Self-Tuning PID Controller Based on PLC

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Abstract: The conventional PID (Proportional-Integral-Derivative) control technique is widely used for the process control in many industries since it is simple in structure and provides the good response. Nowadays, this control technique has been developed on the Programmable Logic Controller (PLC) to use for the process control loop. However, using this technique is difficult when tuning the PID parameters (K_p, T_i *and* T_d) to achieve the best response. Moreover, trial-and-error procedure along with the operator experiences are required to obtain the best results when tuning the PID controller parameters. This paper proposes the self-tuning PID controller based on PLC for the process control in the industries. The proposed self-tuning PID controller uses the PLC-based PID structures to control the process production. The proposed PID tuning utilizes the PLC to synthesize and analyze controller parameter as well as to tune for appropriate parameters using Dahlin method and extrapolation. Experimental results using a self-tuning PID controller to control temperature of the oven show that the controller developed is capable of controlling the process very effectively and provides a good response.

Keywords: Self-tuning, PID controller, PLC and extrapolation

1. INTRODUCTION

PLC is widely used in most industrial control systems as a process controller since it is low-cost, easy to use, and flexible compared with the earlier relay controller. Although, the original PLC is designed for a sequence control system, nowadays, it has been applied to control the continuous system [1-3]. In general, the special function blocks such as PID control, fuzzy logic control, etc. are included in PLC software packages [3-4]. The PID control function block is commonly used to control the process in industries by reason of it can provide good performance [5-6]. However, tuning a variety of values of the PID controller for the best response of the process can be time consuming and may cause a mistake if user lacks skill and sufficient experience. Therefore, most PID controllers used in the real practice still require trial-and-error as well as the operator experiences when tuning to obtain the best results [7-8]. Alternatively, the self-tuning control can be applied [9]. This paper presents an idea of PID tuning which can automatically analyze and tune appropriate parameters for the process using Dahlin method and extrapolation. Using this technique, the parameter of the process used to calculate the PID parameter can be obtained quickly. Not only is this technique very easy to use, it also provides a good response of the process.

2. PRINCIPLE AND THEORY

Most of the automatic control systems in the industrial process are the feedback control as constructed in Fig.1.

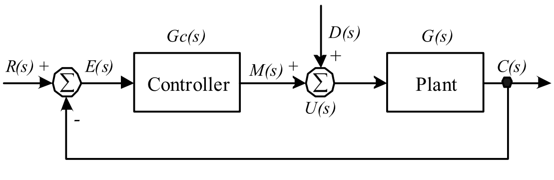


Fig. 1 Structure of the feedback control system.

As shown in Fig. 1, any control system has controller and plant. The plant consists of the final control element and the measurement with physical parameter(s). Controller is used to generate the control signal to the process. Usually, the controller is PID controller having the continuous equation as

$$m(t) = K_p\left[e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right] \tag{1}$$

where $m(t)$ =controller output signal
$e(t)$ =error signal
K_p =Proportional gain
T_i =Integral time
T_d = Derivative time

When the mathematical model of process is known, the process can be easily controlled. However, in the real world, it is difficult to obtain the process model accurately. Thus, the approximation of process parameters by the process testing is still common and being used in industry.

2.1 Process Characterization

Generally, the transfer function of the process is represented by the first-order lag plus dead time (FOPDT) model since it provides the good approximation for the process industries. Hence, there are three parameters to be concerned; the process time constant (τ), the process gain (K) and the process dead time (t_0). The transfer function of a FOPDT model can be written as,

$$G(s) = \frac{Ke^{-t_0 s}}{\tau s+1} \tag{2}$$

The straightforward method to find these three parameters is to test an open loop with unit step signal while the disturbance signal is neglected. Consequently, the S-shaped response sketched in Fig. 2 can be obtained. This response curve covers the second order or higher plants with damping ratio equal or greater than one.

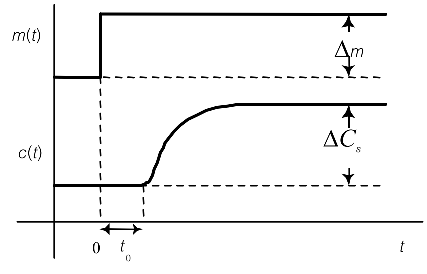


Fig. 2 Open loop step response of the process.

When the step change of controller output with the magnitude of Δm is applied to the process, the Laplace transform of the output response of the FOPDT process can be written as

$$C(s) = \frac{Ke^{-t_0 s}}{\tau s+1}\cdot\frac{\Delta m}{s} = K\Delta m\, e^{-t_0 s}\left[\frac{1}{s} - \frac{\tau}{\tau s+1}\right] \tag{3}$$

and

$$\Delta C(t) = K\cdot\Delta m\cdot u(t-t_0)[1-e^{-(t-t_0)/\tau}] \tag{4}$$

The term $u(t-t_0)$ of Eq. (4) is determined to make the $\Delta C_s = 0$ at $t \le t_0$.

The steady-state response can be given by Eq. (5) and the process gain can be obtained from Eq. (6).

$$\Delta C_S = \lim_{t\to\infty} \Delta C(t) = K\Delta m \tag{5}$$

$$K = \frac{\Delta C_S}{\Delta m} \tag{6}$$

Dead time of the process (t_0) is derived by checking time since the beginning until there is a response of the process about 1%. The time constant of τ can be obtained from the curve fitting procedure.

Given that $t_1 = t_0 + \frac{\tau}{3}$, $t_2 = t_0 + \tau$ (7)

$$\Delta C_1 = \Delta C(t_0 + \tfrac{\tau}{3}) = 0.283K\Delta m = 0.283\Delta C_s$$

$$\Delta C_2 = \Delta C(t_0 + \tau) = 0.632K\Delta m = 0.632\Delta C_s$$

hence, $\tau = \frac{3}{2}(t_2 - t_1)$ (8)

2.2 PID controller Parameter Synthesis

The PID controller parameter synthesis can be performed in closed-loop control. From Fig.1, the closed-loop transfer function with unity feedback can be expressed in terms of the controller transfer function as

$$G_C(s) = \frac{1}{G(s)}\cdot\frac{C(s)/R(s)}{1-[C(s)/R(s)]} \tag{9}$$

Theoretically, the most suitable response to feedback control system is the response in the form of First Order Lag. However, dead time of this control system remains negative making this controller becomes unpractical. Therefore, it is necessary to consider the control system, which provides First Order Lag response with dead time t_0 as shown in Eq. (10).

$$\frac{C(s)}{R(s)} = \frac{e^{-t_0 s}}{\tau_C s+1} \tag{10}$$

where τ_C is the closed-loop response time constant.

From Eq.(1), (9) and Eq. (10), where the exponential term can be approximated by a Taylor series expansion $e^{-t_0 s} = 1 - t_0 s$, the controller transfer function can be rewritten as

$$G_c(s) = \frac{\tau}{K(\tau_c + t_0)}\left[1 + \frac{1}{\tau s}\right] \tag{11}$$

Eq. (11) shows that the controller required for FOPDT model is the PI controller with tuning parameter as

$$K_c = \frac{\tau}{K(\tau_c + t_0)} \quad \text{and} \quad T_i = \tau \tag{12}$$

However, the Dahlin synthesis results for this FOPDT model is the PID controller with tuning parameter as shown in [10]

$$K_c = \frac{\tau}{K(\tau_c + t_0)}, \tau_I = \tau \quad \text{and} \quad \tau_D = \frac{t_0}{2} \tag{13}$$

The PID controller can be applied to the process control system when the process dead time t_0 is greater than $\tau/4$, otherwise, only the PI controller is used. If the response having an overshoot of 5% is required for the setpoint changes, $\tau_c = t_0$.

2.3 Extrapolation

Extrapolation is an estimation of future data by analyzing data obtained from various samplings. A suitable method of numerical analysis is Newton's Divided-Difference Extrapolating Polynomial. It is used in this paper to calculate Δc_s in advance. The value obtained from this calculation method has a slight error by using the following equation

$$\begin{aligned} f(x) &= f(x_0) + (x-x_0)f[x_1,x_0] + (x-x_0)(x-x_1)f[x_2,x_1,x_0] \\ &\quad + \ldots + (x-x_0)(x-x_1)\ldots(x-x_{n-1})f[x_n,x_{n-1},\ldots,x_0] \end{aligned} \tag{14}$$

when $f[x_1,x_0] = \dfrac{f(x_1)-f(x_0)}{x_1-x_0}$

$$f[x_n,x_{n-1},\ldots,x_0] = \frac{f[x_n,\ldots,x_1] - f[x_{n-1},\ldots,x_0]}{x_n - x_0}$$

x_n = data from each sampling

$f(x)$ = value from extrapolation

User is able to select suitable size of the sampling period. In this paper, 3 sampling data, x_0, x_1 and x_2, are selected to calculate future data x_3 and x_4 representing the tendency of process response. If $x_4 > x_3$, then it will calculate x_4 and x_5 from sampling data x_1, x_2, x_3. The calculation repeats until $x_n \ge x_{n+1}$ which is when the response becomes stable. Once the data is obtained, $x_n = \Delta c_s$, the computer will analyze the data and figure out the parameters from the test.

3. DESIGN AND OPERATION

The developed system uses PLC as PID controller to automatically analyze and tune the process's parameter. The process variable (*pv*) or response signal (standard analog signal 4-20 mAdc. or 1-5 Vdc.) from the process will be transmitted to the PLC via analog input module to calculate all parameters. The operation and monitoring of the process can be controlled by PC with the WinCC (Windows Control Center) software via PCI card interface (CP5611). This signal is used to analyze the process parameters and the PID controller parameters according to the proposed procedure.

When analyzing characteristics of the process, there is a test by inputting a unit step signal into the process so that user can select the appropriate size of the signal. In addition, dead time value of the process can be obtained from this test. Once the resulting response becomes stable, Δc_s is used to calculate steadystate gain and time constant of the process. With the test of analyzing the Δc_s the process takes some time until the response becomes stable. Therefore, in this paper, the numerical analysis is used to estimate value of Δc_s by comparing data from sampling while inputting the unit step signal during the test, which is called the extrapolation. The estimation by this method will help the process characteristic analysis take less time. When the process parameters are obtained, the PID parameters are computed and shown on the monitor; thus, user can decide whether this PID parameter's tuning is satisfied. If the user agrees on these parameters, the process will be automatically controlled and the response is shown on the monitor. The operation flowchart of the proposed control technique according to the IEC1131-3 standard [11], which is written using the ladder diagram, function block diagram, and function list, is shown in Fig. 3. The operation diagram can be seen from Fig. 4.

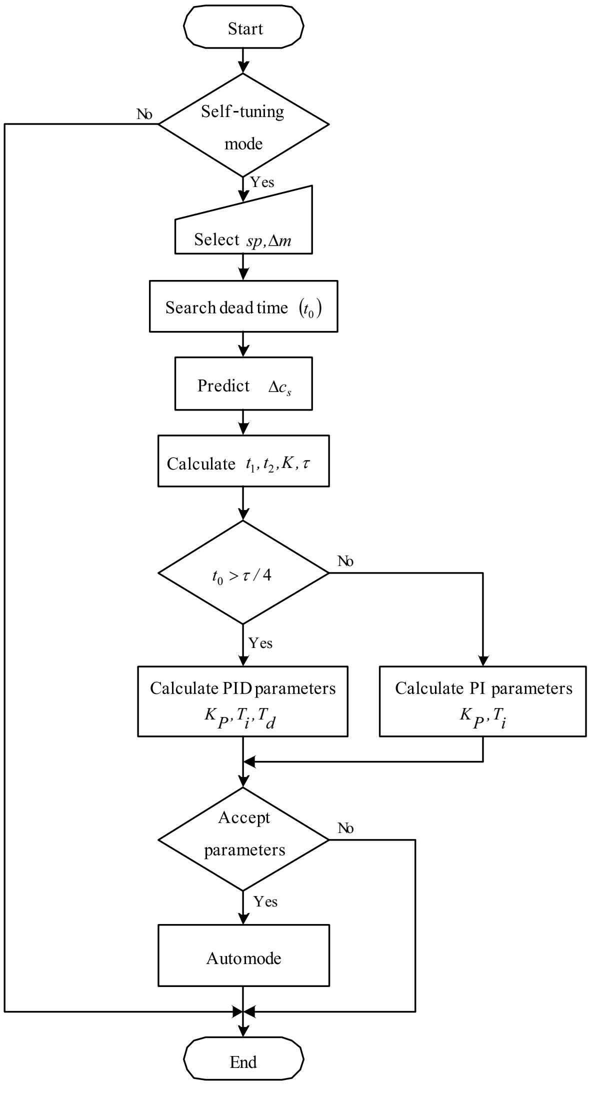


Fig. 3 Operation flowchart.

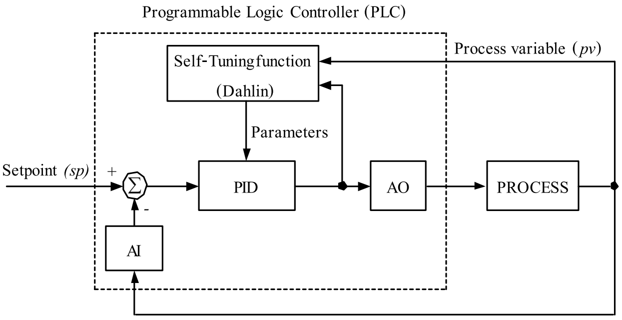


Fig. 4 Operation diagram of the proposed control system.

4. EXPERIMENTAL RESULTS

The performance of the proposed controller was observed from the experiments with temperature control of the oven. Fig. 5 - Fig. 7 show the experimental setup.

Fig. 5 Control station (PC, PLC and PCI interface card).

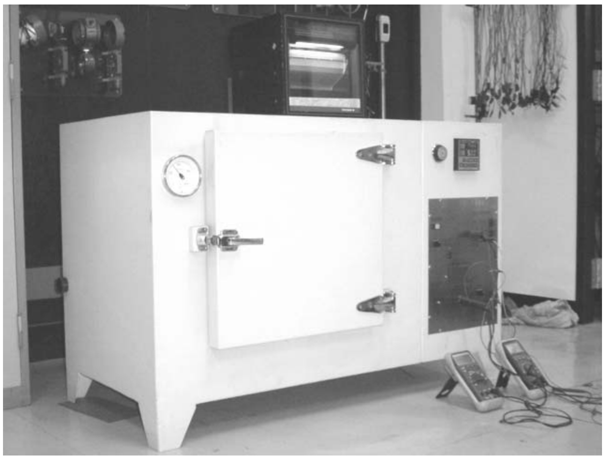


Fig. 6 Temperature control plant model (oven).

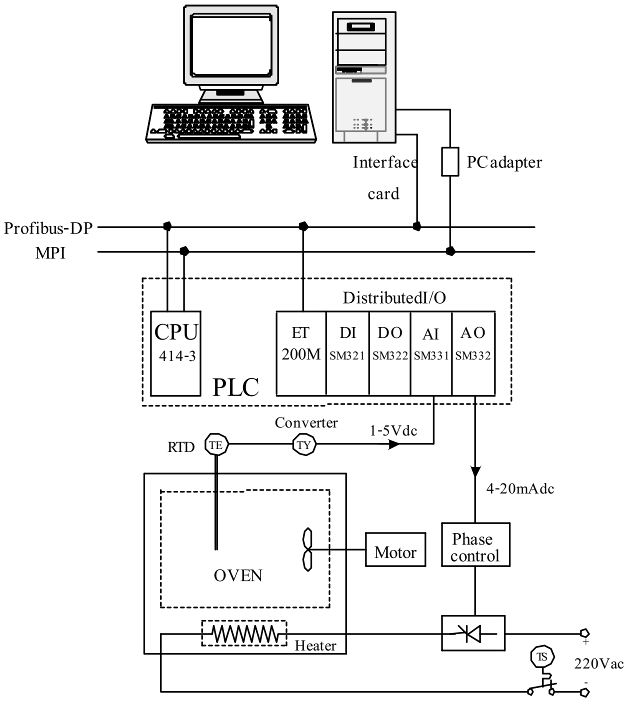
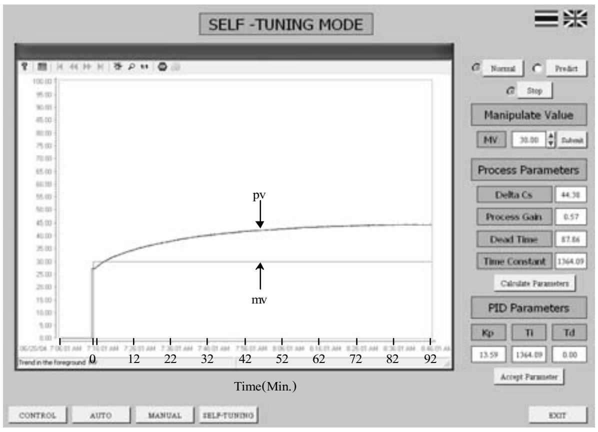


Fig. 7 Experimental setup diagram.

In the experiment, the PLC of SIEMENS by SIMATIC S7 family is used. This PLC system consists of the CPU414-3, Distributed I/O station (ET200M, SM321, SM322, SM331, and SM332), PC Adaptor, CP5611 PCI card, STEP7 Manager software (to write the ladder diagram, function block diagram, and function list), and WinCC software (to design the user interface). All are communicated via Profibus-DP protocol.

The process characterization by the process reaction curve and extrapolation of the experimental thermal plant are shown in Fig. 8 and Fig. 9, respectively. Fig. 10 shows the comparison of the process characterization of both procedures.



MV 30.00

Delta Cs 44.38

Process Gain 0.57

Dead Time 87.86

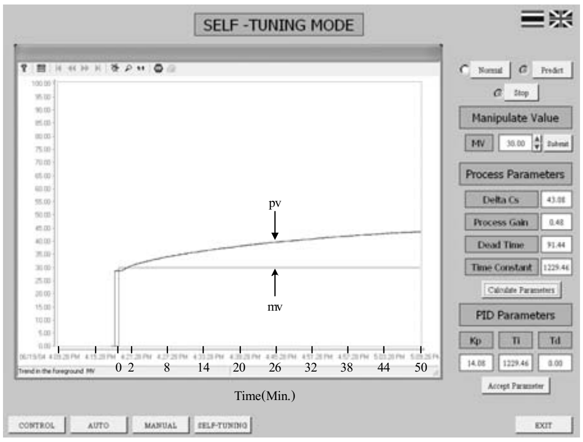
Time Constant 1364.09

Kp 13.59

Ti 1364.09

Td 0.00

Fig. 8 Open loop step response at $\Delta m = 30\%$ in normal mode (process characterization by process reaction curve).



MV 30.00

Delta Cs 43.08

Process Gain 0.48

Dead Time 91.44

Time Constant 1229.46

Kp 14.08

Ti 1229.46

Td 0.00

Fig. 9 Open loop step response at $\Delta m = 30\%$ in the predictive mode (process characterization by extrapolation).

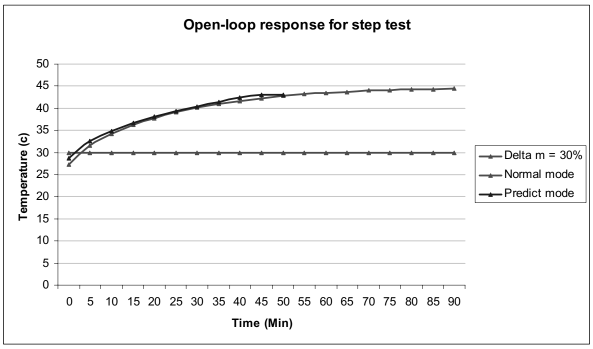


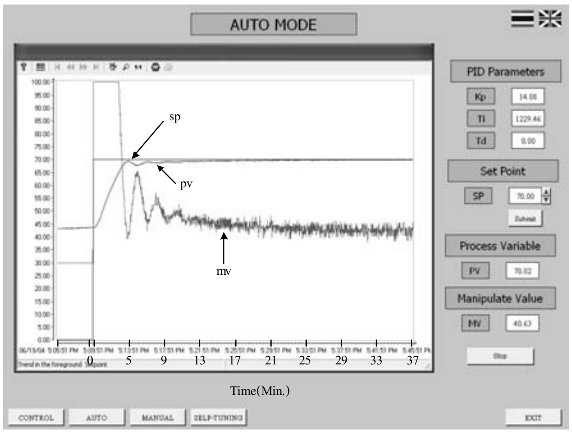
Fig. 10 Open loop step response in normal mode compare with predictive mode ($\Delta m = 30\%$).

From Fig. 8, the process characterization in normal mode by the process reaction curve can be obtained. The time consumed to obtain the process parameters is approximately 90 minutes with $K = 0.57$, $\tau = 1364.09$ sec., $t_o = 87.86$ sec., and $\Delta c_s = 44.38$ °C. The predictive mode gives $K = 0.48$, $\tau = 1229.46$ sec., $t_o = 91.44$ sec., and $\Delta c_s = 43.08$ °C with time spent approximately 50 minutes (Fig. 9). The results show that the performance of the process characterization in predictive mode is fast and Δc_s are slightly different, only 1.3°C.

The step response of temperature control at setpoint 70 °C. and temperature control at setpoint 70 °C with step change to setpoint 90 °C. using the PID parameters obtained from the predictive mode with $K_p = 14.08$ and $T_i = 1229.46$ sec. are shown in Fig. 11 and Fig.12, respectively.

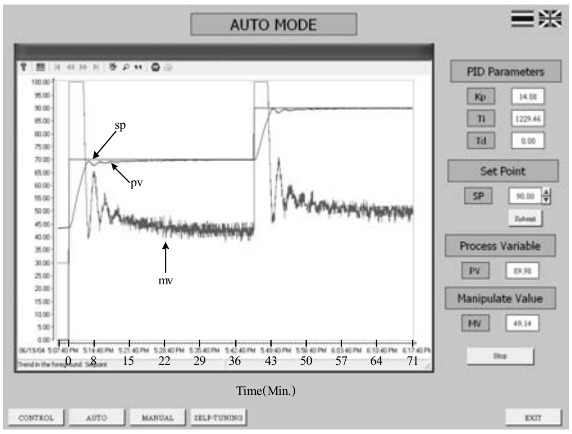
5. CONCLUSIONS

This paper proposes the self-tuning PID controller based on PLC for the process control in the industries. The proposed self-tuning PID controller can automatically analyze and tune the appropriate PID parameter for the process without any error or damage that may occur due to insufficient skill of user. The extrapolation is applied to estimate the process parameters from a process open loop step test based on first-order lag plus dead time (FOPDT) model. Using this technique, the process parameters used to synthesize the PID parameter by the formula of Dahlin can achieve in a short time. In addition, the proposed controller structure can determine to synthesize the PID parameter by Ziegler-Nichols and Coon-Cohen formulas and others methods if required. According to experimental results of the temperature control process, it is shown that using the proposed controller can provide the good performance of the control system.



Kp 14.08
Ti 1229.46
Td 0.00
SP 70.00
PV 70.02
MV 40.63

Fig. 11 Step response of temperature control at setpoint 70 °C.



Kp 14.08
Ti 1229.46
Td 0.00
SP 90.00
PV 89.98
MV 49.14

Fig. 12 Step response of temperature control at setpoint 70 °C and step change to setpoint 90 °C.

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