Control Engineering Practice 57 (2016) 61–71

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

An intelligent switching control for a mixed separation thickener process ☆

Tianyou Chai [a,b,*], Yao Jia [a], Haibo Li [a], Hong Wang [a,c]

[a] State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China
[b] National Engineering Research Center of Metallurgical Automation, Shenyang, China
[c] Control System Centre, The University of Manchester, PO Box 88, Manchester M60 1QD, UK

ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form
3 July 2016
Accepted 4 July 2016

Keywords:
Mixed separation thickening process
Intervals cascade control
Intelligent switching control
Fuzzy control
Unmodeled dynamics compensation
One-step optimal PI control

ABSTRACT

The mixed separation thickening process (MSTP) of hematite beneficiation is a strong nonlinear cascade process. During its operation, some large random disturbances generated from the flotation middling would cause the underflow slurry flowrate (USF) to fluctuate frequently, leading to the deterioration of the concentrate grade. In this paper, a novel intervals intelligent switching control method is proposed. This controller includes a USF presetting unit via a one-step optimal proportional and integral (PI) control with unmodeled dynamics compensation, a fuzzy reasoning based USF setpoint compensator and a switching mechanism using rule based reasoning. Both a simulated experiment and a real industrial application show that the underflow slurry density (USD), the USF and the variation ratio of the USF can all be controlled within their targeted ranges when the proposed control strategy is used.

1. Introduction

The separation thickening process is mainly used to condense the concentrate pulp and control the underflow slurry density (USD) to make sure that it is within its specified range during its operation (Ghose & Sen, 2001). The thickening process, with the underflow slurry pump speed as the input, the underflow slurry flowrate (USF) as the inner-loop output and the USD as the outer-loop output, is a strong nonlinear cascade process. Since the thickening process is nonlinear and the accurate mathematical model is difficult to obtain, the way in which the slurry density is controlled becomes a challenging issue. In this context, a fixed setpoint cascade control method has been proposed for the single separation thickening process with the underflow slurry pump speed as the input, the USF as the inner-loop output and the USD as the outer-loop output (Mular, Barratt, & Halbe, 2002; Diehl, 2008; Segovia, Concha, & Sbarbaro, 2011; Sidrak, 1997). An expert control method was used in the outer loop to ensure that the USD of the single separation thickening process in a gold mine in America tracks its setpoint (Mular, Barratt, & Halbe, 2002). Also, a fuzzy control method was used in the outer loop for a single separation thickening process of a copper mine (Segovia et al., 2011). Furthermore, an intelligent control method using rule-based reasoning was proposed in the outer loop for a bauxite processing plant (Diehl, 2008; Sidrak, 1997).

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 can control the USD within its targeted range, the USF fluctuates strongly in response to the large undulations of the flotation middling generated by the flotation processes and the wastewater (Maldonado, Araya, & Finch, 2011; Shean & Cilliers, 2011). This would shorten the flotation time and make the slurry level fluctuate, and then lead to the unexpected reduction of the concentrate grade at the end of the production. In Li, Chai, and Zhao (2014), an intervals intelligent switching control method of USD and USF has been proposed to overcome the influence caused by the large undulations of the flotation middling and the wastewater. This method generates the pre-setpoint value for the USF using a steady state model. When the disturbance of large variations occurs frequently, it is difficult for the steady state model to generate the appropriate pre-setpoint value. This would cause severe fluctuations between the USF and the USD, leading to the unexpected reduction of the concentrate grade.

Based upon these analysis, a one-step optimal proportional and integral (PI) controller with unmodeled dynamics compensation is

☆This is the extended version of the finalist paper for the IFAC best application paper award at the 2014 IFAC World Congress in Cape Town.

* Corresponding author at: State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China.
E-mail addresses: tychai@mail.neu.edu.cn (T. Chai), jiayao_neu@163.com (Y. Jia), lihbneu@163.com (H. Li), mikewanguk@yahoo.co.uk (H. Wang).

http://dx.doi.org/10.1016/j.conengprac.2016.07.007
0967-0661/

proposed in this paper to generate the pre-setpoint for the USF. A novel intervals intelligent switching control method is established that includes a fuzzy reasoning based USF setpoint compensator and a switching mechanism using rule based reasoning. Both a simulation experiment and an industrial application have demonstrated that the proposed controller can control the USD, the USF and the variation ratio of the USF within their targeted ranges.

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 formulated. The simulation results that compare the proposed method with traditional cascade control method and the control method reported in Li et al. (2014) are presented in Section 4. In Section 5, an industrial application of the proposed method is presented. Finally, some concluding remarks are made in Section 6.

2. Control problem description

2.1. Control objectives

The mixed separation thickening process (MSTP) of hematite beneficiation is shown in Fig. 1, where the concentrate slurry of low density generated by the magnetic separation flows into the thickener at flowrate $q_3(t)$. The high density slurry can thus be obtained at the bottom of the thickener by regular stirring of the rake. In this context, the USD $y_2(t)$ can be controlled within its desired range by adjusting the pump speed $u(t)$ that enables the USF $y_1(t)$ to enter the flotation machine. The low grade and concentrated flotation middling is then discharged from the flotation process and wastewater at flowrates $q_1(t)$ and $q_2(t)$, respectively. This makes the USF fluctuate frequently. As such, improving the concentrate 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 USD $y_2(t)$, the USF $y_1(t)$ and the variation ratio of USF are required to be controlled within their targeted ranges.

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

1) the USD is kept within its specified range, i.e.,

$$y_{2\,\min} \le y_2(T) \le y_{2\,\max}, \tag{1}$$

where $y_{2\max}$ and $y_{2\min}$ are the technologically specified upper and lower limits of the USD, respectively, and T denotes the sample time of the USD;

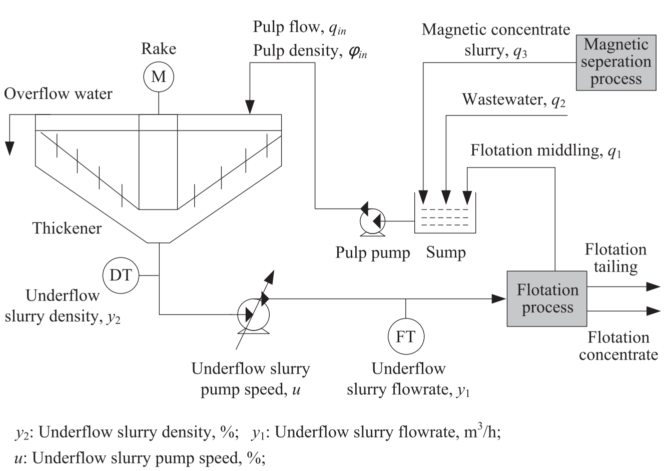

Fig. 1. The structure of MSTP.

2) the USF is controlled within its specified range, i.e.,

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

where $y_{1\max}$ and $y_{1\min}$ are the technologically specified upper and lower limits of the USF, respectively, and k denotes the sample time of the USF;

3) the variations of the USF should be made as small as possible, so that

$$\left|y_1(k) - y_1(k-1)\right| < \delta, \tag{3}$$

where δ is an upper limit which depends on relevant technological parameters.

Therefore, the control task of the MSTP in hematite beneficiation is to design a controller with pump speed $u(k)$ as the input variable and the USF $y_1(k)$ and the USD $y_2(T)$ as output variables. Such a controller should simultaneously ensure that the USD $y_2(T)$, the USF $y_1(k)$ and the variation ratio of USF are all within their targeted ranges by adjusting the pump speed $u(k)$ when the random disturbance of flotation middling happens.

2.2. The analysis of dynamic characteristics

Based upon the results presented in Kim and Klima (2004) and Zheng (2003), a dynamic model with the underflow pump speed $u(t)$ as the input and USF $y_1(t)$ and USD $y_2(t)$ as the outputs can be established to give,

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

$$\dot{y}_2(t) = \frac{1}{k_2 h(y_1, y_2)}\{\frac{-y_2^{\,2}(t)y_1(t)}{y_2(t) + k_3\left[v(t) + Q\right]} + k_1 v_p(y_1, y_2, t)$$
$$\left[v(t) + Q\right], + \frac{k_1(k_i - k_3)v_p(y_1, y_2, t)\left[v(t) + Q\right]}{y_2(t) + k_3\left[v(t) + Q\right]}\} \tag{5}$$

where $k_1 = Ak_i$, $k_2 = Ap$ and $k_3 = k_i\text{-}\mu(\rho_s\text{-}\rho_l)/Ap$, $v_p(y_1, y_2)$ is the sedimentation speed of the slurry particles; $h(y_1, y_2)$ is the height of mud layer interface; μ, p, ρ_s and ρ_l are constants related to slurry properties; k_i and A are constants related to the structure of the thickener. In (4)–(5) $Q = q_3\varphi_3$, φ_3 is the density of the slurry from the 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 density of the flotation middling slurry and φ_2 is the density of wastewater.

Eq. (5) can be simplified to give $dy_2(t)/dt = F(y_1, y_2, v, v_p, h)$, where F represents the nonlinear characteristics. It can be seen from (5) that the relationship between the USD and the USF is nonlinear and the model coefficients [i.e., $v_p(y_1, y_2)$ and $h(y_1, y_2)$] are in fact unknown nonlinear functions related to $y_1(t)$ and $y_2(t)$. As $v_p(y_1, y_2)$ and $h(y_1, y_2)$ are unknown nonlinear functions of $y_1(t)$ and $y_2(t)$, accurate mathematical model cannot be obtained in general.

When the control system for USD is in a steady state under the cascade control, the USD tracks its setpoint y_{2ref}, and the USD can be approximated as $dy_2(t)/dt \approx 0$. It can be obtained from (5) that,

$$y_1(t) = \frac{k_i v_p(\cdot)\left[v(t) + Q\right]}{y_{2ref}^2 p}\{\left[Apk_i - \mu(\rho_s - \rho_l)\right]v(t)$$
$$. + Ap(y_{2ref} + k_i Q) - \mu(\rho_s - \rho_l)(Q - 1)\} \tag{7}$$