Real Time Temperature Control System Using PID Controller and Supervisory Control and Data Acquisition System (SCADA)

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ABSTRACT

Well designed conventional PID controllers using Ziegler-Nichols method are having large overshoot and settling time. Significant research work has been carried out to improve the performance of closed loop response with PID controller so that it can be used for real time temperature control system using SCADA(HC- 900 Honeywell controller). Also performance of PID controller is investigated for different performance metrics such as Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time absolute Error (ITAE), and Integral Time square Error (ITSE) is presented and simulation is carried out. Work in this paper explores basic concepts, mathematics, and design aspect of PID controller. Furthermore, after meticulous analysis of the operation of the plant, PID based schemes are formulated to control the temperature of UT_321 laboratory system, which gives satisfactory performance for various dynamics like low-and high-order, small and large dead time, and monotonic, oscillatory responses.

Index Terms: PID controller, SSR, FOPDT model, SOPDT model, ISE, IAE, ITAE, ITSE, SCADA.

1. INTRODUCTION

PID controllers are widely used in process control industry due to relatively simple structure and easiness in implementation [2, 3, 4]. Since last few decades different methods are proposed to tune PID controller, however, every method have some limitations [2, 3]. Existing control loop uses PID controller more than 90% [12]. As a result, the design of PID controller still remains a challenge before researchers and engineers [7].

To design and tune the controller to achieve the better performance it is essential to,

1. Obtain the dynamic model of a system to control.
2. Specify the desired closed loop performance on the basis of known physical constraints.
3. Adopt controller strategies that would achieve the desired performance.
4. Implement the resulting controller using suitable platform.
5. Validate the controller performance and modify accordingly if required.

The transfer function of PID controller is:

$$G_c(s) = K_c(1 + \frac{1}{T_I s} + T_D s) = K_P + \frac{K_I}{s} + K_D s \qquad (1)$$

Where,

K_P is the proportional gain

T_I is the integral time

T_D is the derivative time

Clearly, this transfer function is improper and practically it can not be used as frequency increases, its gain also increases. Therefore, practical PID controller has the following transfer function:

$$Gc(s) = Kc(1 + \frac{1}{Tis} + \frac{Tds+1}{\lambda s+1}) \qquad (2)$$

Where,

λ is a small parameter and it may be set as 10 % of derivative term [4].

In this paper, methods proposed by Ziegler-Nichols, Cohen-Coon, Wang are implemented for the real time measurement of laboratory temperature control system UT_321. System model for UT_321 laboratory temperature control system using system identification toolbox of MATLAB 7.1 version is determined and this temperature loop is configured with SCADA. Controller performance is determined on the basis of frequency domain specifications, time domain specification, and performance error indices respectively. The purpose of this paper is to present model based PID controller for temperature control system which may be extended for other SISO system like flow, pressure, level of liquid as well as for multivariable systems [11].
Rest of the paper is organized as follows. Section 1 explored introduction of PID controller. Section 2 investigated the problem statement. Section 3 provides basics of controller design for FOPDT/SOPDT systems. Section 4 introduces laboratory set up UT_321 to control the temperature. Section 5 describes the system models. Section 6 explored simulation results. Furthermore, section 7 investigates the robustness of the system. Section 8 draws the conclusions.

2. PROBLEM STATEMENT

The work in this paper elaborates a method of designing PI / PID controller [1], [9] which is model based control strategy, for performance evaluation and real time implementation to temperature control system. The method is based on FOPDT / SOPDT model and closed loop pole allocation through the use of root locus diagram. System model is obtained experimentally from process reaction curve. The objective of this work is to compute PID tuning parameters to get the better performance. The designed controller is implemented using Supervisory Control and Data Acquisition System (SCADA) and also documents a temperature control simulation which is performed using PID controller. All simulations were performed using MATLAB package Version 7.1 and Simulink toolbox (ver. 3.0) on personal computer.

3. CONTROLLER DESIGN FOR FOPDT / SOPDT SYSTEMS

The single loop controller configuration is shown in Fig.1

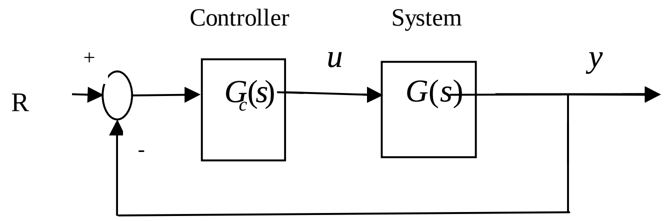

Fig.1 A single loop controller configuration

The controller $G_c(s)$ is a PID controller in the form of (1). The system model $G(s)$ is assumed to be known or determined experimentally. For First Order plus Time Delay (FOPTD) and Second Order plus Time Delay (SOPTD), systems are of the form given in (3) and (4) respectively.

$$G(s) = \frac{Ke^{-t_d s}}{1+\tau s}, \qquad (3)$$

Where,

$G(s)$ is the open loop transfer function

K is the steady state gain

t_d is the dead time

τ is the time constant.

3.1 PID controller Design Method for SOPDT Model

Design method presented in this section is based on second-order plus time delay model and a closed loop pole allocation through the use of root locus. The method is also applicable for FOPTD systems which take a form of PI controller with $K_D = 0$.

First, let us define some terms that are used in the design. The equivalent time constant τ_0 of a process, which is inversely proportional to speed of response. According to equivalent time constant principles [9] it is given by,

$$\tau_0 = \frac{\sqrt{b^2 - 2ac}}{c}, \qquad b^2 - 4ac \geq 0 \qquad (4)$$

$$= \frac{2a}{b}, \qquad b^2 - 4ac < 0$$

Where,

a, b, c are system parameters in (4).

Another variable of interest is the damping ratio ξ_0 of open loop system model which is given by,

$$\xi_0 = 1, \qquad b^2 - 4ac \geq 0 \qquad (5)$$
$$= \frac{b}{2\sqrt{ac}}, \qquad b^2 - 4ac < 0$$

The PID controller in (2) can be written in the form

$$G_c(s) = k\left(\frac{As^2 + Bs + C}{s}\right) \qquad (6)$$

Where,

$$A = \frac{K_D}{k},\ B = \frac{K_P}{k} \text{ and } C = \frac{K_I}{k}$$

In the design procedure if we choose the controller zeros such that they cancel out the poles of system model in (4), we get $A = a, B = b, C = c$. Then the resultant open loop transfer function becomes,

$$G(s)G_c(s) = \frac{ke^{-t_d s}}{s} \qquad (7)$$

The closed loop poles of (7) can be selected from its root locus to get desired dynamics in closed loop. The root locus shown in Fig.2.The desired closed loop poles selected from root locus can be real or complex in nature. This selection depends upon the nature of system model. For highly oscillatory systems, the real poles are selected to reduce the resulting oscillations in closed loop response. On the other hand, for lightly oscillatory systems the complex poles are selected to introduce some overshoot and increase the speed of response.

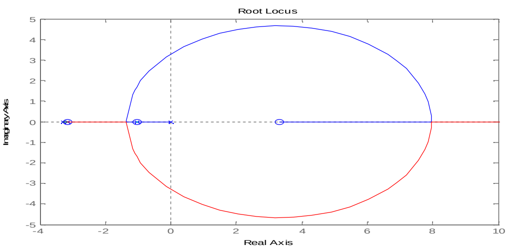

Fig. 2 Root locus of open loop transfer function (7)

On this basis, the two cases are considered for pole selection as follows:

<u>CaseI:</u> $\xi_0 > 0.707$ or $0.05 < \left(t_d/\tau_0\right) < 0.15$

Or $\left(t_d/\tau_0\right) > 1$

From the considerations in this case it can be seen that the system is non-oscillatory or lightly oscillatory and hence complex closed loop poles should be selected from root locus of open loop transfer function in (7). Let, the desired pair of complex poles on root locus be with damping ratio ξ_n and natural frequency ω_n which is given by,

$$s = -\xi_n\omega_n \pm j\omega_n\sqrt{1-\xi_n^2} \qquad (8)$$

For the pole pair in (8) to be on root locus it must satisfy the angle and magnitude conditions given by,

$$\angle G(s)G_c(s) = -\pi$$
$$|G(s)G_c(s)| = 1 \qquad (9)$$

Angle condition in (9) results into,

$$-\omega_n t_d\sqrt{1-\xi_n^2} - \left(\pi - \cos^{-1}\xi_n\right) = -\pi \qquad (10)$$

From (10) we get ω_n as,

$$\omega_n = \frac{\cos^{-1}\xi_n}{t_d\sqrt{1-\xi_n^2}} \qquad (11)$$

Using magnitude condition in (9) and ω_n in (11) the value of k can be computed as,

$$k = \omega_n e^{-\omega_n \xi_n t_d} \qquad (12)$$

For the desired damping ratio ξ_n=0.707 the resulting k is given by,

$$k = \frac{0.5}{t_d} \qquad (13)$$

Case II: $\xi_0 \le 0.707$ and $0.15 \le \left({t_d}/{\tau_0} \right) \le 1$

From the considerations in this case it can be seen that the system is highly oscillatory and hence real double closed loop poles should be selected from root locus of open loop transfer function in (7). The selection of the double real pole on root locus is done on the basis of the location of poles at $s_{1,2} = -{1}/{\tau_0}$ and poles at breakaway point on the root locus. The poles at $s_{1,2} = -{1}/{\tau_0}$ are selected either before breakaway point, or at the breakaway point are selected. This is done to have the speed of closed loop response at least equal to or faster than open loop response of system model. For the poles at $s_{1,2} = -{1}/{\tau_0}$ to be on root locus we get the expression for k from magnitude condition as,

$$k = \frac{1}{\tau_0} e^{-t_d/\tau_0} \qquad (14)$$

Now to calculate the breakaway point on root locus put $\xi_n = 1$ in (11) to get,

$$\omega_n = \frac{\cos^{-1}\xi_n}{t_d\sqrt{1-\xi_n^2}} = \frac{1}{t_d} \qquad (15)$$

From (12) and (15) we get,

$$k = \frac{1}{e\tau_0} \qquad (16)$$

The selection of k from (14) and (16) is done as,

$$k = \min\left\{ \frac{1}{\tau_0} e^{-t_d/\tau_0}, \frac{1}{e t_d} \right\} \qquad (17)$$

Finally the PID tuning parameters are obtained as,

$$\begin{bmatrix} K_P \\ K_I \\ K_D \end{bmatrix} = k \begin{bmatrix} b \\ c \\ a \end{bmatrix} \qquad (18)$$

3.2 Summary of PID controller Design:

For the given system model,

1. Obtain *a*, *b* and *c* from system model.
2. Compute τ_0 from (4) and ξ_0 from (5).
3. For $\xi_0 > 0.707$ or $0.05 < \left(t_d / \tau_0 \right) < 0.15$ or $\left(t_d / \tau_0 \right) > 1$, calculate k from (13).
4. Otherwise, for $\xi_0 \leq 0.707$ and $0.15 \leq \left(t_d / \tau_0 \right) \leq 1$, calculate k from (5).
5. Obtain PID tuning parameters from (14).

4. LABORATORY TEMPERATURE CONTROL SYSTEM UT_321

The process setup consists of heating tank fitted with SSR controlled heater for on-line heating of the water. The flow of water can be manipulated and measured by Rota meter. Temperature sensor (RTD) is used for temperature sensing. The process parameter (Temperature) is controlled by microprocessor based digital indicating controller which manipulates heat input to the process. The controller can be connected to computer through USB port for monitoring the process in SCADA mode. The specifications of the system are:

1. Type of Control: SCADA
2. Control Unit: Digital indicating controller with RS 485 communication
3. Communication: USB port using RS 485-USB converter
4. Temperature Sensor: Type RTD, PT 100
5. Heating Control: Proportional power controller(SSR), input 4-20mA D.C., Capacity 20 A
6. Rota meter: 6-60 LPH
7. Process Tank: SS304, Capacity 0.5 lit, insulated
8. Overall dimensions: 400w*400D*330H mm

Fig. 3 explores the system schematic arrangement of UT_321.

A step input is applied to solid state relay (SSR) and temperature of RTD (PT 100) is recorded in excel format. Stored data is used to plot open loop step response in MATLAB.

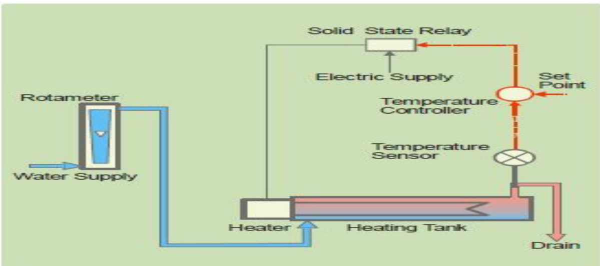

Fig.3 System schematic arrangement of UT_321

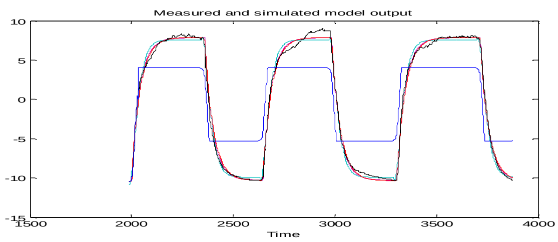

Fig. 4 Measured and simulated output using system identification toolbox of MATLAB

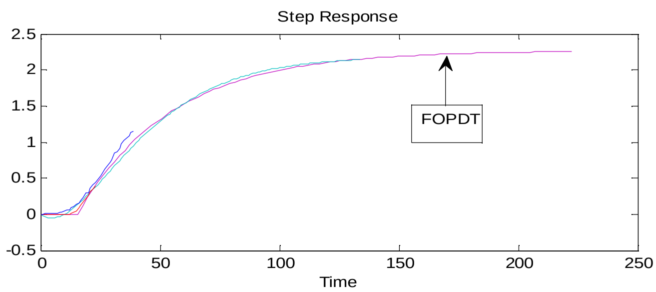

Fig. 5 Experimental step response of temperature system UT_321

5. DETERMINATION OF SYSTEM MODEL

In the design of model based controller, system model is an important element. White box model requires complete and correct physical data of the system under consideration. But this data is not available for the system described. Hence, system model id determined through system identification. We used time domain step test data from the system for determination of model. We considered FOPDT model.

This step response locates the system parameters like steady state gain, time delay and the time constant of the process from which model obtained is of general form as,

$$G(s) = \frac{k_p e^{-t_d s}}{1+\tau s} \qquad (19)$$

Where,

k_p is steady state gain of system,

τ is time constant of system

t_d is dead time of system.

Hence, we get FOPDT model from fig. 5 as,

$$Gp(s) = 2.2 \times \frac{e^{-6s}}{(1+40.484s)} \qquad (20)$$

(Water flow through Rota meter is kept at 40 LPH)

Controller design by Wang method

For the given system model (20), the system parameters are a = 0, b=40.484 and c= 1. The values of τ_0 and ξ_0 are computed using (4) and (5) to be 40.484 and 1 respectively. Since $\xi_0 > 0.707$, (13) is used to calculate k= 0.0833. Hence the PID parameters using (20) are, *KP*=3.374, *Ki*=0.0833 and *Kd*=0

Hence, controller transfer function by Wang method is given by,

$$Gc(wn) = \frac{3.374s + 0.0833}{s} \qquad (21)$$

Thus, PI controller is obtained.

Controller design by Ziegler-Nichols tuning method

For the given system model, from its Bode plot, we get, Gain margin (GM) = 16.38 dB and Phase crossover frequency (ω_{pc}) = 0.3572 rad/sec.

Then, the ultimate gain k_u and period T_u are computed as,

Ku=GM=16.38 dB

$$Tu = \frac{2\pi}{wpc} = 17.6$$

The controller settings for PID controller as per Ziegler-Nichols method are,

Kp=0.6Ku=4.0, Ti=0.4545 and Td=0.6

Hence, Ziegler- Nichols method gives following model

$$Gc(zn) = \frac{0.6s^2 + 4s + 0.4545}{s} \qquad (22)$$

Controller design by Cohen-Coon tuning method

From delay time and time constant of (20), we get, KP=4.203, Ti=13.91 and Td=2.124 [using reference (7)]

Hence, controller transfer function by Cohen-Coon method is

$$Gc(cc) = \frac{0.51s^2 + 4.203s + 0.3022}{s} \qquad (23)$$

Process Rate and Reaction Rate for actual temperature system is:

$$\left(\frac{57.5-39.3}{40.484-3}\right)=0.49\%/s \quad \left(\frac{57.5-39.3}{40.484-3}\right)=0.49\%/s$$

$$\frac{processRate}{mv2-mv1}=\frac{0.49}{8}=0.061\%/s$$

6. SIMULATION RESULT OF SYSTEM MODEL

All above parameters used in local PID controller through SCADA. Table 1 to Table 3 shows comparison of controller tuning methods on the basis of frequency domain specification, time domain specifications and performance indices respectively.

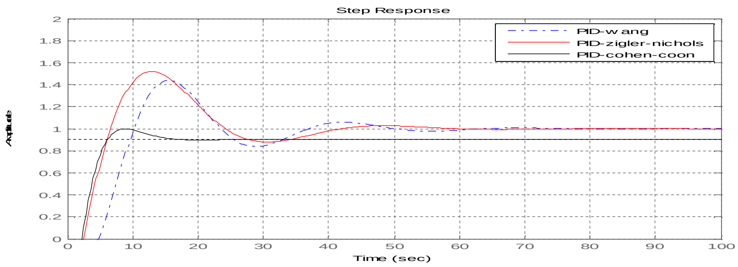

Fig. 6 simulation result of system model (20)

Table 1: Comparison of controller on the basis of frequency domain specification.

Model	Gain Margin in dB			Phase Margin in Degree		
Model given By (20)	W	Z-N	C-C	W	Z-N	C-C
	5.193	6.514	5.99	32.38	27.71	48.90

Table 2: Comparison of controller on the basis of time domain specification.

Model	Peak Overshoot (%)			Settling time (sec)		
Model given By (20)	W	Z-N	C-C	W	Z-N	C-C
	4.4	5.2	1.6	51	65	13

Table 3: Comparison of controller on the basis of performance indices.

Model	ISE			IAE		
Model given	W	Z-N	C-C	W	Z-N	C-C
By (20)	188.7	178.1	148.7	151.99	279.83	295.6
Model	ITSE			ITAE		
Model given	W	Z-N	C-C	W	Z-N	C-C
By (20)	11.58	38.48	42.87	11.4	20.8	21.9

\# W : Wang Method, Z-N: Ziegler- Nichol Method,
C-C: Cohen- Coon Method.

7. ROBUSTNESS ANALYSIS

In order to investigate the robustness of model in presence of uncertainties, the model parameters are randomly altered. For model obtained in (26), k=2.2, td=6 sec and tp= 40.484 sec. Let, these parameters be deviated as much as 20% from their nominal values due to model uncertainty. Let, there is 20% increase in dead time and gain and 20% decrease in time constant. Therefore, new model is:

$$Gp(s)=2.64\times\frac{e^{-7.2s}}{(1+32.3872)}$$

In this case, closed loop step response for Wang and Cohen coon method has more overshoot whereas Ziegler-Nichols result in unstable closed loop system. Figure (7) shows that closed loop response for Cohen-Coon and Wang methods are satisfactory.

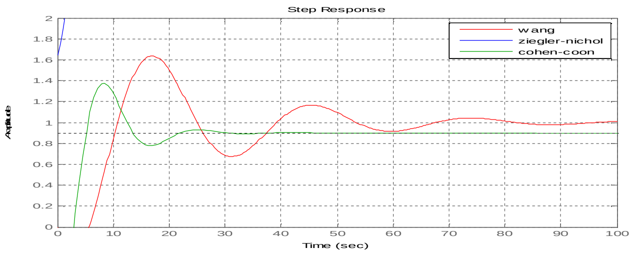

Fig.7 Closed loop step response with uncertainty of 20%

8. CONCLUSION

The temperature control system UT_321 is configured with SCADA system. Proportional band, derivative time and integral time are entered into SCADA and send to local PID controller. Output is recorded into excel file and plotted using MATLAB. It can be seen that the performance by Wang method is superior to remaining two methods. For Cohen-Coon method settling time and overshoot are less but its stability is less. If 20% deviation in system parameters is incorporated, Ziegler-Nichols method crops instability in the closed loop response. The Process Rate for UT_321 is 0.49%/sec and Reaction Rate is 0.061 %/sec.

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