CONTROL OF CRUSHING CIRCUITS WITH VARIABLE SPEED DRIVES

Daniel Sbarbaro. *

* *Department of Electrical Engineering, Universidad de Concepción, Concepción, CHILE.*
dsbarbar@die.udec.cl
http:\\www.die.udec.cl.

Abstract: Crushers play an important role in the comminution of minerals and the control of its operation can lead to an increase of the plant throughput and efficiency. This work presents a simple but effective method for controlling a crusher circuit by acting over the feeder and the speed of the conveyor belt carrying out the mineral up to the crusher. Guidelines for tuning the strategy, as well as practical issues, are discussed and illustrated. A detailed simulation of an existing crushing plant is used to test the proposed approach and to compare its performance with existing industrial strategies.

Keywords: Crusher plants, time delay system, selector based control, variable speed drives.

1. INTRODUCTION

After extraction from the ground, minerals must be prepared for direct use or further processing. The first step in the gradual reduction of the hard mineral to fine powder or dust is carried out by a crushing circuit, which is energy demanding and its smooth operation can represent a big increase in the plant throughput. The goal of the automation system, in this context, is to increase the efficiency and productivity, as well as to assist and support the operation with information.

A comprehensive survey of control techniques and models normally used are described in (Lynch, 1977) and (Whiten, 1984). The operation of a crusher can be limited by one or more of the following factors:power availability, feed constraints, product size distribution and physical limits on the ore transport through the crushing chamber. The main measurements available are power, level of the crusher, and in some installation feed tonnage.

The main actuator to maintain the crusher under control is the feed setting. However, nowadays is common to find in many crushing plants variable speed drives driving conveyor belts, this extra degree of freedom provides the opportunity to improve the speed of response of the control system. This work proposes a simple but effective control structure to achieve this objective.

The organization of this paper is as follows: Section 2 describes the model used to test the control strategy. Section 3 presents a simplified model for control design purposes and the controllers. The main characteristics of the proposed approach is illustrated in section 4 by means of simulations.

2. CRUSHER MODELS

A typical cone crusher and the associated equipments ; i.e. feeder, conveyor belt and screens, as it can be found in some of the Chilean concentrators, is depicted in figure 1. Modelling a crusher

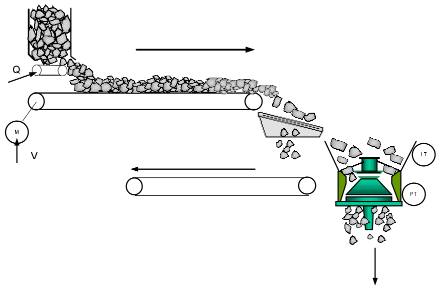

Fig. 1. A crusher and its associated equipments

must consider the different factors affecting the size reduction process and the flow of material through the crushing chamber. Empirical models (Whiten, 1972) (Hatch and Mular, 1982) have been used for simulating crushing plants providing excellent results for operational purposes. On the other hand, there have been few studies on models based on first principles; i.e. mechanic laws (Evertsson, 2000). In this paper, we follow the work done by Whiten (Whiten, 1972), who proposed that size distribution of the crusher discharge could be described by the following mass balance equations:

$$\mathbf{p} = [I - \mathbf{C}][\mathbf{I} - \mathbf{CB}]^{-1}\mathbf{f} \tag{1}$$

where the vectors $\mathbf{p}$ and $\mathbf{f}$ are the products and feed flow rates in each size fraction. The lower triangular matrix $\mathbf{B}$ is the breaking matrix and the diagonal matrix $\mathbf{C}$ is the classification matrix giving the proportion of particles, entering the breakage region. The matrix $\mathbf{B}$ can be broken into two parts as follows:

$$\mathbf{B} = \alpha\mathbf{B}_1 + (1-\alpha)\mathbf{B}_2. \tag{2}$$

The matrix $\mathbf{B}_1$ is associated with the primary breakage, and $\mathbf{B}_2$ is associated with the production of fines. The term α has to be found empirically as function of the operational variables. Here, we consider the following:

$$\alpha = a_o + a_1 T + a_2 S + \frac{a_3}{G} \tag{3}$$

where T is the feedrate, S is the % +1 inch in the crusher feed and G is the crusher close side setting.

The crusher current can be obtained from the vector $\mathbf{Cx}$ which contains no fine particles. The vector $\mathbf{x}$ represents the feeded material plus the material leaving the breakage region. A variable a is defined as:

$$a = \sum \frac{z_i}{s_i + s_{i+1}} \tag{4}$$

where z_i is the i-th element of $\mathbf{Cx}$ and s_i are the upper and lower limits of the i-th fraction. Then the crusher current can be predicted as:

$$A = b_0 + b_1 a + b_2 a^2 + b_3 W_i \tag{5}$$

where W_i is the work index.

The total throughput q_T is calculated as a function of the crusher geometry, speed, ore hardness and the bulk density of the material (Evertsson, 2000). To obtain the level of the material we perform a simple material balance :

$$\frac{dM}{dt} = q_i - q_o \tag{6}$$

with $q_o = q_T$ only if there is some material accumulated in the chamber. Otherwise, if there is no material and $q_i < q_T$, then $q_o = q_i$. The total mass accumulated in the crusher is given by $M = \rho_c V$, where ρ_c is the density calculated as a function of the product size distribution (Evertsson, 2000). The level depends on the geometry of crusher; i.e. it is a nonlinear function of the volume V.

The screen is modelled by the following efficiency curve

$$E(s) = \left[1 - \left(\frac{h-s}{h-d}\right)^2\right]^m \tag{7}$$

where $E(s)$ is the weight fraction of a narrow size range s of feed that reports to oversize, h is the screen opening, d is wire diameter and m is a measure of a number of times that a particle attempts to pass through the screen.

Finally, the model of the conveyor with variable speed belt requires special attention, since the conventional model considering a discretization with respect to the time taking the material to reach its end, leads to a buffer of a given size for a given speed; unfortunately, this approach does not give accurate results when the speed varies. We modelled the conveyor considering a discretization with respect to length of it. The elements of the resulting buffer are updated a number of times according to the speed of the conveyor belt. In this way, a fixed buffer is used in the simulations.

All these elements were programmed as Simulink blocks to ease their use and leave the option for configuring a complete crushing plant.

3. A MODEL FOR CONTROL AND CONTROLLER DESIGN

The model presented in section 2 is too complicated for controller design; therefore, a simpler model is required. In order to have a suitable model for control design we consider a linearized approximation around an operational condition. This model is depicted in figure 2, where the main variables are: the feeder tonnage T, the speed v, the output power p, the level h and the output flow q_o. The screen is modelled as a simple gain k_s. This model also considers the constraints on the input variables.

The standard control structure for this type of system is given in figure 3 (Whiten, 1984). The

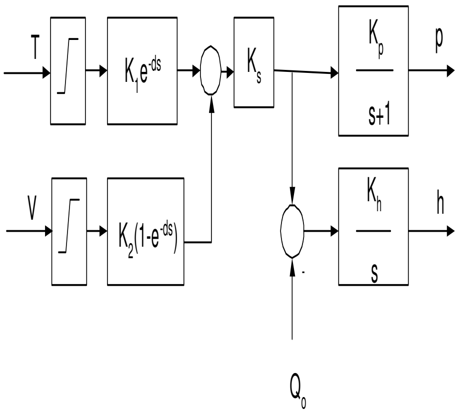

Fig. 2. Simplified Block diagram

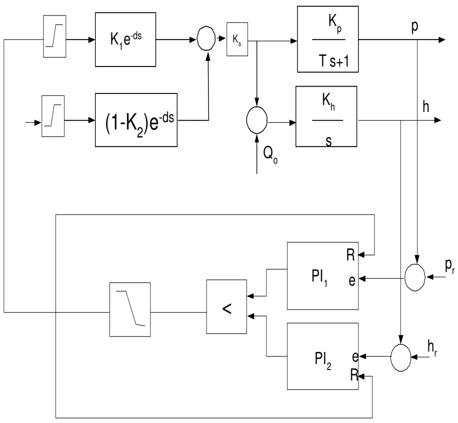

Fig. 3. Block diagram of the standard control structure

main objective is to maintain the crusher chamber always with some mineral inside while keeping the power under safe margins. To accomplish this objective, a classical selector based strategy is used. Normally, if the transport delay associated to the conveyor belt is no significant, a couple of PI controllers will provide a stable operation. The controllers should also consider the appropriate mechanisms to track the current control output.

The controllers PI_1 and PI_2 are described by the following transfer function:

$$PI_1: \quad \frac{u_1(s)}{e_1(s)} = \frac{\alpha_1 s + \beta_1}{s} \tag{8}$$

$$PI_2: \quad \frac{u_2(s)}{e_2(s)} = \frac{\alpha_2 s + \beta_2}{s} \tag{9}$$

From a practical viewpoint, the tuning of both controllers can be carried out by considering the following transfer functions:

$$\frac{p}{p_r} = \frac{k_1 k_p e^{-sd}(\alpha_1 s + \beta_1)}{Ts^2 + s + (\alpha_1 s + \beta_1)k_1 k_p e^{-sd}} \tag{10}$$

$$\frac{h}{h_r} = \frac{k_1 k_h e^{-sd}(\alpha_2 s + \beta_2)}{s^2 + (\alpha_2 s + \beta_2)k_1 k_h e^{-sd}} \tag{11}$$

where p_r and h_r represent the reference signals for power and level respectively. The PI_1 controller can be tuned following the IMC tuning

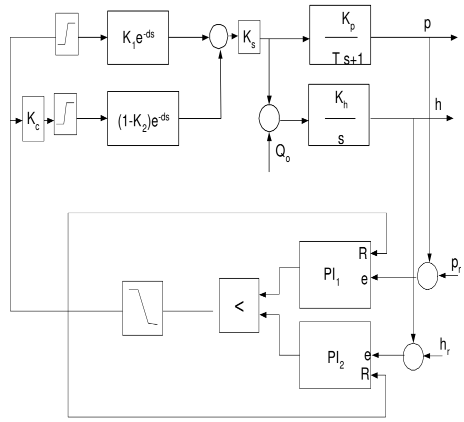

Fig. 4. Block diagram of the proposed control structure

rules (Morari and Zafiriou, 1998) and the PI_2 following the guidelines provided in (Chidambaram and Sree, 2003). In order to verify stability the method described in (Glattfelder and Schaufelberger, 2003) can be used.

The proposed strategy only adds an additional gain; i.e. k_c, to the speed path as shown in figure 4. Notice that the output tracking signals are taken from the output of the feed limiting block, since the feed is the ultimate limiting factor. To look at the effect of this gain, let us write down the closed loop transfer functions for this new configuration:

$$\frac{p}{p_r} = \frac{k_p(\alpha_1 s + \beta_1)(k_1 e^{-sd} + k_c k_2(1 - e^{-sd}))}{Ts^2 + s + k_p(\alpha_1 s + \beta_1)(k_1 e^{-sd} + k_c k_2(1 - e^{-sd}))} \tag{12}$$

$$\frac{h}{h_r} = \frac{k_h(\alpha_2 s + \beta_2)(k_1 e^{-sd} + k_c k_2(1 - e^{-sd}))}{s^2 + k_h(\alpha_2 s + \beta_2)(k_1 e^{-sd} + k_c k_2(1 - e^{-sd}))} \tag{13}$$

Clearly, if $k_c = k_1/k_2$ the dead time is cancelled. Thus, the controllers can be tuned considering nominal transfer functions without delay;i.e. the following closed loop transfer functions:

$$P(s) = \frac{k_p k_2 k_c(\alpha_1 s + \beta_1)}{Ts^2 + s + k_p k_c k_2(\alpha_1 s + \beta_1)} \tag{14}$$

$$H(s) = \frac{k_h k_2 k_c(\alpha_2 s + \beta_2)}{s^2 + k_h k_2 k_c(\alpha_2 s + \beta_2)} \tag{15}$$

In order to analyze when $k_c \neq k_1/k_2$, the term $(k_1 - k_c k_2)e^{-sd}$ can be considered as perturbation. The neglected term $l_m(s)$, associated with the time delay, can be written as:

$$l_m(s) = \frac{k_1 - k_c k_2}{k_2 k_c} e^{-sd}. \tag{16}$$

In order to verify the robustness, the transfer functions $M_p(s)$ and $M_h(s)$ defined as:

$$M_p(s) = P(s)l_m(s) \quad M_h(s) = H(s)l_m(s), \tag{17}$$

must satisfy the Nyquist criteria (Gawthrop, 1987).

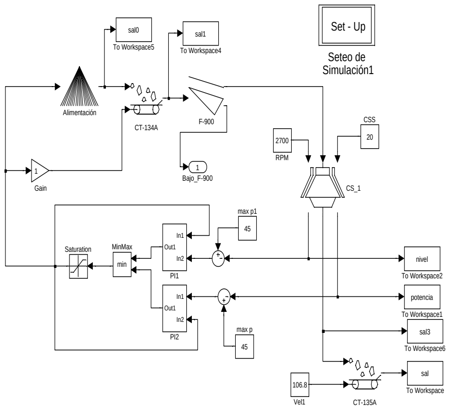

Fig. 5. Simulink model

4. SIMULATION RESULTS

The example considers a crusher system as shown in the simulation set up depicted in figure 4. The parameters of the model were adjusted by considering data from a Chilean concentrator. The length of the conveyor belt is 100 mts, its speed varies between $80 - 160$ mts/min. The nominal tonnage is $1000 ton/h$. The parameters of the crusher and the screen were adjusted using empirical methods and data obtained from sampling campaigns. Five size fractions were considered in the simulations. The parameter of the simplified linear model were obtained from tests applied to the simulator, considering a nominal speed of 100 mts/min and a feed of 600 ton/h.

Figure 8 shows the results obtained for different values of the tuning parameter k_c. For small values, the system presents oscillations due to the effect of the time delay. As the gain increases, better responses are obtained, since the velocity is limited by the saturation nonlinearity further increase in the gain will not produce any changes in the response.

The Nyquist diagram for $M_p(s)$ when $k_c k_2 = \frac{k_1}{2}$ is shown in figure 6; clearly under this condition the closed loop is stable; but looking at the Nyquist diagram for $M_h(s)$,Figure 7, we see that it is necessary to increase the value of k_c in order to reach stability. These diagrams can also be used to analyze, for a given gain, how much time delay can be tolerated without making the system unstable.

The effect of a sudden change in the ore hardness is illustrated in figure 9. Under this situation the feedrate must decrease in order to maintain the power at its upper limit. As seen in figure 10, not only the tonnage is decreased but also the speed. The level loop, then is not active, leaving a steady state error.

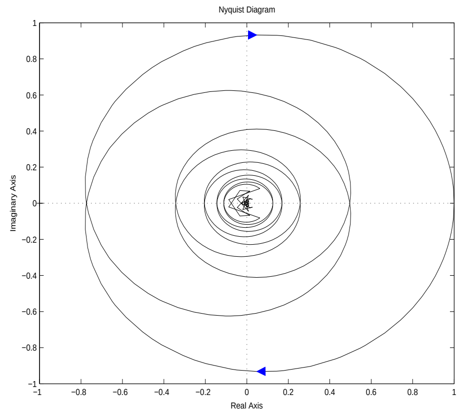

Fig. 6. Nyquist for M_p

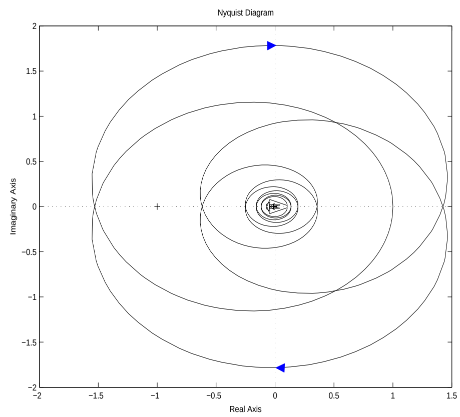

Fig. 7. Nyquist for M_h

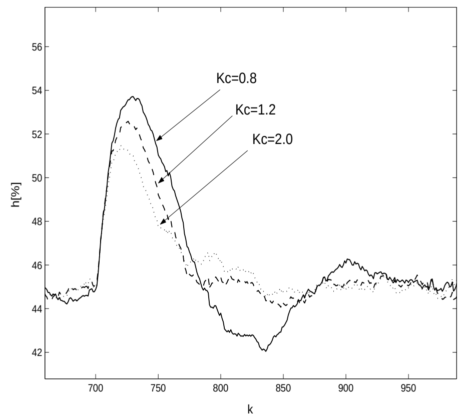

Fig. 8. Simulation results for a change in the feed size distribution

In order to illustrate the benefits of having variable speed drives, Figure 11 shows the response for a system with and without compensation. The tuning of the PI controller must be done conservatively when the system has no variable speed drives in order to consider the effect of time delay.

5. FINAL REMARKS

This paper has demonstrated that the use of variable speed drives can reduce the effects of

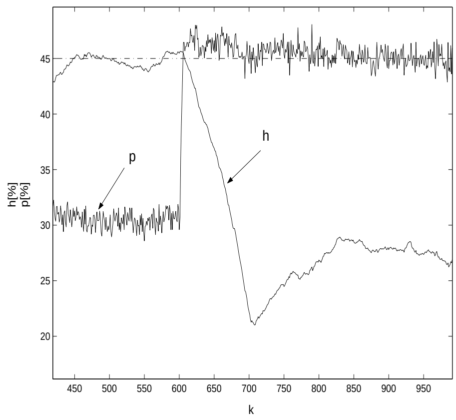

Fig. 9. Simulation results for a sudden change in the ore hardness

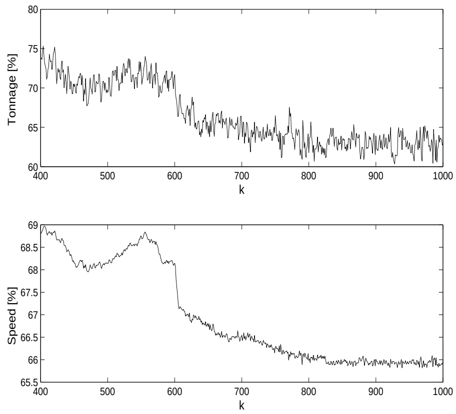

Fig. 10. Tonnage and speed for a sudden change in the ore hardness

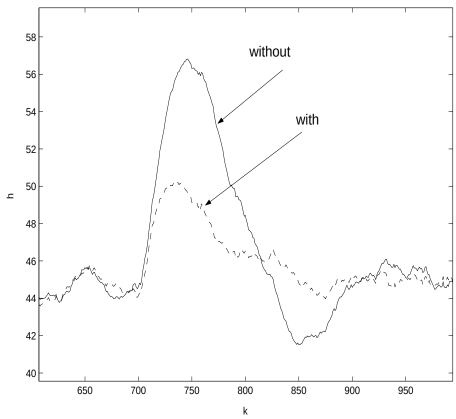

Fig. 11. Closed loop response with and without variable speed drives

time delays normally found in crushing circuits, enabling a much tight control over the relevant variables. Some guidelines on how to tune this strategy and a tool to asses its robustness are also provided. The proposed control structure is based on simple building blocks, which can be easily implemented on Programmable Logic Controller.

REFERENCES

Chidambaram, M. and R. Padma Sree (2003). A simple method of tuning pid controllers for integral/dead-time process. *Computers & Chemical Engineering* (27), 211–215.

Evertsson, C.M. (2000). Cone crusher performance. PhD thesis. Department of Machine and vehicle design, Chalmers University of Technology, Goteborg, Sweden.

Gawthrop, P.J. (1987). *Continuous time self-tuning control*. John Wiley.

Glattfelder, A.H. and W. Schaufelberger (2003). *Control systems with input and output constraints*. Springer.

Hatch, C.C. and A.L. Mular (1982). Simulation of the brenda mine ltd. secondary crushing plant. *Mining Engineering* pp. 1354–1362.

Lynch, A.J. (1977). *Mineral Crushing and Grinding Circuits: Their Simulation, Optimization , Design and Control*. Elsevier.

Morari, M. and E. Zafiriou (1998). *Robust Process Control*. Prentice-Hall.

Whiten, W.J. (1972). The simulation of chrushing plants with models developed using multple spline regression. *Journal of the South African Institute of Mining and Metallurgy* pp. 257–264.

Whiten, W.J. (1984). Models and control techniques for crushing plants. In: *Control'84, Minl. Metall. Process, AIME Annual Meeting,*. Los Angeles, California USA, February. pp. 217–225.