Internal Model Control based Preheating Zone Temperature Control for Varying Time Delay Uncertainty of the Reheating Furnace

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Abstract: ***This paper proposes an Internal Model Control (IMC) and IMC based PID, for zone temperature control of a steel slab reheating furnace. A second order plus time-delay model of the pre-heating zone of the process is used. This process experiences time-delays that alter with the operating conditions. An Internal Model Control is designed which is robust to changes in such time-delay and is simulated in MATLAB. The analysis on the simulated results show that robustness features of IMC and IMC based PID, overdo the performance of other controllers.***

Keywords: Internal Model Control (IMC), IMC based PID control, time delay, robustness

1. Introduction

The reheating furnaces are used to heat steel blocks to the required temperature, prior to the rolling process. Steel slab reheating furnaces are considered to be one of the plants with the most energy consumption in the steel industry[1]. However a large amount of energy is lost due to the lack of efficient control. The reheating furnaces are separated into three controllable zones; the preheating zone, the heating zone and the soaking zone. In the preheating zone moisture content in the slab is removed and heated to a temperature of 750 to 850℃. The heating zone heats the slab to a required temperature of 950 to 1150℃ and the soaking zone maintains the zone temperature from 1000 to 1100℃. The preheat zone has 10 burners, the heating and soaking zone have 12 burners each. The furnace has 8 thermocouples in each zone. It measure the furnace temperature and based on it the slab temperature is adjusted. In industrial practice a hierarchical control structure is arranged in cascade, which consists of a low level controller and a supervisory level control. Recent researches on furnace preheating zone by various experts identifies that the process experience a very large time delay changes depending upon the changes in the dynamic parameters of the furnace. The variations in time delay is due to the changes in the parameters or operating conditions of the furnace.

Several control strategies had been applied to the steel slab reheating furnace and the most widespread are PID controllers.However some studies have shown that the PID controllers[4], do not perform well when the furnace zone possess large varying time-delays. It results in large settling time in each zone which leads to an excessive fuel consumption and consequently to an inadequate combustion and a large environmental pollution. In the past years, fractional operators have been applied to process model and to control the process with complex dynamic behaviour[5]. A FI controller combined with a Smith predictor was developed[7],[6] to guarantee the stability of the closed-loop system to moderate changes of time delay. A fractional order controller plus prefilter combined with a Smith predictor was also developed, that guarantees stability in all range of time-delays but results in large settling time. In this paper the proposed IMC for the preheating zone, exhibits the system robustness in varying time delay conditions and also in turn reduces the fuel consumption.

The Paper has been organised as follows. A linear model of the slab reheating furnace process are introduced in SectionII. SectionIII explains the theory of Internal Model Control and IMC based PID for delay process. SectionIV contains the design procedure of IMC and IMC based PID for delay process. Simulations with the controllers are shown in SectionV. Finally some conclusions are drawn in SectionVI.

2. Mathematical Modelling of the Preheating Zone of Reheating Furnace

The mathematical model of the preheating zone of the reheating furnace is considered here and is shown in Figure1. The reason for this is, this zone experiences a large changes in the dynamic parameters with varying time delays. A pusher type furnace is used here which is diesel powered. The model input is the fuel flow rate and the output is the zone average temperature [7].

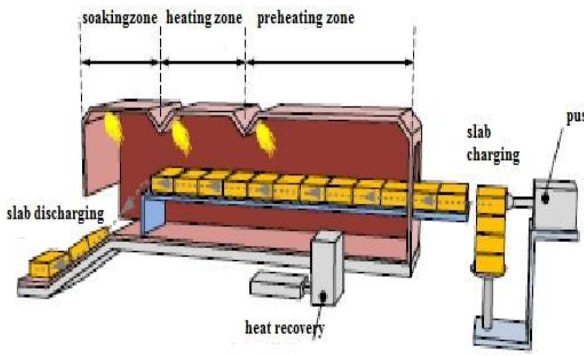

Figure 1: Push type slab reheating furnace under study

The preheating zone transfer function is obtained by considering the burners, fuel flow valve and the furnace zone dynamics. Initially the heat transfers in various zones should be considered. The reheating furnace zones is divided into 3 zones. The soaking zone is zone1, heating zone is zone 2 and the preheating zone is zone3. A simple model of heat transfer of reheating furnace is shown in Figure2.

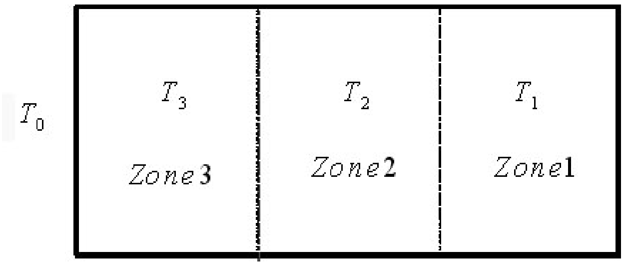

Figure 2: Simple model of push type reheating furnace

The thermal capacitance and thermal resistance heat flow rate from zone 1 to zone 2 is given as

$$C_1\frac{dT1}{dt} = Q_1 - Q_2 \quad (1)$$

$$Q_2 = \frac{T1-T2}{R1} \quad (2)$$

The thermal capacitance and thermal resistance heat flow rate from zone 2 to zone 3 is

$$C_2\frac{dT2}{dt} = Q_2 - Q_3 \quad (3)$$

$$Q_3 = \frac{T2-T3}{R2} \quad (4)$$

The thermal capacitance and thermal resistance heat flow rate from zone 3 to the environment is

$$C_3\frac{dT3}{dt} = Q_3 - Q_4 \quad (5)$$

$$Q_4 = \frac{T3-Tair}{R3} \quad (6)$$

So, we can arrange the equation 4,5 and 6 to

$$\dot{T}_1 = \frac{1}{R1C1}T_1 + \frac{1}{R1C1}T_2 + \frac{1}{C1}Q_1 \quad (7)$$

$$\dot{T}_2 = \frac{1}{R1C2}T_1 - \left(\frac{1}{R1C2} + \frac{1}{R2C2}\right)T_2 + \frac{1}{R2C2}T_3 \quad (8)$$

$$\dot{T}_3 = \frac{1}{R2C3}T_2 - \left(\frac{1}{R2C} + \frac{1}{R3C3}\right)T_3 + \frac{1}{R3C3}T_{air} \quad (9)$$

The mathematical model of the preheating zone of the reheating furnace can be obtained from the preheating zone equation. The process parameters are estimated by a nonlinear least squares method and pattern search. A mathematical model of the preheating zone (the furnace preheating zone will be denoted hereinafter as *FPZ*) was experimentally determined in[5] under nominal operation:

$$G_0(s) = \frac{Y(s)}{U(s)} = \frac{Kp}{(1+\tau 1s)(1+\tau 2s)}e^{-\theta s} \quad (10)$$

where y(t) is the variation of the zone average temperature and u(t) is the variations of the fuel flow valve opening magnitude.

3. Theory of Internal Model Control and IMC based PID for Time Delay Process

The internal model control is based on the principle of the internal model. The process-model mismatch is common. The process model may not be invertible and the system is often affected by unknown disturbances.. It forms the basis for the development of a control strategy that has the potential to achieve perfect control. This strategy is known as internal model control IMC[8],[9]. The general structure is shown in Figure3, where,d(s) is disturbance, $\tilde{d}(s)$ is estimated disturbance, $Gp(s)$ is process, $G\tilde{p}(s)$ is process model, $G_c(s)$ is Internal Model Controller, R(s) is set point, E(s) is modified set point, U(s) is the manipulated input which is introduced to both the process and its model. Y(s) is the process output compared with the output of the model, resulting in a signal $\tilde{d}$(s).

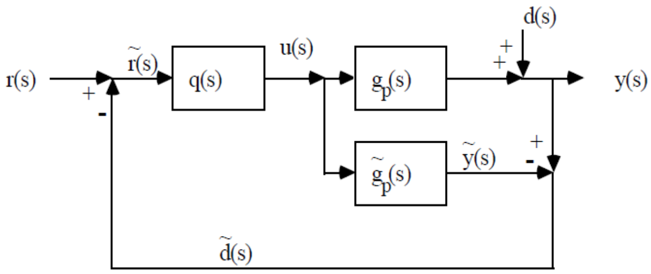

Figure 3: Schematic of the Internal Model Control scheme

3.1 Internal Model Control(IMC)

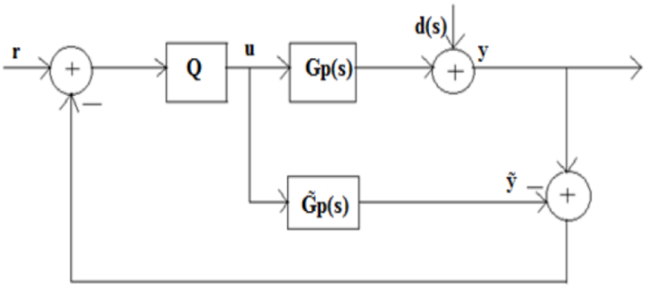

Figure 4: Modified structure of IMC

The model output error y-y˜ is subtracted from the reference signal and fed into the internal model control controller[9] which calculates the control signal, as shown in Figure4.

An internal model controller Q(s) is calculated so that the process model is divided into two parts

$$\tilde{G}_p(s) = \tilde{G}_{+p}(s)\tilde{G}_{-p}(s) \quad (11)$$

$\tilde{G}_{+p}(s)$ is the non-invertible part of the model including all delays. The rest of the model is included in $\tilde{G}_p(s)$.

The controller is given as,

$$Q(s) = (\tilde{G}_{-p}(s) - 1)f(s) \quad (12)$$

where 'f' is a low pass filter transfer function of order n given as

$$f(s) = \frac{1}{(1+s\lambda IMC)^{\wedge}n} \quad (13)$$

λ_{IMC} is the tuning parameter of internal model control method.

The internal model control law in the classical control loop is given by

$$G_c(s) = \frac{Q(S)}{1-G^{\sim}(s)Q(s)} \quad (14)$$

A constant delay of τ seconds corresponds to an exponential function $e^{-\tau s}$ in the Laplace domain, and the delay can be approximated with the Taylor series expansion or the first order Pade's approximation

$$e^{-\tau s} = \frac{(1-\frac{s\tau}{2})}{(1+\frac{s\tau}{2})} \quad (15)$$

3.2 Internal Model Control based PID

It is possible to obtain the propotional integral control structure[9] from the internal model control design. Q(s) needs to be improper, For integrating or unstable process or for better disturbance rejection, a filter with the following form will often be used.

$$f(s) = (\lambda s+1)/(\lambda s+1)^n \quad (16)$$

From this the equivalent standard feedback controller using the transformation is given by,

$$G_c(s) = \frac{Q(s)}{1-G^{\sim}p(s)Q(s)} \quad (17)$$

The above equation needs to be shown in PID form, then evaluate K_c,τ_i,τ_d. Sometime it results in an ideal PID controller cascaded with a first order filter with a filter time constant(τf),

$$Gc(s) = K_c[(\tau_i\tau_d s^2+\tau_i+1)/\tau_i s]*[1/\tau fs+1] \quad (18)$$

Adjust λ considering a tradeoff between performance and robustness[10] sensitivity to model error. Initial values of λ will be around 1/3 to 1/2 the dominant time constant.

4. Design of IMC and IMC based PID of a Second Order plus Time Delay Process

4.1 IMC design procedure for delay process

The process is given as ,

$$G_p(s) = K_p\frac{e^{-\theta s}}{(\tau 1s+1)(\tau 2s+1)} \quad (19)$$

Disturbance is taken as a first order transfer function

$$G_d(s) = 1/(\tau_d s+1) \quad (20)$$

4.2 Plant Reduction Model

As it is difficult to implement IMC controller directly to higher order system due to increased complexity, it is reduced to a low order model. The method used to reduce the model in this paper is given by the half rule.

The second order plus dead time process transfer function is reduced to a first order model. For a first order model τ_2 =0 and the parameter is given as;

$$\tau_I = \tau_{10} + \tau_{20}/2 \quad (21)$$

$$\theta = \theta_0 + \tau_{20}/2+\sum_{i\geq 3}\tau io \sum_j T_{jo}^{inv} \quad (22)$$

by using half rule, reduced model is given as

$$G^{\sim}_p(s) = \frac{Kp}{(\tau 1s+1)}*e^{-\theta s} \quad (23)$$

Factor out the non-invertible elements to avoid the bad part all-pass

$$G^{\sim}_p(s) = G^{\sim}_{+p}(s)G^{\sim}_{-p}(s) \quad (24)$$

$$G^{\sim}_{-p}(s) = \frac{Kp}{(\tau 1s+1)(\frac{s\theta}{2}+1)} \quad (25)$$

$$G^{\sim}_{+p}(s) = (1-s\theta/2) \quad (26)$$

Let , $Q^{\sim}(s) = (\tau_1 s+1)(1+s\theta/2)$ (27)

Now the value of f(s) = $1/(\lambda s+1)^2$, to make the controller semiproper, therefore

$$Q(s) = (1/ G^{\sim}_{-p}(s))*(1/(\lambda s+1)^2) \quad (28)$$

$$Q(s) = Q^{\sim}(s)*f(s) \quad (29)$$

The values of 'λ' lie between 1/3 to 1/5 of the time constant[8]. Put the value of λ in equation (20) to get the value of internal model controller Q(s).

4.3 IMC based PID design procedure

The filter f(s) is added to make the Q(s) proper. But Q(s) will be made semi-proper to get the proportional integral derivative controller.

The derivative option will be used to allow the numerator of Q(s) to be one order higher than the denominator[10]. It is done only to obtain an ideal proportional integral derivative controller.

$$Q(s) = Q^{\sim}(s)*f(s) = (1/ G^{\sim}_{-p}(s))*f(s) \quad (30)$$

$$Q(s) = (\tau_1 s+1)(1+s\theta/2)/K_p(\lambda s+1) \quad (31)$$

The proportional integral derivative equivalent can be given as,

$$G_c(s) = Q(s)/1-G_{p^{\sim}}(s)Q(s) \quad (32)$$

$$= Q^{\sim}(s)f(s)/1- G_{p^{\sim}}(s)f(s)Q(s) \quad (33)$$

$$G_c(s) = Q^{\sim}(s)f(s)/1- G^{\sim}_{+p}(s)G^{\sim}_{-p}(s)(1/G^{\sim}_{-p}(s))f(s) \quad (34)$$

$$G_c(s) = \frac{Q^{\sim}(s)f(s)}{1-Gp^{\sim}(s)}f(s) \quad (35)$$

The value of the proportional integral derivative tuning parameter is given by

$$\tau_c = \theta \quad (36)$$

$$K_1 = K_p/\tau_1 \quad (37)$$

$$K_c = (1/K_1)*(1/\tau_c+\theta) \quad (38)$$

$$\tau_i = 8*\theta \quad (39)$$

$$\tau_D = \tau_2 \quad (40)$$

by getting the above values PID transfer function can be evaluated as

$$G_c(s) = K_c[\frac{\tau i\,\tau Ds2+\tau is+1}{\tau is}]*[\frac{1}{\tau fs+1}] \quad (41)$$

The controllers with above modifications are designed and the system along with the controller is subjected to test robustness[10].

5. Simulation Results and Discussion

The preheating zone process model of the slab reheating furnace was used in this paper and IMC and IMC based PID controller were applied to it. Figure5 shows the step response of Internal model control for a 1st order disturbance. The response results in a small overshoot with a settling time of 1200s.

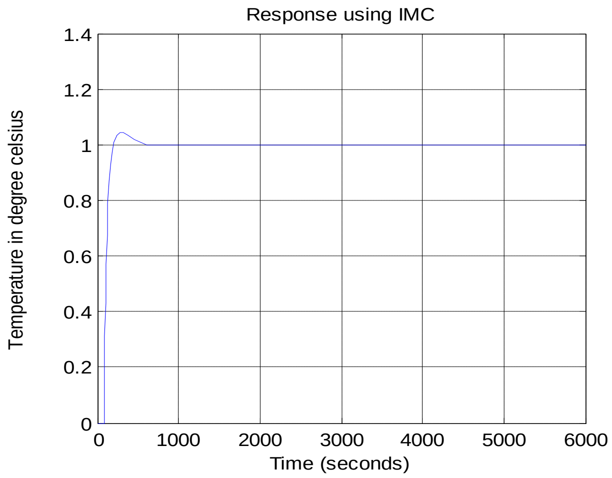

Figure 5: Response using IMC controller

Then IMC based PID controller was also applied to the model with a 1st order disturbance. The response has no overshoot and takes less settling time as compared to IMC and reduced order IMC. Figure7 shows the response of IMC based PID controller. The step response for a IMC model with a 1st order disturbance is shown in Figure6. The response shows that the IMC has a good performance as compared to PID and PI controllers combined with the Smith predictor. Internal Model Control has been applied for varying time delays.

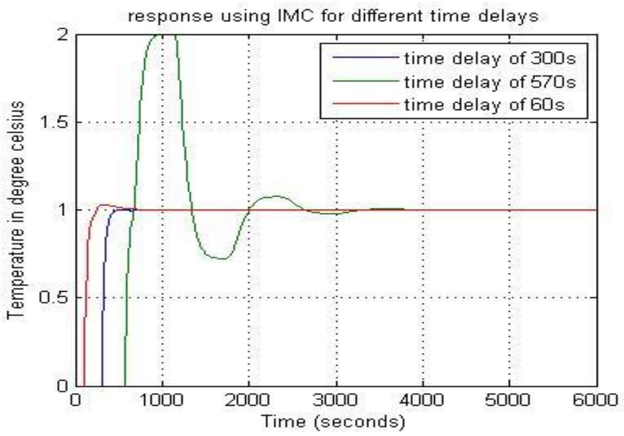

Figure 6: Response of IMC for varying time delays

The responses shows that the IMC controller keep the system robust even if the time delay changes. Fig.6 shows the responses of the IMC model for time delays of 60s, 300s and 570s. For a time delay of 60s there is a small overshoot and has a settling time of 890s, and when the time delay is changed to 300s there is no overshoot and the response settles with a little more time than, when the delay was 60s and the settling time is found to be 950s. But the system robustness was not lost with the changes in time delay. When a time delay of 570s were applied to the system, response began to oscillate and settles within 3200s. But the responses shows a good performance with IMC when compared to the response of the other controllers [6][7] which were done earlier.

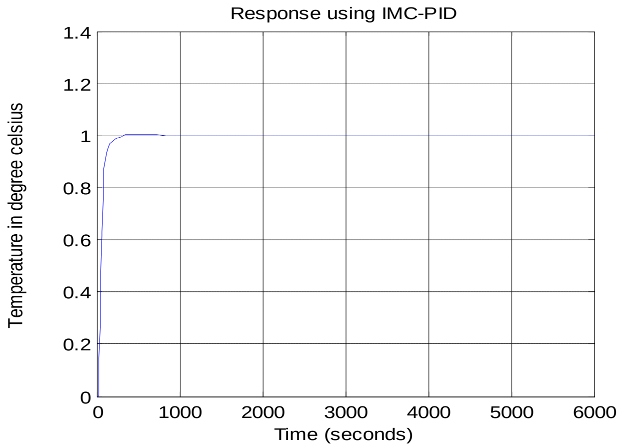

Figure 7: Response of IMC based PID for varying time delays.

Then IMC based PID controller was also applied to the model with a 1st order disturbance. The response has no overshoot and takes less settling time as compared to IMC and reduced order IMC. Figure7.shows the response of IMC based PID controller.

6. Conclusion

The IMC provides a transparent frame works for control system design and tuning. The internal model control design results in only one tuning parameter λ. The IMC based PID tuning parameters are then a function of closed loop time constant. The selection of the closed loop time constant is directly related to the robustness sensitivity. IMC provides a good solution to the process with significant time delays which is actually the case with working in real time environment. The IMC based PID is able to compensate for disturbances and model uncertainty. Thus in varying time delay systems, where robustness with respect to delay variance plays a crucial role, the tuning of λ_{IMC} turns out to be crucial

7. Future Scope

So due to speed in their execution, accuracy of control, ease of configuration, low energy consumption, probability etc, FOPID based IMC should also be applied to the process and tuning rule can be obtained without any approximation for a time delay.

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