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An Intelligent Switching Control for the Intervals of Concentration and Flow-rate of Underflow Slurry in a Mixed Separation Thickener

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Abstract: The mixed separation thickening process (MSTP) of hematite beneficiation is a strong nonlinear cascade process where the input is the underflow slurry pump speed and the outputs are the inner loop underflow slurry flow-rate (USF) and the outer loop underflow slurry concentration (USC). During its operation, some large random disturbances generated from the flotation middling would cause the underflow slurry flow-rate (USF) to fluctuate frequently, making it outside the technologically specified range. This would decrease the flotation time and cause the unexpected level fluctuations of flotation machines, leading to the deterioration of the concentration grade. In this paper, a cascade control structure based upon the USC and USF intervals is proposed for such an un-modellable nonlinear cascade process, where the fuzzy control, rule-based reasoning, switching control and cascade control are combined together. A novel intelligent switching control method is established that includes a USF presetting unit via system static model, a fuzzy reasoning based USF set-point compensator, a maintainer of USF set-point and a switching mechanism using rule based reasoning. The successful application to a real hematite concentration plant has shown the effectiveness of the proposed method. In particular, the real application has shown that the proposed method can ensure the USC, the USF and the fluctuation of its rate of change within their target ranges when the process is subject to the flotation middling random disturbance. As a result, the concentration grade has been much improved.

Keywords: Mixed separation thickening process; intervals cascade control; intelligent switching control, fuzzy control

1. INTRODUCTION

The separation thickening process is mainly used to condense the concentrate pulp and control the underflow slurry concentration within its specified range (Ghose, & Sen, 2001). The thickening process, with the underflow slurry bump speed as input, the USF as the inner-loop output and the USC as the outer-loop output, is a strong nonlinear cascade process. Since the thickening process is nonlinear and the mathematical model is difficult to be established, how the slurry concentration is controlled becomes a challenging issue. In this context, cascade control method has been suggested for the single separation thickening process in a gold mine in American, with the underflow slurry bump speed as input, the USF as the inner-loop output and the USC as the outer-loop output. An expert control method was used in the outer loop to ensure the USC to track its set-point (Schoenbrun, Hales, & Bedelll. 2002). Also, a fuzzy control method was used in outer loop for a single separation thickening process of a copper mine (Segovia, Concha, &Sbarbaro. 2011). Furthermore, an intelligent control method based on rule-based reasoning was proposed in the outer loop for a bauxite processing plant (Sidrak. 1997; Diehl. 2008).

Due to the characteristics of low grade, fine-grained and non-homogenous distribution particles of hematite ore, a magnetic-thickening-flotation separation process must be employed to obtain high concentrate grade. Although the above methods (Schoenbrun, Hales, & Bedelll. 2002; Segovia, Concha, &Sbarbaro. 2011; Sidrak. 1997; Diehl. 2008) can control the USC within its target range, the USF fluctuates seriously in response to the large undulations of the flotation middling and the rinse water generated by flotation processes (Shean, & Cilliers. 2011; Maldonado, Araya, & Finch. 2011). This would shorten the flotation time and make the slurry level fluctuate, and then lead to the unexpected reduction of the concentration grade at the end of the production.

In this paper, for the above strong nonlinear cascade process that is difficult to model, an interval cascade intelligent switching control method based upon the USC and USF intervals is proposed by combining the fuzzy control, rule-based reasoning, switching control and cascade control. The proposed method has been successfully applied to a thickening process in a large-scale hematite beneficiation plant in China. The application results show that the USC, the USF and its rate fluctuation have been controlled within their desired ranges, where satisfactory control effect has been achieved.

This paper is organized as follows. The control problem description is given in section 2. This is then followed by section 3, where control method is developed. In section 4, an industrial application of the proposed method is presented. Finally, some concluding remarks are made in section 5.

2. CONTROL PROBLEM DESCRIPTION

2.1 Control objectives

The mixed separation thickening process of hematite beneficiation is as shown in Fig. 1. The concentrate slurry of low concentration generated by the magnetic separation flows into the thickener via flow-rate q_3 . The high concentration slurry can thus be obtained at the bottom of thickener by regularly stirring of rake. In this context, the underflow slurry concentration y_2 can be controlled within its desired range by adjusting the pump speed u that enables the slurry via flow-rate y_1 to enter the flotation machine. The low grade and concentrated flotation middling and rinse water is then discharged from the flotation process via flow-rate q_1 and q_2 , respectively. This makes the underflow slurry flow-rate fluctuate frequently. As such, improving the concentration grade and metal recovery rate requires the flotation time and the slurry level of flotation machine to be as steady as possible. This means that the USC y_2, the USF y_1 and the fluctuation of its rate of change are required to be controlled within their target ranges.

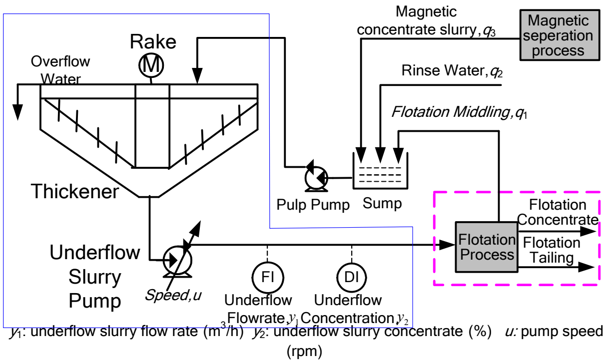

Fig. 1. The structure of mixed separation thickener

To summarize, the control objectives of mixed separation thickening are as followes,

1) the underflow slurry concentration is kept within its specified range, i.e.,

$$y_{2\min} < y_2(k) < y_{2\max} \tag{1}$$

where $y_{2\max}$ and $y_{2\min}$ are the technologically specified upper and lower limits of the underflow slurry concentration, respectively, and k denotes the sample time.

2) the flow-rate of the underflow slurry is controlled within its specified range, i.e.,

$$y_{1\min} < y_1(k) < y_{1\max} \tag{2}$$

where $y_{1\max}$ and $y_{1\min}$ are the technologically specified upper and lower limits of the underflow slurry flow-rate, respectively.

3) the variations of the slurry flow-rate should be made as small as possible, so that

$$|y_1(k) - y_1(k-1)| \le \delta \tag{3}$$

where δ is an upper limit which depends on technology parameters.

Therefore, the control task of the thickening process in hematite beneficiation is to design a controller with pump speed u as input variable, the flow-rate of underflow slurry y_1 and slurry concentration y_2 as output variables. Such a controller should simultaneously ensure that the underflow slurry concentration y_2 and the underflow slurry flow-rate y_1, together with the fluctuation of its rate of change, are all within their target ranges by adjusting the pump speed u when the random disturbance of flotation middling happens.

2.2 The analysis of dynamic characteristics

Based upon the results presented in literature (Kim, & Klima. 2004; Yale, & Zheng. 2003), a dynamic model with the underflow pump speed u as the input and USF y_1 and USC y_2 as the outputs can be established to give,

$$\dot{y}_1(t) = -\frac{y_1(t)}{\tau} + \frac{k_0}{\tau} u(t) \tag{4}$$

$$\begin{aligned}\dot{y}_2(t) = \frac{1}{k_2 h(y_1, y_2)} \Big(& \frac{-y_2{}^2(t) y_1(t)}{y_2(t) + k_3 v(t) + k_3 Q} + k_1 v_p(y_1, y_2, v)(v(t) + Q) \\ & + \frac{k_1(k_i - k_3) v_p(y_1, y_2)(v(t) + Q)}{y_2(t) + k_3(v(t) + Q)} \Big)\end{aligned} \tag{5}$$

where $k_1 = Ak_i$, $k_2 = Ap$, $k_3 = k_i - \mu(\rho_s - \rho_l) / Ap$, $v_p(y_1, y_2)$ is the sedimentation speed of the slurry particles; $h(y_1, y_2)$ is the height of mud layer interface; μ, p, ρ_s, ρ_l are constants related to slurry properties; k_i and A are constants related to the structure of the thickener. In (4)-(5) $Q = q_3 \varphi_3$, where φ_3 is the concentrate slurry from magnetic separation and $v(t)$ is the disturbance given by,

$$v(t) = q_1(t)\varphi_1(t) + q_2(t)\varphi_2(t) \tag{6}$$

where φ_1 is the concentration of the flotation middling slurry and φ_2 is the concentration of rinse water.

Equation (5) can be simplified to give $\dot{y}_2(t) = F(y_1, y_2, v, v_p, h)$, where F represents the nonlinear characteristics. It can be seen from (5) that the relationship between the concentration and the flow-rate of the underflow slurry is nonlinear and the model coefficients (i.e., $v_p(y_1, y_2)$ and $h(y_1, y_2)$) are in fact an unknown nonlinear function related to y_1 and y_2.

When the control system for underflow slurry concentration is in a steady state under the cascade control, the slurry concentration tracks its set-point y_{2ref} , and the derivative of slurry concentration can be approximated as $\dot{y}_2(t) \approx 0$. It can be obtained from (5) that,

$$y_1(t) = \frac{k_i A v_p(\cdot) v(t) + k_i A Q v_p(\cdot)}{y_{2ref} - k_i v(t) - k_i Q} \tag{7}$$

For single separation thickening process, there is no disturbance $v(t)$. According to (7), $y_1(t)=\dfrac{k_i A v_p(\cdot)Q}{y_{2ref}-k_iQ}$. The concentrate slurry Q is steady. Therefore, the flow-rate is also steady.

For the mixed separation thickening process, it can be seen from (7) that $y_1(t)$ varies along with the changes in the disturbance $v(t)$. Since the middling slurry in the flotation process varies frequently and its maximum variation can be over 60% of the concentrate slurry of the magnetic separation process, the flow-rate of the underflow slurry might exceed its target range. This often leads to the flow-rate and its rate of changes exceeding their target ranges. As a result, the necessary flotation time is shortened and the slurry level fluctuates. Moreover, this also causes unexpected reduction of the concentrate grade in the end of the production.

Based on the analysis of the control objectives and the dynamic characteristics, it can be concluded that the mixed separation thickening process is a nonlinear cascade process that is difficult to model and being subject to random disturbances. It requires the outer-loop output, the inner output and its rate of changes to be within their target ranges simultaneously. Therefore, the existing cascade control method is difficult to be applied directly. At present, the mixed separation thickening process still adopts a control method that combines the manual operation with the flow-rate PI control, as shown in Fig. 2.

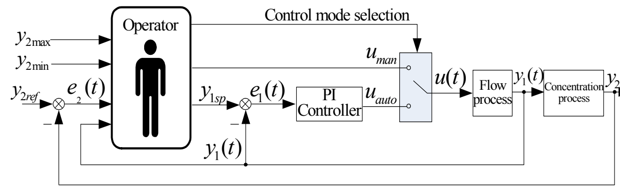

Fig. 2. The existing manual-based control status of MSTP

When the system is subject to large disturbances $v(t)$, such a manual operation cannot realize a precise switching between manual and PI control modes. This would cause the concentration and the flow-rate of slurry to often exceed their target ranges and then to affect the final concentration grade and the metal recovery rate.

3. CONTROL METHOD

3.1 The proposed control structure

Based upon the analysis of dynamic characteristics, and taking into account the fact that the control objectives of the USC and the USF are for their intervals, an interval cascade control structure of the USC and the USF is proposed as shown in Fig. 3 and Fig. 4. It consists of the outer-loop namely the intelligent switching control of the flow-rate set-point and the inner-loop that realizes a good tracking with respect to the set-point. The outer-loop includes the USF presetting, the compensator of the USF set-point, the maintainer of the USF set-point and the switching mechanism. The inner-loop is realized by a PI controller.

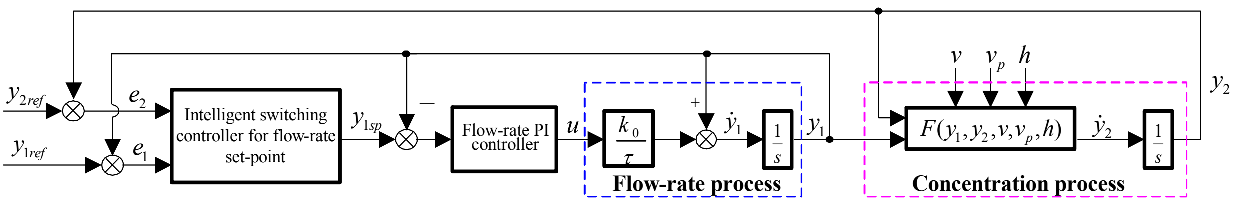

Fig. 3. The cascade control structure for underflow concentration and flow-rate intervals of MSTP

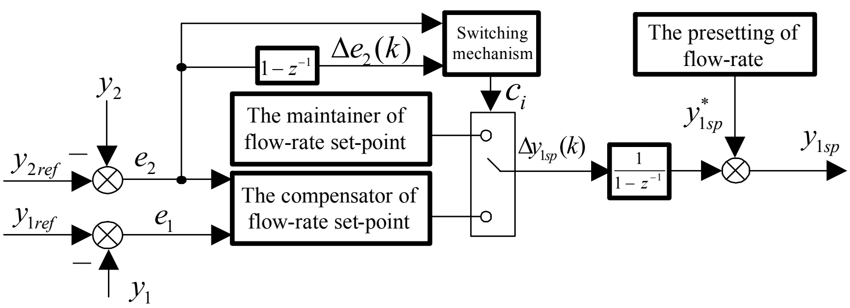

Fig. 4. The intelligent switching control structure for underflow flow-rate set-point

The function of each part is described as follows,

The presetting of the USF: In this part, the reference values y_{2ref} of the slurry concentration is selected as

$y_{2ref} = (y_{2\max} + y_{2\min})/2$, so that the concentration is controlled as much as possible within its target range. This module generates the initial set-point value y^*_{1sp} for the slurry flow-rate using the steady state model obtained by substituting y_{2ref} into (7).

The compensator of the USF set-point: In this part, the reference values y_{1ref} of the slurry flow-rate is selected as $y_{1ref} = (y_{1\max} + y_{1\min})/2$, so that the flow-rate is controlled as much as possible within its target range. Using the reference value y_{2ref}, the slurry concentration y_2, the slurry flow-rate reference value y_{1ref} and the slurry flow-rate y_1, the error signals $e_1(k) = y_{1ref} - y_1(k)$ and $e_2(k) = y_{2ref} - y_2(k)$ can be obtained respectively. Then, this module uses $e_1(k)$ and $e_2(k)$ as the inputs to obtain the compensated value $\Delta y_{1sp}(k)$ for the set-point of the slurry flow-rate using fuzzy reasoning. This leads to the final compensated set-point of the slurry flow-rate as $y_{1sp}(k) = y^*_{1sp} + \sum_{i=1}^{k} \Delta y_{1sp}(i)$, so that the concentration and the flow-rate of slurry are both controlled inside their target ranges.

The maintainer of the USF set-point: This module ensures that $\Delta y_{1sp}(k) = 0$ (i.e., $y_{1sp}(k) = y_{1sp}(k-1)$)

The switching mechanism: The purpose of this module is to use $e_2(k)$ and its rate of changes $\Delta e_2(k)$ to realize the effective switching between the compensator of the USF set-point and the maintainer of the USF.

Accordingly, the PI controller for the slurry flow-rate is used to ensure that the actual flow-rate follows its set-point $y_{1sp}(k)$, so that the concentration and the flow-rate, as well as the variation of the flow-rate, are all controlled well within their target ranges.

3.2 Intervals intelligent switching control algorithms

The intelligent switching control algorithm for the flow-rate set-point consists of the flow-rate presetting based upon the steady state model, the flow-rate set-point compensator based upon fuzzy reasoning, the maintainer of the flow-rate set-point and the switching mechanism using rule-based reasoning. The algorithm of each part is as follows.

1).The presetting algorithm of the USF

The set-point for USF is selected as y_{2ref}. When the slurry concentration is at its steady state, it can be obtained from (4) that,

$$y^*_{1sp} = \frac{k_i A v_p (\overline{v} + Q)}{y_{2ref} - k_i (\overline{v} + Q)} \tag{8}$$

where k_i and A are coefficients related to the thickener; v_p, $\overline{v}$ and Q are the particle flotation speed of slurry, the solid slurry content in flotation process and the solid slurry content in magnetic separation phase, respectively. These values can be determined by on-site laboratory experiment.

2). The flow-rate set-point compensation algorithm based upon fuzzy reasoning

Referring to the previous works (Fileti. Et al. 2007; Zheng, Zhao, & Wei. 2009; Precup, & Hellendoorn. 2011) and the actual process analysis, the fuzzy compensation algorithm is proposed as shown in Fig. 5, including fuzzification of e_1 and e_2, fuzzy reasoning of compensator U_i and defuzzification to solve $\Delta y_{1sp}(k)$.

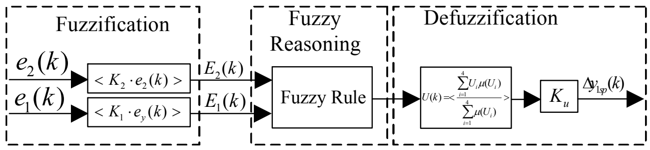

Fig. 5. The compensation algorithm structure for the flow-rate set-point

A. Fuzzification of e_1 and e_2

In this part, the upper limit α of the flow-rate error is selected as $(y_{1\max} - y_{1\min})/2$. The upper limit β of the concentration error is set to $(y_{2\max} - y_{2\min})/2$. By denoting quantization factors of { e_1, e_2 } as { K_1, K_2 }, $K_1 = n/\alpha$, $K_2 = n/\beta$ and with the domain upper limit of fuzzy subsets given by $n = 6$, the inputs to the fuzzy controller (i.e., $E_1(k)$ and $E_2(k)$) are given by

$$E_1(k) = < K_1 . e_1(k) >$$

$$E_2(k) = < K_2 . e_2(k) >$$

where symbol $< \ >$ denotes the rounding operator.

B. Fuzzy reasoning of compensator U_i

There are 7 fuzzy subsets established on the universes of E_1 and E_2 which represent negative big (NB), negative middle (NM), negative small (NS), zero (ZE), positive small (PS), positive middle (PM), and positive big (PB). The symmetrical triangular-shaped membership functions of E_1 and E_2 are selected in line with real time requirements. The membership function of compensator U_i adopts the singleton membership function. The above membership functions are shown in Fig. 6.

The fuzzy rule base contains 49 rules established through experiments as shown in Table. 1. The compensator U_i is obtained via fuzzy reasoning by using fuzzified error E_2 and E_1.

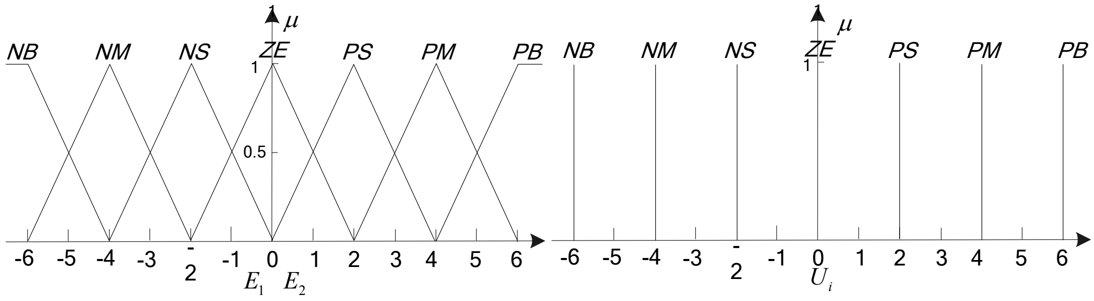

Fig. 6. The membership functions of E_1, E_2 and U_i

Table 1. The fuzzy reasoning rule base for $\Delta y_{1sp}(k)$ of flow-rate

U		E_2						
		PB	*PM*	*PS*	*ZE*	*NS*	*NM*	*NB*
E_1	*PB*	*ZE*	*PS*	*PS*	*PM*	*PM*	*PB*	*PB*
	PM	*NS*	*ZE*	*PS*	*PS*	*PM*	*PM*	*PB*
	PS	*NS*	*NS*	*ZE*	*ZE*	*PS*	*PM*	*PM*
	ZE	*NM*	*NS*	*NS*	*ZE*	*PS*	*PS*	*PM*
	NS	*NM*	*NM*	*NS*	*ZE*	*ZE*	*PS*	*PS*
	NM	*NB*	*NM*	*NM*	*NS*	*NS*	*ZE*	*PS*
	NB	*NB*	*NB*	*NM*	*NM*	*NS*	*NS*	*ZE*

The membership of E_1 and E_2 is $\mu(E_1)$ and $\mu(E_2)$, respectively, according to Fig. 6. Correspondingly, four rules can be obtained from Table 1. For example, when $E_1(k)=5$, $E_2(k)=-3$, E_1 belongs to PM and PB, respectively, while E_2 belongs to NS and NM, respectively. Thus, the followed rules can be obtained from Table. 1.

1) IF E_1 is PM and E_2 is NS THEN U_1 is PM

2) IF E_1 is PM and E_2 is NM THEN U_2 is PM

3) IF E_1 is PB and E_2 is NS THEN U_3 is PM

4) IF E_1 is PB and E_2 is NM THEN U_4 is PB

For the above 4 fuzzy rules, the fuzzy subset of compensator can be obtained. Thus, corresponding eigenvalues $U_i(i=1,2,3,4)$ can be given from Fig. 6. The membership of U_i is $\mu(U_i)=\min(\mu(E_1),\mu(E_2))$, where $\mu(E_1)$ and $\mu(E_2)$ is membership of fuzzy subset corresponding to E_1 and E_2, respectively.

C. Defuzzification

The crisp solution of compensator U_i can be obtained to read:

$$U(k) = < \frac{\sum_{i=1}^{4} U_i \mu(U_i)}{\sum_{i=1}^{4} \mu(U_i)} > \tag{9}$$

The output $\Delta y_{1sp}(k)$ of the set-point compensator can be obtained from:

$$\Delta y_{1sp}(k) = U(k) \times K_u \tag{10}$$

In order to ensure that the fluctuation of the flow-rate meet the control objective (3), one can adopt $K_u = \delta / U_{\max}$ and $U_{\max} = Max(|U_i|)(i=1,2,3,4)$, thus $|U(k)| \le U_{\max}$ and then $|\Delta y_{1sp}(k)| \le \delta$ according to (9).

Finally the set-point value of USF $y_{1sp}(k)$ at the current time can be calculated as:

$$y_{1sp}(k) = y_{1sp}^{*} + \sum_{i=1}^{k} \Delta y_{1sp}(i) \tag{11}$$

3). Switching mechanism based on rule-based reasoning

The "If <*premise*> then <*conclusion*>" rule-based reasoning (Li, Shue, & Shiue. 2000; Lin, Tseng, & Teng. 2008) is used in this paper. The "*premise*" variables are $e_2(k)$ and $\Delta e_2(k)$.

Their limits ε is determined through experiment. Indeed, when the error of the slurry concentration $|e_2(k)| > \varepsilon$ and $e_2(k) \cdot \Delta e_2(k) > 0$, the compensator of the USF set-point is switched on so as to obtain the compensated value $\Delta y_{1sp}(k)$ for the slurry flow-rate. On the other hand, when the concentration error $|e_2(k)| \le \varepsilon$ or $|e_2(k)| > \varepsilon$ with $e_2(k) \cdot \Delta e_2(k) \le 0$, the maintainer of the USF is switched on.

Finally the PI controller is designed using Z-N method given in (Lequin, et al. 2003).

4. INDUSTRIAL APPLICATION

4.1 Parameter selection of the controller

The proposed control method has been applied to the mixed separation thickening process of a hematite concentration plant in China, as displayed in Fig. 7. This process consists of the thickener (of type HRC25/2 with the diameter 25m and the depth 9.5m), a rake (with driving motor power of 5.5 KW) and the underflow pump (of type 300ZJ-I-A56 with the motor power 75 kw).

Fig. 7. The mixed separation thickening process

The upper and lower limitations of USC and USF are given as $y_{1\max} = 420$ m^3/h, $y_{1\min} = 340$ m^3/h, $y_{2\max} = 35\%$ and $y_{2\min} = 31\%$, respectively. The fluctuation upper value of USF is set to $\delta = 20$ m^3/h. The purpose is to achieve the following

$$31 \le y_2(k) \le 35 \tag{12}$$

$$340 \le y_1(k) \le 420 \tag{13}$$

$$|y_1(k) - y_1(k-1)| < 20 \tag{14}$$

Based on the upper and lower limitation of the USC and the UCF, the reference value of USC is determined as $y_{2ref} = (0.31+0.35)/2 = 0.33$ and the reference value of USF is selected as $y_{1ref} = (340+420)/2 = 380$ m^3/h. The presetting of the USF is calculated to give y_{1sp}^* =368.4m^3/h according to (8). Then the maximum deviation of USC is given by $\alpha = (0.35-0.31)/2 = 0.02$. The universe of the deviation $e_2(k)$ of USC is defined by $[-0.02, 0.02]$ and the quantification factor is given by $K_2 = 6/0.02$. Moreover, the maximum deviation of USF is given by $\beta = (420-340)/2 = 40$ m^3/h and the universe of the deviation $e_1(k)$ of USF is $[-40, 40]$ with the quantification factor being set to $K_1 = 6/40$. The mean value of the inlet slurry total flow-rate is 610m^3/h when USC is stable. Since the maximum fluctuation value of USF is 20m^3/h, the universe of Δy_{1sp} is calculated as [-20,20] with the scale factor K_u =20/6.

The well-known Z-N method is used to design the PI controller for USF and this leads to the proportional gain as $K_p = 1.5$ and integration time as $T_i = 0.4$. The sampling period is selected as $T_1 = 1s$.

4.2 Industrial application effectiveness analysis

The controller of the USC and USF intervals is designed by adopting the proposed control method. On the basis of simulation studies (Li, Chai, & Zhao. 2014), a control software is developed. Moreover, the computer control system of the mixed separation thickening process is designed. The hardware of control system is shown in Fig. 8. The system consists of three sets of CLX distributed control systems, two sets of operator stations of RSView32 and one multimedia monitor station. The system has also the corresponding instruments, electrical equipments and actuator such as the AB-PowerFlex 70 transducer, etc.

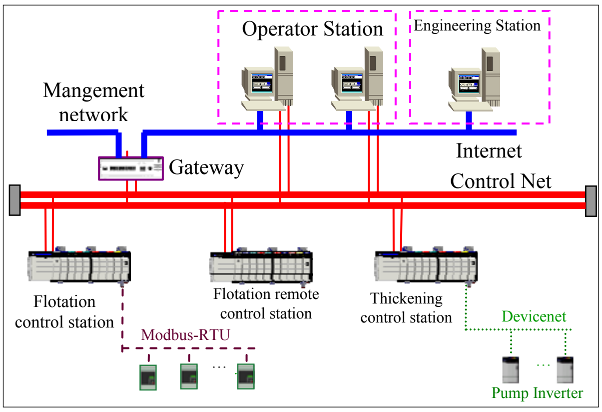

Fig. 8. Control system hardware platform for MSTP

The software includes one set of PLC programming software (RSLogix5K), one set of PC configuration software (RSView32) and one set of communication software (RSLinx). It also has one set of network planning software (RSNetwork) and the corresponded computer operation system. In line with the structure of the mixed separation thickening process and the status of its equipments, a human machine interface is designed as shown in Fig. 9.

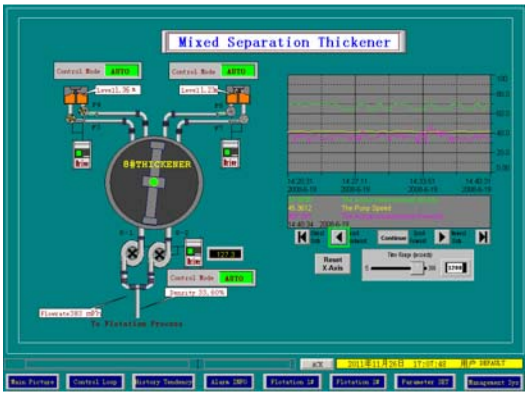

Fig. 9. Human machine interface of MSTP

Before the computer control system is applied, this process has been in a manual control mode. The historical responses of USF, its set-point and USC are shown in Fig. 10.and Table 2.

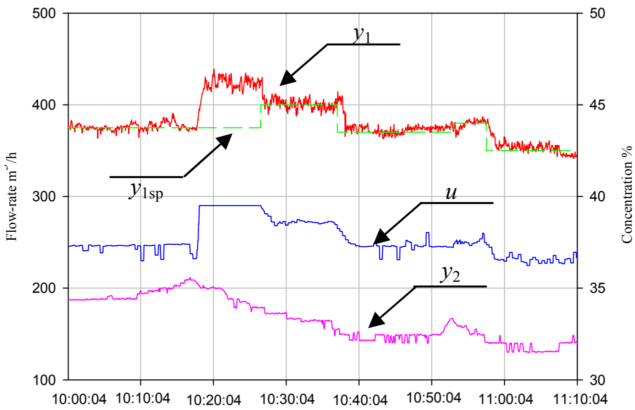

Fig. 10. The responses of y_1 and y_2 using manual control

Table 2. Operating states by manual regulation

	y_1 (m^3/h)	$\lvert \Delta y_{1sp} \rvert$ (m^3/h)	y_2 (%)
Min	345.2	5	31.5
Max	439.4	49	35.34

The historical responses show that USC increases from 33.2% to 33.9% at the time 10:17 because of a large random disturbance generated by the flotation middling. This has exceeded the region of USC (32.5%-33.5%). As a result, the on-site operator adjusted the set-point of USF from 375m3/h to 400 m3/h empirically. When USC decreases to 31.8% at 10:36, the on-site operator changed the set-point of USF from 400m3/h to 340m3/h empirically. It can be seen that USC and USF fluctuate largely as the manual control could not adjust the set-point of USF timely and accurately according to the deviation of USC. During time interval [10:18, 10:42], USC changed from 31.8% to 34.05%. Also, during time interval [10:16, 10:24], USF changed from 365 to 439 m3/h, where the maximum value of USF is 439 m3/h which exceeded the maximum specified value of 420 m3/h and the maximum flow-rate of 49 m3/h was beyond its upper value 20 m3/h.

By adopting the proposed intelligent switching control method, a fully automated control has been realized as shown in Fig. 11 and Table 3.

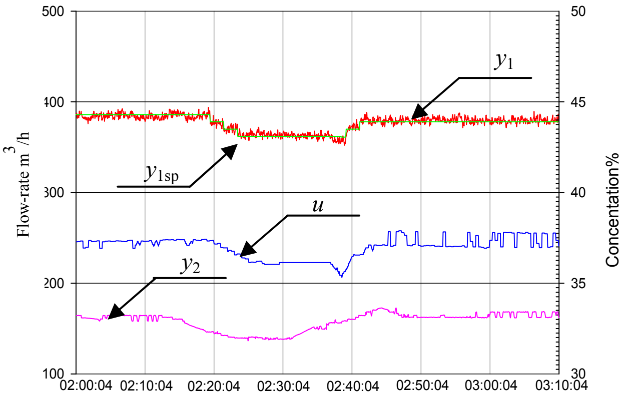

Fig. 11. The responses of y_1 and y_2 using the proposed method

Table 3. Operating state with the proposed method

	y_1 (m^3/h)	$\lvert \Delta y_{1sp} \rvert$ (m^3/h)	y_2 (%)
Min	358.4	5	31.9
Max	396.7	12	33.7

Fig. 11 shows that the values of USC are between 32.7% and 32.9%, which are well inside the specified small range defined by $32.5\% < y_2(t) < 33.5\%$. In this case, the set-point of USF y_{1sp} =386.21m^3/h is not adjusted and the PI controller of USF can track the set-point. At 02:18, USC detected by control system is 32.12% and USF is 372.61m^3/h, where the USC deviation is $e_2(k) = 0.88$ corresponding to the fuzzy universe $E_2(k) = 3$ and USC deviation is $e_1(k) = 7.39$ corresponding to $E_2(k) = 1$. Using the proposed control strategy, the incremental value of USF set-point through the fuzzy controller can be obtained to give $\Delta y_{1sp} = -6$. At last, the set-point of USF can be obtained as $y_{1sp}(k) = 386 - 6 = 380$ m^3/h. At 02:30, USF was not adjusted as USC was moved back to the range of $32.5\% \le y_2(t) \le 33.5\%$ and the controller tracked the set-point of USF by adjusting the underflow pump speed through PI controller. Therefore, USC and USF are both inside their targeted ranges.

From the responses in Fig. 10, Fig. 11, Table 2 and Table 3, it can be concluded that the proposed intelligent switching control method of USC and USF is superior to the manual control.

In order to evaluate the proposed control method against manual operation, the concentrate grade and the metal recovery rate of 8 months before and after the control system was put into operation have been obtained. The average values of the concentration grade and the metal recovery rate are shown in Table 4. It has also been observed that the flotation concentrate grade has been increased from 60.69% to 60.82%, with improvement of 0.13%, when the metal recovery rate is fixed.

Table 4. Comparison of the performance of MSTP

	Before put into operration	After put into operation
Concentrate grade (%)	60.69	60.82
Metal recovery rate (%)	93.98	93.97

5. CONCLUSIONS

This paper has presented a new intervals cascade intelligent switching control method for a mixed separation thickening process. The controller is composed of the outer-loop (i.e., the intelligent switching control of flow-rate set-point) and the inner-loop (i.e., the tracking control flow-rate set-point), where the former consists of the flow-rate presetting based upon the steady state model, the fuzzy reasoning based compensator of the USF, the set-point maintainer of the USF and the switch mechanism based upon the rule-based reasoning. It has been shown that the proposed intelligent switching control method can sufficiently utilize the variation range of the USC and the USF to reduce the variations of the USF set-point by effective switching between the maintainer and the compensator. As a result, the fluctuations of the set-point are constrained within their target ranges. The real industrial application result has shown that the proposed method can control the USC, the USF and its rate fluctuation within their target ranges when the process is subject to the flotation middling random disturbance. The concentration grade has been well improved. It can also be concluded that the proposed control method provides a novel framework that can be used to control nonlinear cascaded systems so that the outputs of inner and outer loops as well as their fluctuations can be controlled well inside their targeted ranges when the system is subject to random disturbances.

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References

Diehl, S.A. (2008). Regulator for Continuous Sedimentation in Ideal Clarifier–Thickener Units [J]. *Journal of Engineering Mathematics*, 60(3-4): 265-291.

Fileti, A.M.F., Antunes, A.J.B., Silva, F.V., Silveira, J., and Pereira, J.A.F.R. (2007). Experimental Investigations on Fuzzy Logic for Process Control [J]. *Control Engineering Practice*, 15(9): 1149-1160.

Ghose, M.K., Sen, P.K. (2001). Characteristics of Iron Ore Tailing Slime in India and its Test for Required Pond Size [J]. *Environmental monitoring and assessment*, 68(1): 51-61.

Kim, B.H., Klima, M.S. (2004). Development and Application of a Dynamic Model for Hindered-Settling Column Separations [J]. *Minerals engineering*, 17(3): 403-410.

Lequin, O., Gevers, M., Mossberg, M., Bosmans, M., Bosmans, E., and Triest, L. (2003). Iterative Feedback Tuning of PID Parameters: Comparison with Classical Tuning Rules [J]. *Control Engineering Practice*, 11(9): 1023-1033.

Li, H.B., Chai, T.Y., and Zhao, D.Y. (2014). Intelligent Switching Control of Underflow Slurry Concentration and Flowrate Intervals in Mixed Separation Thickener [J]. *Acta Automatica Sinica*, (to be published)

Li, S.T., Shue, L.Y., and Shiue, W. (2000). The Development of a Decision Model for Liquidity Analysis [J]. *Expert Systems with Applications*, 19(4): 271-278.

Lin, S.C, Tseng, S.S., and Teng, C.W. (2008). Dynamic EMCUD for Knowledge Acquisition [J]. *Expert Systems with Applications*, 34(2): 833-844.

Maldonado, M., Araya, R., and Finch, J. (2011) Optimizing Flotation Bank Performance by Recovery Profiling [J]. *Minerals Engineering*, 24(8): 939-943.

Precup, R.E., Hellendoorn, H. (2011) A survey on industrial applications of fuzzy control [J]. *Computers in Industry*, 62(3): 213-226.

Schoenbrun, F., Hales, L., and Bedell, D. (2002). Mineral Processing Plant Design, Practice and Control, volume 2, chapter Strategies for instrumentation and control of thickeners and other solid-liquid separation circuits, 2164–2173. SME.

Segovia, J.P., Concha, F., and Sbarbaro, D. (2011). On the Control of Sludge Level and Underflow Concentration in Industrial Thickeners [C]. In *Preprints of 18th IFAC World Congress Milano (Italy)*. 18(1): 8571-8576.

Shean, B.J., Cilliers, J.J. (2011).A Review of Froth Flotation control [J]. *International Journal of Mineral Processing*, 100(3): 57-71.

Sidrak, Y.L. (1997) Control of the Thickener Operation in Alumina Production [J]. *Control Engineering Practice*, 5(10): 1417-1426.

Zheng, Y.Y. (2003). *Mathematical Mode of Anaerobic Processes Applied to the Anaerobic Sequencing Batch Reactor* [D], University of Toronto, 2003.

Zheng, J.M., Zhao, S.D., and Wei, S.G. (2009). Application of Self-Tuning Fuzzy PID Controller for a SRM Direct Drive Volume Control Hydraulic Press [J]. *Control Engineering Practice*, 17(12): 1398-1404.