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The Design of PIP Controller for a Thermal System with Large Time Delay

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***Abstract*—**This paper will first describe predictor controllers when the proportional-integral-derivative (PID) controllers are inactive for procedures that have large delay time (LDT) in transfer stage. Therefore in those states, the predictor controllers are better than the PID controllers, then compares three types of predictor controllers. The value of these controller's parameters are obtained by trial and error method, so here an effort has been made to obtain these parameters by Ziegler-Nichols method. Eventually in this paper Ziegler-Nichols method has been described and finally, a PIP controller has been designed for a thermal system, which circulates hot air to keep the temperature of a chamber constant.

***Keywords*—**Proportional-integral-predictive controller, Transfer function, Delay time, Transport-lag.

I. Introduction

An automatic controller compares the actual value of the plant output with the reference input, and produces a signal that will reduce the deviation to zero or to small value. The first significant work in automatic control was James Watt's centrifugal governor for the speed control of a steam engine in the eighteenth century [1]. Generally, many control designers prefer the use of the PID controllers to the complicated controllers for example adaptive controller [2]. In industry, problems are solved by the use of PID controllers.

In these controllers, parameters are regulated by means of trial and error method, which is one of the useful aspects of PID controllers. Even though, there are automatic regulation ways, but when we have large time delay in industrial processes these controllers are inactivated [3]. Therefore this problem leads to the limitation in wide range use of PID controllers. For dealing with this issue we should use PIP controllers. These types of controllers can predict output. In this paper we have tried to design a PIP controller for a thermal system with large delay time processes.

Any types of procedures that have LDT that leads to the differentiator part of PID controllers will get inactivated. Why does this happen? A large number of expert engineers have the opinion that one of the best methods for the change and regulation of variables is Ziegler and Nichols method [4]. The present paper has explained Ziegler-Nichols method and at the next stage has considered three types of predictive controllers and compared them with each other and has reviewed their advantages and disadvantages. Then modeling and implementation of a scheduled gain and regulation of parameters by Ziegler-Nichols Method for the control of thermal processes are described.

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II. Predictor Controllers

The response of PID controller for a transfer functions with LDT is as shown in Fig. 1.

$$G_p(s) = [\exp(-3.9s)/s+1] \quad (1)$$

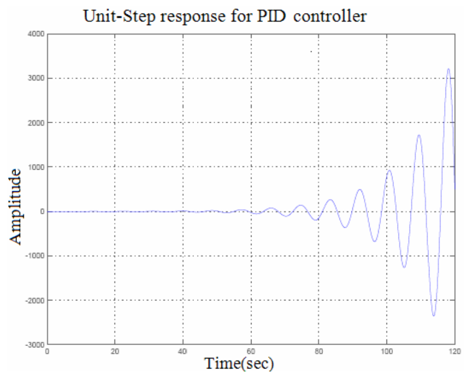

Fig. 1 Response of system by PID

The prevention of this trend can be done with prediction of input signal.

A. Regulating with Prediction

The prediction of predictive controller is dependent on the change of pattern signal in future. The transfer function of PID controller comes below:

$$U_{PID}(t) = k[e(t) + (1/T_i)\int e(t)dt + T_d(de(t)/dt)] \quad (2)$$

In PID controller, prediction is done by differentiator part; this procedure is more obviously in a proportional-derivative controller (PD).

$$U_{PD}(t) = k[e(t) + T_d(de(t)/dt)] \quad (3)$$

If the input signal was a linear time variant, we would have had:

$$de(t)/dt = [e(t+T_d) - e(t)]/T_d \quad (4)$$

Therefore:

$$e(t) + T_d(de(t)dt) = e(t+T_d) \quad (5)$$

$$U_{PD}(t) = k_e(t+T_d) \quad (6)$$

It is obtained with this method that the input signal in time t is proportional to the error signal in time t+Td. If we want to have change in output signal through the input signals for a process that has LDT transport-lag and is controlled by a PID controller, the proportional and integral parts of controller provide enough energy to access the favorite signals before that the differentiator part can be active. Actually, in LDT there aren't any changes in output signals, hence we should use only PI controller, it means that it will regulate slowly. It shows the regulation of parameters can be difficult in LDT processes and the use of PIP controllers is very necessary. The act of prediction must be done by a model of process that is used as the output signals. In other words these controllers allow predicting the output signals at the time t+τ, where τ is a delay time. The structures of controller that can modulate the effect of delay in transport-lag is as shown in Fig 2.

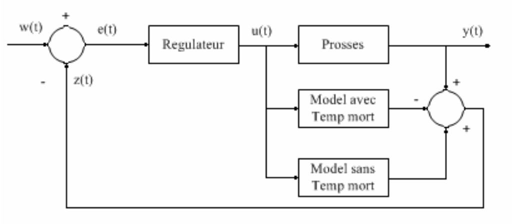

Fig. 2 The structure of controller can modulate the effect of delay

These controllers will predict the change of pattern in output signal by feed of input signal from another and the same model of process without delay time in transport-lag.

B. Types of Predictor, Controllers

IMC Controller

The structure of IMC controller as shown in Fig. 3.

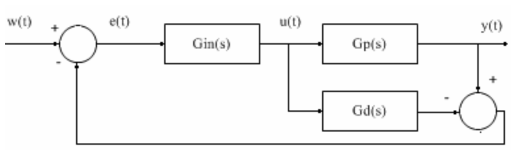

Fig. 3 The structure IMC controller

$G_{in}(s)$ and $G_d(s)$ are the inverse model and the forward model of $G_p(s)$, respectively. The same block diagram of IMC is shown in Fig. 4.

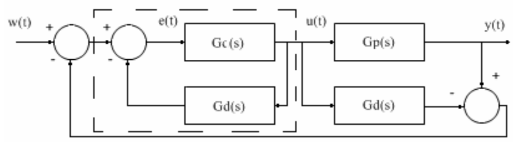

Fig. 4 The same block diagram of IMC controller

$G_c(s)$ is a contractual controller. In fact, the IMC controller is a specific structure of a contractual controller [6], [7].

$$G_{in}(s) = [G_c(s)/(1+G_c(s)G_d(s))] \quad (7)$$

The general form of $G_p(s)$ when it has a delay in transport-lag is shown below:

$$G_p(s) = [K_p \exp(-\tau s)B(s)/A(s)] \quad (8)$$

If we assume:

$$G_d(s) = G_p(s) \quad (9)$$

For ideal inverse model we obtain:

$$G_{in}(s) = 1/G_p(s) \quad (10)$$

For this model there must be an extra filter:

$$F(s) = [\exp(-\tau s)/(1+\lambda s)^{(n-m)}] \quad (11)$$

Therefore:

$$G_{in}(s) = [A(s)/K_p(1+\lambda s)^{(n-m)}B(s)] \quad (12)$$

The value of λ is regulatable and it should be greater than the time constant ($G_p(s)$). It cause the rate of the system to be faster than before. The IMC controllers don't show the overshoot of response to the reference input signal in close-loop, because:

$$G_{tot}(s) = [\exp(-\tau s)/(1+\lambda s)^{(n-m)}] \quad (13)$$

SMITH controller

The structure of SMITH controller is shown in Fig. 5.

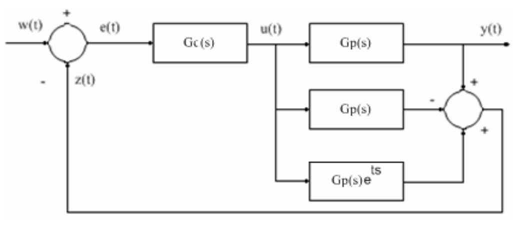

Fig. 5 The structure of SMITH controller

This controller can modulate the delay in transport-lag, because the prediction of output signal's changes in future can be done by signal Z(s).

$$Z(s) = \exp(\tau s)Y(s) \quad (14)$$

SMITH controller can be equal to IMC controller as shown in Fig. 6. The part of block diagram is situated in discrete line cadre is equal to inverse model in IMC.

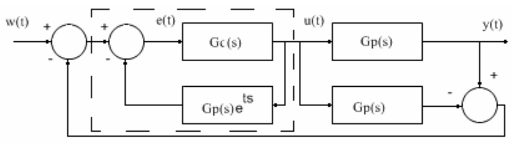

Fig. 6 The same block diagram for IMC & SMITH

Generally, industrially used the transfer function comes below:

$$G_{in}(s) = [K_p \exp(-\tau s)/(Ts+1)] \quad (15)$$

The regulatable parameters in IMC such as τ, T and K_p, must be regulated by systematic method because the regulation of these parameters manually are difficult. In SMITH controller the act of prediction is done by delay time modulator, therefore the regulatable parameters are reduced to five parameters τ, T, K_p, K and T_i. But the regulation of these parameters is difficult and we can’t regulate by trial and error method easily.

PIP controller

The basic idea for the design of PIP controller is creating a PI controller with prediction ability. It has only three regulatable parameters that can regulate their parameters manually by trial and error method. The structure of PIP controller is shown in Fig. 7. In fact, the PIP is especial forms of SMITH controller [3], [8].

$$K_p = f_1(K, T_i, \tau) \quad (16)$$

$$T = f_2(K, T_i, \tau) \quad (17)$$

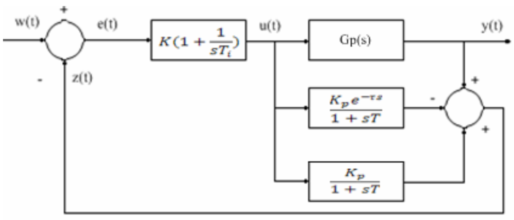

Fig. 7 The structure of PIP controller

In ideal form, PI controllers in delay time modulator can be used for converting the state of system to the same system but without the delay time, so it can be said that f_1 and f_2 are independent of τ, also K is independent of T_i, and T_i is independent of K_p [3], [8].Hence:

$$K_p = f_1(K) \quad (18)$$

$$T = f_2(T_i) \quad (19)$$

There are related between K, K_p, T_i and T:

$$K_p = \alpha / K \quad (20)$$

$$T = \gamma T_i \quad (21)$$

Where α and γ are arbitrary constant, and they are obtained by experimental work. The transfer function of block diagram in Fig. 7 comes in the following equations:

$$U(s) = K[1 + 1/T_i s][E(s) - [K_p/(1+Ts)] [U(s) - U(s)\exp(-\tau s)]] \quad (22)$$

$$U(s) = K[1 + 1/(T_i s)][E(s) - [(\alpha/K)/(1+T_i\gamma s)] [U(s) - U(s)\exp(-\tau s)]] \quad (23)$$

So:

$$U_{PIP}(s) = K[1 + 1/T_i s]E(s) - [\alpha(1+T_i s)/ sT_i(1+T_i\gamma s)][1-\exp(-\tau s)]U(s) \quad (24)$$

Above formulas are lead to below diagram for the design of the PIP controller (Fig. 8).

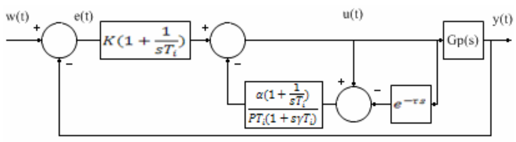

Fig. 8 Another type of structure for PIP controller

$$U_{PID}(s) = K[1 + 1/T_i s + T_d s]E(s) \quad (25)$$

Comparing (24) and (25), we will see that both of them are the same, because each controller has three parameters, but there is only one basic difference between them. In PIP controller the act of prediction is done by a filter that is situated on the input signal. In PID controller this action is done by differentiator part on the output signal.

III. Ziegler-Nichols Method

In this section discussed how to assess the amount of parameters α, γ and how to select the values of K, T_i and τ for receive a response with good rate and without a large overshoot. By converting of block diagram in Fig. 7 to Fig. 9 then site equivalent the part of block diagram is situated in discrete line cadre in Fig. 9 to invert model in Fig. 3, which leads to obtained a first order transfer function with delay time.

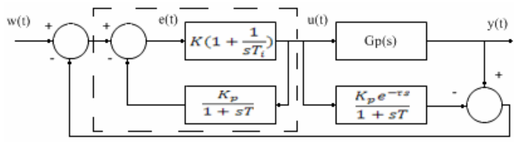

Fig. 9 Another type structure for PIP controller

$$G_{in}(s) = G_{ine}(s) \quad (26)$$

$$G_{ine}(s) = [(1+T_i s)(1+Ts) / (K_p(1+T_i s) + T_i s(1+Ts))] \quad (27)$$

$$G_{in}(s) = [(1+Ts) / K_p(1+\lambda s)] \quad (28)$$

Where assumed λ=T, α=1, γ=1 and by simplification we will receive:

$$K = 1/K_p \quad (29)$$

$$T_i = T = \lambda \quad (30)$$

These simplification leads to:

$$U(s) = K[1+1/T_i s]E(s) - (1/T_i s)[1-\exp(-\tau s)]U(s) \quad (31)$$

In general state with λ≠T, we will have:

$$\alpha = T/\lambda \quad (32)$$

$$\gamma = 1 \quad (33)$$

The PIP controller with these value of α and γ has faster response to PID controller. The parameters of PID controller regulate by trial and error method. The PID controllers can be influence on the transient response, for example if response was very oscillatory, designers reduce the amplification factor or increase the integrator time. Now, describe how to regulate the parameters K, T_i and τ in PIP controllers. The PIP controllers have two interesting characteristic. One of them is two parameters of three, they are similar to amplification factor and integrator time is regulated by above method. For regulating of third parameter that is a delay time τ. The regulating of τ is more complicated by trial and error method, so the designers prefer, this parameter assess through the response to unit step function in open-loop process.

There is another basic different between the regulating of parameters in PID and PIP controllers. In Ziegler-Nichols method, select of parameters for PID basically depend on the relation between τ and T, where as for PIP there isn't any relation between amount of τ, K and T_i because the influence of delay time eradication by delay time modulator. They have the same dynamics except delay time. For finding a start point of trial and error method to obtain the static amplification factor of process K_p, delay time τ and time constant T, can be exploit two methods from Fig. 10 These methods have only one different in calculating of time constant. First method: The line D is a slope of response in transport-lag. This line is stroke with the time axis and the maximum level of the output signal in point B and A, respectively. The time constant T_{ZN} is equal to distance between B and C in Ziegler-Nichols method. Second method: The time constant is equal to distance between point B and the time when response obtained %63 of maximum value of output. This method is exactly solution for first order plant with delay time. If assumed α=1 and γ=1, it is a good start point for regulation of parameters through open-loop response.

$$K = 1/K_p \quad (34)$$

$$T_i = T_{\%63} \quad (35)$$

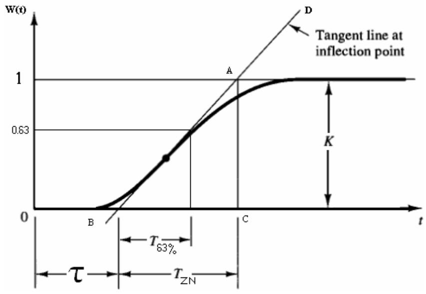

Fig. 10 Diagram for obtain constants

IV. Thermal System Modeling

Fig. 11 illustrates a thermal system in which hot air is circulated to keep the temperature of a chamber constant. In this system, the measuring element is placed downstream a distance *L* from the furnace, the air velocity is *υ* and *T=L/υ* would elapse before any change in the furnace temperature is sensed by the thermometer. These systems have any delay for example there is a delay in measuring, delay in controller action or delay in actuator operation, and the like is called transport-lag.

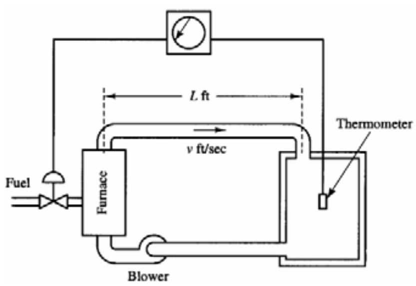

Fig. 11 The thermal system

The input *x(t)* and the output *y(t)* of a transport-lag element are related by:

$$y(t) = x(t-T) \quad (36)$$

Where *T* is delay time. The transfer function of transport-lag is given by:

$$G_c(s) = [L(x(t-T)1(t-T)) / L(x(t)1(t))] \quad (37)$$

$$G_c(s) = [X(s)\exp(-\tau s) / X(s)] = \exp(-\tau s) \quad (38)$$

The feed forward transfer function of this thermal system can be approximated by:

$$G_p(s) = [K \exp(-Ts) / (s+1)] \tag{39}$$

In this paper this system is controlled by use of PIP controller that it shown in Fig. 7.

The parameters of PIP controller selected from Table I, these value calculated by Zeigler-Nichols method.

TABLE I
THE VALUE OF PIP'S PARAMETERS FOR GP(S)

N	K	T_i	T
1	1	1.35	3.9
2	1	1	3.9

The responses of system for the value of table I, are shown in Fig. 12 and Fig. 13.

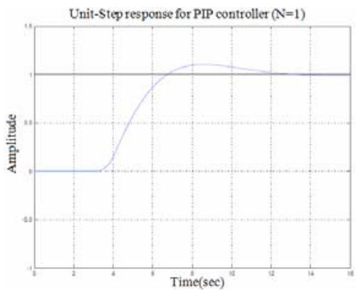

Fig. 12 The response of system for PIP controller (N=1).

After achievement favorite response with manual regulation, there are two ways for improvement of response. The first one, can be received faster response by increase of λ and the second one, can be reduce the overshoot with import factor $\beta<1$ in below formula. It is called Refined Proportional-integral- predictor controller (RPIP).

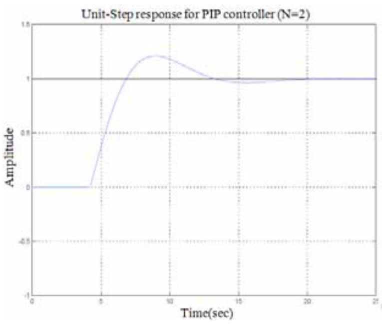

Fig. 13 The response of system for PIP controller (N=2)

V. CONCLUSION

In this paper three kinds of predictor controllers are presented. All of them are suggested for any processes that they have LDT; also these controllers have the same structure with a small difference. The number of regulatable parameters is different, but the number of regulatable parameters of IMC and SMITH are more than the PIP and PID. It shows that the IMC and SMITH are more flexible than the PIP and PID, but the regulation of their parameters are more difficult. PIP controllers are as similar as the PIDs because they have three regulatable parameters. PIP's parameters are regulated by Ziegler-Nichols method. PIPs are predictor controllers that do this action by filtrations of input signals. Moreover, the thermal systems have a LDT. In this paper one kind of these systems that circulates the hot air to keep the temperature of chamber constant is controlled by PIP, which leads to the decrease of fluctuation in transient part of response to unit-step input proportional to PID controller.

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