFF, specific energy consumption decreased when FECS was responsible for SAG mill control. This is due to decreased SAG mill speed by FECS in order to save energy when possible. The average of decreased specific energy consumption is 6.29%.

6.2. Solid percent of the mill content

Table 6 shows the results of the mill content solid percent for the comparison time. As can be seen, FECS was successfully maintained mill load solid percent within acceptable limits (64–67 %). On the other hand, the water consumption per ton–of mill feed, decreased when FECS was ON. Average of decreased in water consumption is 2.51 percent.

6.3. Effect of FECS on SAG mill product size

As a result of decrease in mill feeding regimen and fluctuations in mill rotational speed by FECS, the breakage process inside the mill was more stable when FECS was ON, which means narrower size distribution of the SAG mill product. Although the SAG mill product

6. Results and discussions

Almost three months after online application of the FECS for one operating shift (pre-commissioning), another online test has been conducted for a total time of 120 h at Sungun SAG mill circuit. Again, data for equal periods, before and after the test collected for evaluation of the effectiveness of the FECS.

The effect of increasing mill speed by FECS at the time of 525 min (due to unreal value of BP in event 1) can be seen as a small bump in PD at the same time in Fig. 11.

On the other hand, at the time of 675 min, the value of the bearing pressure has been set to 7.6 MPa (Event 2 in Fig. 10) and the value of power draw enforced to 7500 kW (Event 3 in Fig. 11). Events 2 and 3 happened at the same time.

In response to Events 2 and 3, the FECS also increased mill speed (Response 2 in Fig. 12) and decreased mill feed rate (Response 4 in Fig. 13).

It worth to note that Events 2 and 3 have been happened at the same time (T = 675 min.). For Event 2, as the unreal values have been set for both BP and PD, the effect of increase in mill speed on PD, is masked by high unreal value of PD (Event 3 at T = 675 min).

It is clear that, process values for mill feed, are following set points very well. Event 4 in Fig. 13 (time of 625 min), has been occurred due to blockage of feeder chute and resolved very soon. As can be seen, the set point for feed rate has not been changed at that point, but the process values, decrease due to feeder blockage.

It is obvious that such unusual changes in controlled variables are not expected to happen in real situations. Indeed, the aim of applying these artificial abruptions was to evaluate the control actions of FECS.

Fig. 12. FECS response to impulse changes in bearing pressure and power draw in terms of mill speed.

Fig. 13. FECS response to impulse changes in bearing pressure and power draw in terms of mill feed.
size distribution was not measured during tests, the data of pebble tonnage during tests shows this, which presented in Table 7.

In the case of “after test” period, it should be noted that, as the feed rate to SAG mill was considerably lower than previous period (853 t/h vs. 882 t/h), the tonnage of pebbles also decreased during that period.

6.4. Effect of FECS on SAG mill liners

With online monitoring of the SAG mill operating conditions, FECS will prevent damage to the mill liners. Damage to mill liners can be happened in two cases: operation of mill with low charge level or in very high speeds, which in both cases, ball impacts to liners can be occurred. FECS monitors mill operating condition (i.e. BP, PD, MT and MC) and prevents the mill to operate in those conditions by changing mill speed or tuning mill feed.

7. Conclusions

A MATLAB-based fuzzy expert control system has been developed, verified and validated by real operating data from Sungun SAG mill copper grinding circuit. Installation of the FECS as a supervisory controller on the Sungun DCS control system showed an increase of 3.26% in mill throughput and decrease in feeding fluctuations by 26.01%. At the same time, specific energy and water consumption per tonne of feed, decreased by 6.29% and 2.51% respectively. A knowledge base, consisting 13 inferencing rules, was built which embodies the SAG mill control strategy (have been using by control room operators) using fuzzy variables and membership functions and can be universally applied and customized to other industrial plants. Installation and commissioning of the system in Sungun SAG mill circuit took about 4 months. The payback period of the proposed FECS is estimated to be around 5 months, depending on majority of improvements in mill throughput. The performance of the FECS was calibrated under different operating conditions and in forward and reverse rotation of the mill. The main risk of the proposed FECS is the fact that proposed FECS cannot distinguish between the real and faulty signals as well as its weakness in noise reduction. In the event of disconnections between MATLAB and plant PLC, the last SPs calculated by FECS will be remained unchanged on plant PLC and human operator should take control of plant manually. These issues should be rectified in future developments of the proposed FECS.

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References


