LOAD CONTROL OF BALL MILL BY A HIGH PRECISION SAMPLING FUZZY LOGIC CONTROLLER WITH SELF-OPTIMIZING

Hui Cao, Gangquan Si, Yanbin Zhang, Xikui Ma, and Jingcheng Wang

ABSTRACT

A self-optimizing, high precision sampling fuzzy logic controller for keeping a ball mill circuit working stably and efficiently is proposed in this paper. The controller is based on fuzzy logic control strategy, and a fuzzy interpolation algorithm is presented to improve the control precision. The final output of the controller is calculated through the interpolation calculation of the observation and its neighboring antecedents, and the interpolation weight coefficients are obtained according to a fuzzy inference algorithm. In the proposed controller, the sampling control strategy is used to deal with a large delay time and a controller set value which can be adjusted by a self-optimizing algorithm, which can overcome the time-varying characteristic. Simulation results verify that the controller can control the ball mill circuit effectively and have higher control quality. Field service results also verify that the controller can successfully optimize the control of ball mill circuit.

Key Words: Ball mill, high precision, fuzzy interpolation, sampling control, self-optimizing.

I. INTRODUCTION

The grinding process, which is a significant part of the cement industry, is particularly energy-consuming. The energy consumption associated with grinding amounts to approximately 75% of the cement production cost [1]. Moreover, only 2%-20% of the energy supplied to the grinders is effectively used in the pulverization process, while the remainder is essentially dissipated into heat. Therefore, to control the ball mill circuit work stably and efficiently is to increase the productivity of the ball mill circuit and lower the energy consumption [2].

The cement ball mill circuit is a complex system consisting of nonlinearity, large delay and time-variation. The classical controllers, such as Proportional Integration Differential (PID), are of no effect. Recently, many advanced control methods for the ball mill circuit have been introduced and discussed. A nonlinear learning control method is introduced in [3], and predictive control is introduced in [4, 5]. However, these control methods mainly depend on the model of ball mill circuit. Moreover, papers [6, 7] bring forward a model of a mill circuit, but it is so complex that some parameters cannot be measured online. In addition, the model is not fit for every type of ball mill. In paper [8], a kind of neural network control method is introduced. As the neural network method includes the training algorithm, the work of designing the controller becomes difficult. Fuzzy control does not need the mathematical model of the plant in addition to that of the ball mill. A controller based on fuzzy rules is introduced in paper [9]. The control rules of the fuzzy controller are obtained from the knowledge of experts and operators. As the accumulation of errors cannot be estimated easily, the analysis and manipulation of experts and operators are usually based on the error and the error change of a controlled variable, which are usually the input variables of the general fuzzy controller. Paper [10] proves that...
motor. Fig. 2 shows the functions $p(f)$, $m(f)$ and $v(f)$ versus $f$. $P_{\text{max}}$, $M_{\text{max}}$ and $V_{\text{max}}$ are maximum values of $p(f)$, $m(f)$, and $v(f)$.

As the energy consumption of the ball mill motor is far larger than the other equipment, such as the classifier and the elevator, $p$ can show the energy consumption of ball mill circuits.

When $f < F_1$, $v$ is so small that the ball mill works inefficiently and the lower level of the ball mill load leads to the mill wall being worn faster. When $f > F_2$, the ball mill works in the unstable region and the higher level of the ball mill load may lead to the ball mill getting clogged. When $f \in (F_1, F_2)$, $p$ is less and $v$ is larger, the ball mill works stably and efficiently. Since the change of $p$ becomes smaller when $f$ is in $(F_1, F_2)$, to control the ball mill so that it works at the optimal state is to control $f$, keeping it in proximity to $V_{\text{max}}$ all along. However, as the ball mill is a time-varying system, the point $(F_0, V_{\text{max}})$ will change with the change of the material grindability, the shatter of the steel ball, the abrasion of the mill wall, and so on. In addition, there exists a delay time between $r$ and $f$. This delay time is relatively long, which is influenced by the length of feed belt, the type of ball mill, etc.

### III. THE CONTROLLER DESIGN

A fuzzy controller is in essence an interpolator [12]. For this reason, an interpolation algorithm can be used to improve the precision of a fuzzy controller. Papers [13–16] introduce some interpolation methods to fuzzy rules, but these methods are either too complex to be applied, or the interpolation coefficients are fixed such that this method cannot be modified by the different states of the plant. Moreover, the large delay time and the time variation create difficulties that the general fuzzy controller cannot solve.

This paper proposes a fuzzy interpolation algorithm for improving the precision of a fuzzy controller and designs the controller based on a sampling control strategy and a self-optimizing algorithm. The control block structure of this controller is shown in Fig. 3. Fig. 3 includes four main parts: the self-optimizing algorithm, sampling controller, fuzzy logic controller, and fuzzy interpolation algorithm. $f$ is the measured value of the ball mill load and $f_{SP}$ is the set value of $f$, which can be adjusted by the self-optimizing algorithm. $T_s$ is a sampling switch which is controlled by the sampling controller. $e$ and $ec$ are the error and the error change of $f$, respectively. The final output, $u$, can be obtained by the fuzzy interpolation algorithm and fuzzy logic.
controller. In the following, the design of this controller will be explained in detail.

3.1 Self-optimizing algorithm

In order to control the ball mill circuit work efficiently, the ball mill must work at the optimum point throughout [17]. However, because the optimal point \((F_0, V_{\text{max}})\) in Fig. 2 may shift with a change in work condition, and the mathematical model of a ball mill circuit cannot be established accurately, \(f_{SP}\) cannot be determined easily in time. In order to keep the ball mill working at the optimum point throughout, the self-optimizing algorithm is presented.

The self-optimizing algorithm increases (or decreases) \(f_{SP}\) in the beginning of every self-optimizing
cycle, and the fuzzy logic controller controls the ball mill pulverizing system so that it works at the set value steadily. When the system is stable, according to the change of \( v \), the algorithm judges whether the current set value is the optimal point. If it is not the optimal point, \( f_{SP} \) will be increased (or decreased) in the next self-optimizing cycle. Finally, the optimal point can be found. For example, let the set value be as \( f_{SP1} \) in the previous self-optimizing cycle. At the beginning of the following cycle, \( f_{SP1} \) plus \( \Delta f_{SP} \) equals \( f_{SP2} \). \( f_{SP2} \) is the set value of the present cycle and \( \Delta f_{SP} \) is the fixed self-optimizing step. Since \( r \) can be measured directly, \( v \) can be calculated by equation (3). When the control plant is stable, if \( v \) is increased compared to the previous period, \( f_{SP2} \) will add \( \Delta f_{SP} \) in the next self-optimizing cycle. If \( v \) is decreased in the next self-optimizing cycle, \( f_{SP2} \) is the optimal point; otherwise, the set value will add \( \Delta f_{SP} \) again. However, according to the stability of system and the large delay, the self-optimizing cycle must be set longer.

### 3.2 Sampling control

When the pure delay time, \( \tau \), is in industrial process, the response to an error will come after \( \tau \) if the general control methods are used. This delay may let the output of the controller become larger and overshoot the optimal value. So, the control quality becomes lower and the system may be unstable.

The sampling Proportional Integration (PI) control is more suitable for the control of the pure delay process in industrial control [18]. Therefore, this paper designs a sampling switch, which is \( T_s \) in Fig. 3, based on sampling control strategy to the controller to overcome the large delay of the ball mill.

Let the function \( h_1(t) \) and \( h_2(t) \) be the ramp input and the output of the sampling switch \( T_s \), respectively. Then, let the control cycle be \( T_c \) and the action point of this sampling switch be \( t_e \). Fig. 4 can directly explain the effect of the sampling control strategy. During \( 0 \sim t_e \), named as control phase, \( h_2(t) \) equals \( h_1(t) \), and during \( t_e \sim T_c \), named as waiting phase, \( h_2(t) \) holds the value of \( h_1(t) \) at time \( t_e \).

For the proposed controller, the control period is divided into two phases by the switch. In the control phase, the controller works normally according to the input, the error of \( f \). In the waiting phase, the error of \( f \) is not updated and the value at the final moment of the control phase is held to be used as the control input. Although this method can overcome the large delay time, setting \( T_c \) and \( t_e \) must vary according to the response time and the delay time of the plant.

### 3.3 Fuzzy logic controller

According to the analysis in Section II, the ball mill circuit is a nonlinear complex system and its mathematical model cannot be built. However, there is plenty of expert knowledge and manual experience, so a fuzzy controller based on the error and the error change of controlled variable is chosen.

There are three basic implementation methods for fuzzy reasoning of control applications: 1) fuzzy table method, 2) analytic expression method, and 3) rule inference method. None of the three methods can completely eliminate the steady state error [19]. The first method provides a control value without reasoning because the fuzzy table can be calculated during the period of design. Therefore, the first method simplifies the implementation of control procedure and facilitates the industrial field application. We use the fuzzy table method in the fuzzy logic controller and discuss the design process in detail in the following.

The scope of \( e \), \( ec \), and \( u \) are \([-12\%, 12\%], [-12\%, 12\%], [-18\%, 18\%]\), respectively. If \( i \) and \( j \) are input variables of the fuzzy logic controller and \( u' \) is the output variable, \( i, j, \) and \( u' \) have the same scope as \( e, ec, \) and \( u \), respectively. To facilitate the controller design, the unified fuzzy universe, \([-6, 6]\), is adopted. Moreover, \( I, J, \) and \( U' \) are linguistic variables of \( i, j, \) and \( u' \), respectively. When \( i \) and \( j \) are in the fuzzification process, Equations (4) and (5) exist:

\[
I = (k_e \cdot i + 0.5) \tag{4}
\]
\[
J = (k_{ec} \cdot j + 0.5) \tag{5}
\]

where \( k_e \) and \( k_{ec} \) are the scale coefficients, “\( \cdot \)” and “\( + \)” mean round operation and add operation, respectively.

According to experience, the sets of \( I, J, \) and \( U' \) are adopted as \{NB, NM, NS, ZO, PS, PM, PB\}, representing negative big, negative middle, negative small, zero, positive small, positive middle, and positive big, respectively. Tables I–III show the value of membership with respect to \( I, J, \) and \( U' \).

The fuzzy rules are set based on the experience of experts and operators. The fuzzy rules table is shown in Table IV.

The max-min algorithm is used in fuzzy logic inference, and the defuzzification is accomplished by the largest of maximum method. So, the polling table of fuzzy control can be calculated during the period of design, which is shown as Table V.

### 3.4 Interpolation algorithm

In order to improve the control precision without increasing the difficulty of controller design, this paper proposes a fuzzy interpolation algorithm.
Fig. 4. The effect of the sampling control strategy.

Table I. Value of membership with respect to $I$.

<table>
<thead>
<tr>
<th></th>
<th>$-6$</th>
<th>$-5$</th>
<th>$-4$</th>
<th>$-3$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NM</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>0</td>
<td>0.8</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ZO</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
<td>0.8</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table II. Value of membership with respect to $J$.

<table>
<thead>
<tr>
<th></th>
<th>$-6$</th>
<th>$-5$</th>
<th>$-4$</th>
<th>$-3$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NM</td>
<td>0.2</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ZO</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.7</td>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table III. Value of membership with respect to $U'$.

<table>
<thead>
<tr>
<th></th>
<th>$-6$</th>
<th>$-5$</th>
<th>$-4$</th>
<th>$-3$</th>
<th>$-2$</th>
<th>$-1$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NM</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ZO</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>0.7</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.7</td>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>
If \((e, ec)\) is the input of this controller and \(u\) is the final output, there exist two conditions:

1. When \(k_e e = \langle k_e e + 0.5 \rangle\) and \(k_{ec} ec = \langle k_{ec} ec + 0.5 \rangle\).

The final output can be obtained directly by querying the polling table of fuzzy control, which is mentioned above.

2. When \(k_e e \neq \langle k_e e + 0.5 \rangle\) or \(k_{ec} ec \neq \langle k_{ec} ec + 0.5 \rangle\)

Let \(I_0, J_0, I_1, \) and \(J_1\) be as follows:

\[
I_0 = \langle k_e \cdot e \rangle \\
J_0 = \langle k_{ec} \cdot ec \rangle \\
I_1 = \langle k_e \cdot e + 1 \rangle \\
J_1 = \langle k_{ec} \cdot ec + 1 \rangle.
\]

Then, the output of \((I_0, J_0)\) is \(U'_{00}\), which can be attained by querying the polling table of fuzzy control. \(U'_{00}\) multiplies by the scale coefficients of \(U'\) to get \(u'_{00}\).

In a similar manner, \(u'_{01}, u'_{10}\) and \(u'_{11}\) can be obtained. So, the final output \(u\) is:

\[
u = \frac{1}{1} \sum_{m=0}^{1} \sum_{n=0}^{1} k_{mn} u'_{mn}
\]  \(\text{(10)}\)

where \(k_{mn}\) is the interpolation weight coefficient and satisfies \(\sum_{m=0}^{1} \sum_{n=0}^{1} k_{mn} = 1\).

Let \(a\) and \(b\) be as follows:

\[
a = |k_e \cdot e - \langle k_e \cdot e \rangle| \\
b = |k_{ec} \cdot ec - \langle k_{ec} \cdot ec \rangle|.
\]  \(\text{(11)}\)  \(\text{(12)}\)

The scope of \(a\) and \(b\) are \([0, 1]\) and \([0, 1]\), respectively. To facilitate the calculation, \([0, 5]\) is adopted as the fuzzy universe. Moreover, \(A\) and \(B\) are linguistic variables of \(a\) and \(b\), respectively. The set of \(A\) and \(B\) are adopted as \(\{\text{ZO}, \text{PVS}, \text{PS}, \text{PM}, \text{PB}\}\), representing zero, positive very small, positive middle, positive big, and positive very big, respectively. Based on the knowledge of experts and operators, a series of rules for the

<table>
<thead>
<tr>
<th>(U')</th>
<th>(NB)</th>
<th>(NM)</th>
<th>(NS)</th>
<th>(ZO)</th>
<th>(PS)</th>
<th>(PM)</th>
<th>(PB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I)</td>
<td>(NB)</td>
<td>(NB)</td>
<td>(NB)</td>
<td>(NB)</td>
<td>(NB)</td>
<td>(NM)</td>
<td>(NM)</td>
</tr>
<tr>
<td>(NM)</td>
<td>(NB)</td>
<td>(NB)</td>
<td>(NM)</td>
<td>(NM)</td>
<td>(NM)</td>
<td>(NM)</td>
<td>(NS)</td>
</tr>
<tr>
<td>(NS)</td>
<td>(NM)</td>
<td>(NM)</td>
<td>(NM)</td>
<td>(NS)</td>
<td>(ZO)</td>
<td>(ZO)</td>
<td>(ZO)</td>
</tr>
<tr>
<td>(ZO)</td>
<td>(NM)</td>
<td>(NM)</td>
<td>(NS)</td>
<td>(NS)</td>
<td>(ZO)</td>
<td>(ZO)</td>
<td>(ZO)</td>
</tr>
<tr>
<td>(PS)</td>
<td>(PS)</td>
<td>(PS)</td>
<td>(ZO)</td>
<td>(ZO)</td>
<td>(ZO)</td>
<td>(ZO)</td>
<td>(ZO)</td>
</tr>
<tr>
<td>(PM)</td>
<td>(PS)</td>
<td>(PS)</td>
<td>(PM)</td>
<td>(PM)</td>
<td>(PM)</td>
<td>(PM)</td>
<td>(PM)</td>
</tr>
<tr>
<td>(PB)</td>
<td>(PS)</td>
<td>(PM)</td>
<td>(PB)</td>
<td>(PB)</td>
<td>(PB)</td>
<td>(PB)</td>
<td>(PB)</td>
</tr>
</tbody>
</table>

Table V. Polling table of fuzzy control.
interpolation weight coefficient can be set. Using the max-min fuzzy inference method and the largest of maximum defuzzification method, the polling table of interpolation weight coefficient can be calculated during the period of design, which is shown as Table VI. Querying the table, \( k_{00}, k_{01}, k_{10}, \) and \( k_{11} \) can be obtained.

In actual control process, \( e \) and \( ec \) are obtained first. Second, \( I_0, J_0, I_1, J_1, A, \) and \( B \) are calculated. Third, through looking up the polling tables and using equation (10), the final output of the controller can be obtained. Finally, the final output of the controller is used as the control voltage of the material feeders to adjust the feeding rate of material so that the ball mill load is regulated.

**IV. SIMULATION AND EXPERIMENT RESULT**

Simulation is performed using MATLAB 7.0, and a second-order plus dead-time model can demonstrate the ball mill circuit. The transfer function of the simulation plant can be chosen as follows:

\[
G(s) = \frac{1}{s^2 + 2s + 1} e^{-40r}.
\]  

There are three controllers to be chosen: the general fuzzy controller with discrete universes, the general fuzzy controller with continuous universes, and the high precision fuzzy controller. They are added to the same sampling switch in Fig. 3 and named as GSFCD, GSFC, and HPSFC, respectively. The fuzzy logic controller discussed in Section 3.3 is adopted as GSFCD, and HPSFC is proposed in the paper. To facilitate the simulation, the membership functions of the input variables and the output variable of GSFC are the same and are shown in Fig. 5. GSFCD, GSFC, and HPSFC have the same fuzzy rules; GSFC also uses the max-min fuzzy inference method and the largest of maximum defuzzification method in the simulations.

With the working state changing, the controller designed here can adjust the control set value. However, between the two changes, the set value can be considered as being fixed.

To compare the control quality of three controllers with the control set value changed, simulations are also performed. In addition, the same control plant and the same parameters are used in the following simulations.

The input signal is Step Input, and the simulation result of step response is shown in Fig. 6. As there exists delay time in the control plant, the responses of three controllers are delayed about 90 s. GSFC enters the steady state quickly, while GSFCD and HPSFC enter the steady state after about 150 s. However, Fig. 6 shows that the responses of GSFCD and GSFC both have a steady state error of about 0.1 and 0.04, respectively, but HPSFC has almost no steady state error.

The amplitude of the input signal is changed from 1.0 to 1.4 after 300 s delay, and the simulation result is shown in Fig. 7. During 0 ~ 300 s, GSFCD, GSFC, and HPSFC have the same control quality as in Fig. 6. After 300 s, when the responses of three controllers each enter the next steady state, they all have some steady state error. However, the steady state error of HPSFC is only about 0.04, which is much less than that of GSFCD and GSFC. The steady state error of GSFCD and GSFC are 0.1 and 0.32, respectively.

The existence of a steady state error means that some fuzzy rules or the value of membership may be set improperly. However, in order to keep the simulations integral and fair, the fuzzy rules and value of membership are not adjusted in the following simulation.

The amplitude of input signal is changed from 1.0 to 2.0 after 400 s delay, and the simulation result is shown in Fig. 8. During 0 ~ 400 s, the control quality of GSFCD, GSFC, and HPSFC are no different from that shown in Fig. 6. However, after 400 s, the response of HPSFC enters the steady state rapidly and has almost

<table>
<thead>
<tr>
<th>((k_{00}, k_{01}, k_{10}, k_{11}))</th>
<th>(0)</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B)</td>
<td>((1.0, 0, 0, 0))</td>
<td>((0.8, 0.2, 0, 0))</td>
<td>((0.7, 0.3, 0))</td>
<td>((0.5, 0.5, 0))</td>
<td>((0.3, 0.7, 0))</td>
<td>((0.0, 1.0, 0))</td>
</tr>
<tr>
<td>(1)</td>
<td>((0.8, 0.2, 0, 0))</td>
<td>((0.8, 0.1, 0.1, 0))</td>
<td>((0.6, 0.1, 0.3, 0))</td>
<td>((0.5, 0.1, 0.4, 0))</td>
<td>((0.3, 0.1, 0.6, 0))</td>
<td>((0.1, 0.1, 0.8, 0))</td>
</tr>
<tr>
<td>(2)</td>
<td>((0.7, 0.3, 0, 0))</td>
<td>((0.6, 0.3, 0.1, 0))</td>
<td>((0.3, 0.2, 0.3, 0))</td>
<td>((0.3, 0.2, 0.3, 0))</td>
<td>((0.3, 0.1, 0.4, 0.2))</td>
<td>((0.1, 0.1, 0.5, 0.3))</td>
</tr>
<tr>
<td>(3)</td>
<td>((0.5, 0.5, 0, 0))</td>
<td>((0.5, 0.4, 0.1, 0))</td>
<td>((0.3, 0.3, 0.2, 0))</td>
<td>((0.2, 0.2, 0.3, 0.3))</td>
<td>((0.2, 0.1, 0.3, 0.4))</td>
<td>((0.1, 0.1, 0.3, 0.5))</td>
</tr>
<tr>
<td>(4)</td>
<td>((0.3, 0.7, 0, 0))</td>
<td>((0.3, 0.6, 0.1, 0))</td>
<td>((0.3, 0.4, 0.1, 0.2))</td>
<td>((0.2, 0.3, 0.1, 0.4))</td>
<td>((0.1, 0.1, 0.8))</td>
<td>((0.1, 0.1, 0.8))</td>
</tr>
<tr>
<td>(5)</td>
<td>((0, 1.0, 0, 0))</td>
<td>((0.1, 0.8, 0.1, 0))</td>
<td>((0.1, 0.5, 0.1, 0.3))</td>
<td>((0.1, 0.3, 0.1, 0.5))</td>
<td>((0.1, 0.1, 0.8))</td>
<td>((0.0, 0, 1.0))</td>
</tr>
</tbody>
</table>
Fig. 5. Membership function of GSFCC.

Fig. 6. Simulation result of step response.

Fig. 7. Simulation result of control set value changing.
no steady state error, but GSFC and GSFC cannot work normally. The simulation result illuminates the idea that GSFC and GSFC may not be suitable for this kind of plant.

In addition, the high precision sampling fuzzy logic controller with self-optimizing has been put into practice in the clinker cement production workshop of a cement mill. However, because there is a large delay time characteristic in the ball mill circuit, some of the original rules of the interpolation weight coefficient, which are obtained by the expert knowledge, are not suitable. After amending the rules based on the field experience, the controller performs the controlling ball mill circuit successfully. The curve of ball mill load, which is shown in Fig. 9, is drawn based on the records in the database of the system. It is obvious that this controller can improve the steady accuracy of ball mill circuit. Although the volume of production cannot be measured in real-time, the later numerical statements prove that the production is increased, the energy...
consumption is decreased, and the particle size distribution of ground material measures up to the manufacturing standard.

V. CONCLUSION

For the ball mill circuit of cement mill, a high precision sampling fuzzy logic controller with self-optimizing algorithm is designed and discussed in this paper. Based on fuzzy control theory, designing the controller attains greater facility without working out the cement ball mill model and this controller becomes more practical. Based on the sampling control strategy, this controller can solve the problem of the large delay time which is the difficulty of the cement ball mill load control. With the self-optimizing algorithm, this controller can find the optimal set value itself and maintain it, so it can be better modified with the change of controlled plant. Moreover, the fuzzy interpolation algorithm allows the controller to be more sensitive, and simulation results also verify that the high precision fuzzy controller has less steady state error, compared with the general fuzzy controller. Furthermore, the field service result also demonstrates that the controller works well in a cement mill. This controller can be applied in other situations, including ball mill circuits, such as Turbine Governor Systems of Thermal Power Plants and mineral processing of mines. In addition, the fuzzy interpolation algorithm, which is an improved method of fuzzy control, the sampling control strategy and the self-optimizing algorithm, is useful in control of such complex industry systems.

REFERENCES


Hui Cao was born in Shaanxi, China, in 1978. He received B.E. and Master degrees in engineering from Xi’an Jiaotong University, Xi’an, China, in 2000 and 2004, respectively. He is currently a Ph.D. student of the Electrical Engineering School in Xi’an Jiaotong University. His current research areas are industrial intelligent control and data mining.

Gangquan Si was born in Shandong, China, in 1980. He received B.E. and Master degrees in engineering from Xi’an Jiaotong University, Xi’an, China, in 2002 and 2005, respectively. He is currently a Ph.D. student of the Electrical Engineering School in Xi’an Jiaotong University. His current research areas are industrial intelligent control and information fusion.

Yanbin Zhang was born in Shaanxi, China, in 1952. He is a Professor and doctoral supervisor at Xi’an Jiaotong University. He is currently the Dean of the Department of Industrial Automation and the Chair of the Industrial Computers Committee of China Computer Federation. He devotes himself to research concerning the development and the application of industrial intelligent control. He won the second prize of National Technical Invention Award 1 time and the Science & technology Award at provincial level two times. He has authored or coauthored over 60 scientific and technical papers and has also authored five books.

Xikui Ma was born in Shaanxi, China, in 1958. He received the B.Sc. and M.Sc. degrees in electrical engineering from Xi’an Jiaotong University, Xi’an, China, in 1982 and 1985, respectively. In 1985, he joined the Faculty of Electrical Engineering, Xi’an Jiaotong University, as a Lecturer, and became a Professor in 1992. He is currently the Vice Dean of the Faculty of Electrical Engineering and the Chair of the Electromagnetic Fields and Microwave Techniques Research Group. During the 1994–1995 academic year, he was a Visiting Scientist with the Power Devices and Systems Research Group, Department of Electrical Engineering and Computer, University of Toronto. He has authored or coauthored over 140 scientific and technical papers and has also authored five electromagnetic fields books. His main areas of research include electromagnetic field theory and its applications, analytical and numerical methods in solving electromagnetic problems, the field theory of nonlinear materials, modeling of magnetic components, chaotic dynamics and its applications in power electronics, and the applications of digital control to power electronics. He has been actively involved in over 15 research and development projects. Prof. Mawas the recipient of the 1999 Best Teacher Award presented by Xi’an Jiaotong University.

Jingcheng Wang was born in GanSu, China, in 1980. He received B.E. and Master degrees in engineering from Xi’an Jiaotong University, Xi’an, China, in 2004 and 2007, respectively. He is currently a Ph.D. student of the Electrical Engineering School in Xi’an Jiaotong University. His current research areas are industrial intelligent control and information fusion.