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Research Article

PLC-based Smith Predictor for Control of the Temperature Process with Long Dead Time

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Abstract: This study presents the development of dead-time compensator with Proportional Integral-Derivative (PID) controller and their implementation in real-time using the Programmable Logic Controller (PLC) on a heater-furnace system that constitute the temperature process. Though PID controller is effective to most of the processes, it has draw backs when used to control the processes with significant dead time. Therefore to eliminate the effects of long dead time, the dead-time compensator combined with PID is proposed. The control equation for the proposed dead time compensator is developed using the mathematical model of heater-furnace system and ladder logic program is created in GE Fanuc Versamax PLC. The PID controller is tuned using process reaction curve method and programmed in PLC. The proposed controller has an outer loop control mechanism with dead time compensator which feeds the inner loop PID controller. The effects of dead time on the performance of PID controller are eliminated through the outer loop control mechanism whose output does not contain modelling errors. The results of the proposed dead-time compensator with PID are compared with the results of the conventional PID controller without dead time compensation for both steady state response and servo-regulatory response. The results of the proposed controller show better improvement in the time domain specifications compared to conventional PID controller.

Keywords: Dead-time compensator, GE Fanuc PLC, long dead time, PID controller, temperature process

INTRODUCTION

Most control problems in the process industry are solved using PID controllers. The predominant reason is that the PID controller can be tuned manually by “trial and error” procedures, as it only has three adjustable parameters. The possibility to make manual adjustments in the controller parameters is significant though automatic tuning procedures are available, Astrom and Hägglund (1995). The PID control algorithm is widely used in process industries because of its simplicity, robustness and successful practical application. When there are long dead times in the process, the control performances obtained with a PID controller are, however, limited. For these processes, Dead Time Compensating controllers (DTCs) may improve the performance considerably (Smith, 1959). These controllers require a process model to develop model predictive control. This usually means a significant increase in controller parameters and thus the complexity of the controller design, Astrom and Hägglund (1995). It has been found in practice that the widely used PID controller would rapidly lose its effectiveness when the process dead time becomes significant, Astrom *et al*. (1994). PID controllers with dead time compensation are reported to eliminate dead time. However, for unmeasured load disturbances at the process input, the ultimate performance is set by the total dead time from the process equipment, piping, control valves, instrumentation and digital devices. This shows that a dead time compensator can offer some improvement in load rejection by facilitating more aggressive tuning of the PID but with a considerable risk of oscillations from an inaccurate dead time. In the process industries, the occurrence of “dead time” or “transportation lag” is very common. For the majority of simple control loops, the amount of dead time is usually not significant when compared to the time constant, Astrom *et al*. (1994). For more complicated control loops like those for quality control, dead time can be very significant and may even be longer than the system time constant. The reasons for this include analysis delay and the down-stream location of the sampling point for the quality analyser. Another class of examples is characterized by a multitude of small lags, such as a long bank of heat exchangers, or a distillation column with many trays, giving rise to what is called “apparent” dead time.

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Normey-Rico and Camacho (1999) proposed a dead time compensator with three adjustable parameters. Matausek and Micic (1996) proposed a modified Smith predictor (MSP) for controlling higher-order processes with integral action and long dead-time. Matausek and Micic (1999) proposed a MSP with tuning formulae. Furukawa and Shimemura (1983) proposed a prdeictive control mechanism to stabilize an unstable plant with time delay. Gawthrop (1977) proposed a predictive controller based on adaptive least square method. Guzmán *et al*. (2008) presented an interactive tool for studying and understanding the different alternatives available for controlling systems with large delay. Hagglund (1992) described a predictive PI (proportional-integral) controller with dead-time compensation. Hamamchi *et al*. (2001) considered the Coefficient Diagram Method to achieve a good step response to a set point change. Ingimundarson and Hägglund (2001) described tuning procedures for dead-time compensating controller by considering both stable and integrating processes. Ingimundarson and Hägglund (2002) validated the dead-time compensator (DTC) using the performance criterion integrated absolute error when a step load disturbance is applied at the plant input. Kristiansson and Lennartson (2006) presented tuning methods for PI and PID controller. Kaya (2003) extended the modified PI-PD Smith predictor which leads to significant improvements in the control of processes with large time constants. Liu *et al*. (2005), proposed a proportional controller is subtly employed to stabilise the setpoint response and then an optimal controller is analytically designed for setpoint tracking. Normey-Rico and Camacho (2002) proposed a unified 2 degrees of freedom robust dead-time compensator, for both stable and integrative plants. Normey-Rico and Camacho (2008) reviewed the main dead-time compensators (DTC) described in literature. Palmor and Blau (1994) developed an automatic tuning algorithm for DTC common to industrial process controllers. The auto-tuner is capable of setting eight tuning parameters. Pagano *et al*. (2001), analysed the methods of stability for MSP with integrative plant. García and Albertos (2013) proposed a general structure to control long time-delay plants is proposed without approximating the delay. Rao and Chidambaram (2005) suggested a modified form of Smith predictor for unstable processes with time delay. Vrečko *et al*. (2001) presented a new MSP for processes with a long time delay as an extension of the double controller-scheme. Watanabe and Ito (1981) proposed a new process-model control system which can yield zero steady-state error and desired transient responses.

In the proposed approach Smith Predictor based dead-time compensator is added to the PID control loop to eliminate effects caused by the long delay time in the process. This model-based controller is theoretically a good solution to the problem of controlling the time delay systems. This approach improves the performance and robustness of the system in the real time applications. This helps in maximized utilization of the PLC ladder logic functions. Another important part is that the cost spent on purchasing PLC software with the non-conventional PID toolboxes can be greatly reduced. The GE Fanuc Versamax PLC that supports arithmetic operation and floating-point data types is used to develop the control program for dead-time compensator. The heater-furnace system available in the process control lab is considered for implementing the control scheme. Therefore to eliminate the effects of long dead-time in temperature of the heater-furnace system, DTC with PID controller is proposed and implemented using the GE Fanuc Versamax PLC. The steady-state and servo-regulatory responses of DTC-PID controller is validated with conventional PID controller.

MATERIALS AND METHODS

Heater-furnace system: The heater-furnace (known as temperature system) system that is available in the process control lab of the institution is used as the test system. The furnace takes considerable time to respond to the heat supplied by the heater. This creates a dead time in the process and is significantly high. The front panel of the heater-furnace system is shown in the Fig. 1. The system contains an electrically heated furnace, a k-type thermocouple, temperature transmitter, Silicon Control Rectifier unit (SCR) and a blower. The output range of thermocouple is 0 mV to 49.988 mV with a temperature range of about 0 to 1000°C. An electrical heater is used to heat the furnace and a blower is used to maintain a uniform temperature around the furnace. The thermocouple senses the temperature and the transmitter converts the mV signal into 4 to 20 mA current standard. The transmitter output is connected to the PLC analog input module. The 4 to 20 mA output from the PLC is wired to the SCR circuit which actuates the heater.

GE Fanuc Versamax PLC: The GE (General Electric) Fanuc Versamax PLC available in the process control lab is chosen as controller to develop smith predictor. The PLC has 16 numbers of digital inputs and 16 numbers of digital outputs. It also has 4 analog inputs and 4 analog outputs. The analog Input-output module supports both (0-10) V range and (4-20) mA standard. The PLC supports arithmetic instructions and floating-point data types other than integer-type data. The IC200CPU001 is used as the processor for the PLC module (VersaMax® PLC User's Manual, 2001).

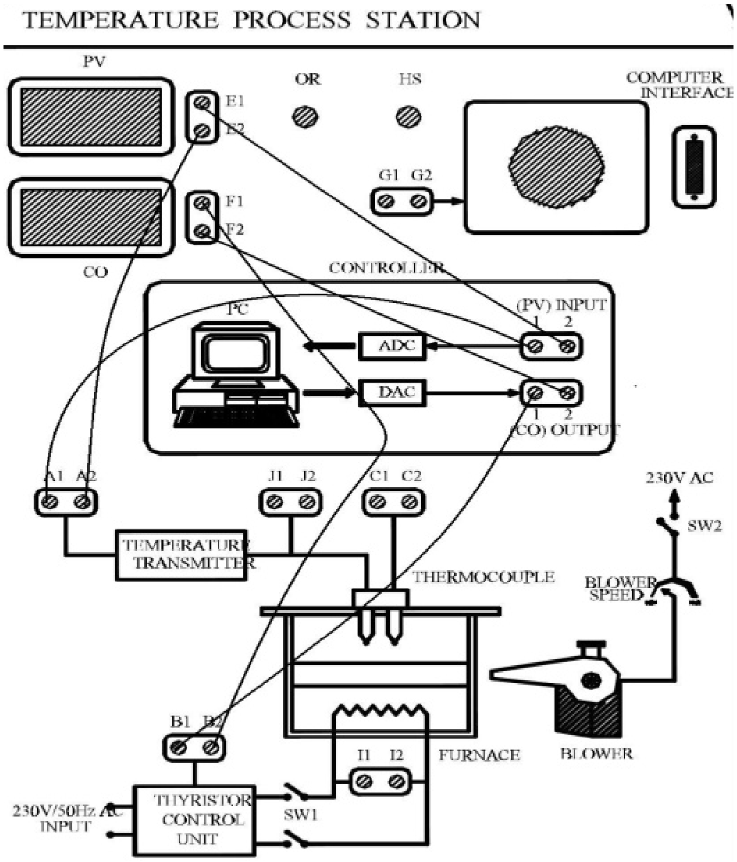

Fig. 1: The front panel of the heater-furnace system

The processor, input and the output modules are powered by a 24 VDC power supply module. The PLC has a RS 232 communication interface to communicate with the Personal Computer (PC). The control algorithm is programmed in the PC and downloaded into the PLC's CPU using the RS 232 communication interface.

PID Controller: The Proportional Integral Derivative (PID) control is widely used in process industries because of its simplicity, robustness and successful practical application. Although advanced control techniques can show significantly improved performance, a PID control system can suffice for many industrial control loops. Although, a PID controller has only three adjustable parameters, finding appropriate settings is not simple, resulting in many controllers being poorly tuned and time consuming plant tests often being necessary to obtain process parameters for improved controller settings.

There are several approaches for controller tuning, with that based on an open-loop model being most popular. This model is typically given in terms of the plant's gain (K), time constant (τ) and time delay (θ). For a given a plant model, controller settings are often obtained by direct synthesis.

The following is the control equation of PID Controller which has several variants in discrete form:

$$u(t) = K(e(t) + \frac{1}{\tau_i}\int_0^t e(\tau)d\tau + T_d \frac{d_{e(t)}}{dt}) \tag{1}$$

$$e(t) = y_r(t) - y(t) \tag{2}$$

where,
u = The control signal
e = The error signal
$y_r(t)$ = The reference signal
$y(t)$ = The process variable
K = The gain
T_i = The integration time
T_d = The derivative time

Thus, the PID controller can be understood as a controller that takes the present, the past and the future of the error into consideration. The transfer function $G_C(s)$ of the PID controller is:

$$G_c(s) = K_p(1 + \frac{1}{s\tau_i} + T_d s) \tag{3}$$

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{4}$$

It is difficult to obtain satisfactory performances of control systems with time delay, which is a well-recognized problem in many control processes. Time delay, also called dead time, is mostly aroused by transportation lags, measurement lags, analysis times, computation and communication lags and Sensor lags. It exists in a lot of systems such as industrial process control systems, engineering systems, economical and biological systems.

These dead times can stem from process dynamics, actuators or sampling. The delays are often either assumed negligible or constant, but in some cases the variance in delay times (jitter) plays a significant role. There exists a variety of methods for control of time-delay systems with constant delays, but the toolset for dealing with varying time-delays is much more limited.

The general first-order transfer function in continuous domain is described by equation:

$$G_p(s) = \frac{K}{1+s\tau} \tag{5}$$

Dead time (θ) is the time delay between the process and the sensor. The transfer function for dead time is:

$$G_p(s) = e^{-\theta ds} \tag{6}$$

Causes of dead time:

- **Transportation lag:** The Transportation Lag is the delay between the time an input signal is applied to a system and the time the system reacts that input signal. It is common in Industrial process.
- **Sensor lag:** Sensors and analyzer can take precious time to yield their measurement results

Effects of dead time on the system: Time delay occurs in the control system when there is a delay between command response and the start of output response. The delay cause a decrease phase margin which implies a lower damping ratio and a more oscillatory response for the close-loop system. Further it decreases the gain margin thus moving the system to instability. First-order process model with dead time which is represented as:

$$G_p(s) = \frac{K}{1+sT}\, e^{-\theta ds} \tag{7}$$

where,
K : Process gain
T : Process time constant
θ : Dead time constant

Figure 2 depict the occurrence of oscillation with delay which will affect the system. This will automatically produce more delay. Therefore eliminating the effects of dead time from the system becomes more significant.

Dead-time compensator with PID: A new control strategy for the Dead Time Compensator (DTC) that replaces the conventional controller by a PID structure is proposed. The Smith Predictor is one of the most popular dead-time compensating controller and most widely used algorithm for dead-time compensation in industry. The proposed controller uses the Smith Predictor dead time compensator with PID thus eliminating the effect of dead time from the control performance, meanwhile with holding the effectiveness of PID. This is a model-based controller effective for processes with long dead time. It has an inner loop with a main controller that is designed without the dead time.

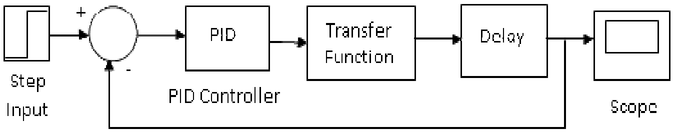

Fig. 2: Simulink diagram of PID controller with dead time

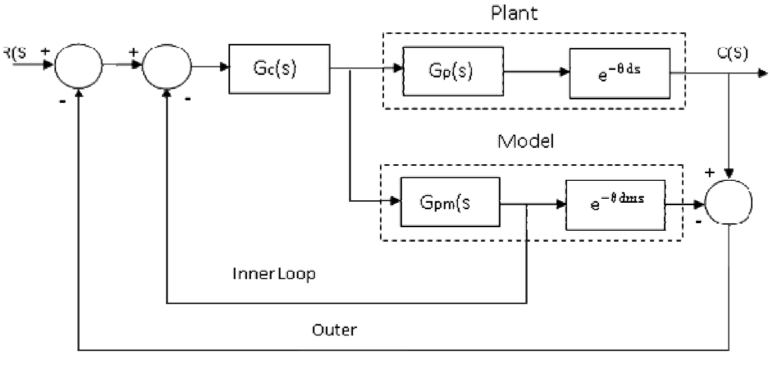

Fig. 3: The structure of Dead time compensator (Hamamchi *et al.*, 2001)

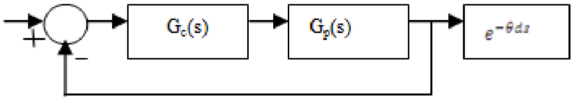

Fig. 4: Equivalent form of DTC with PID

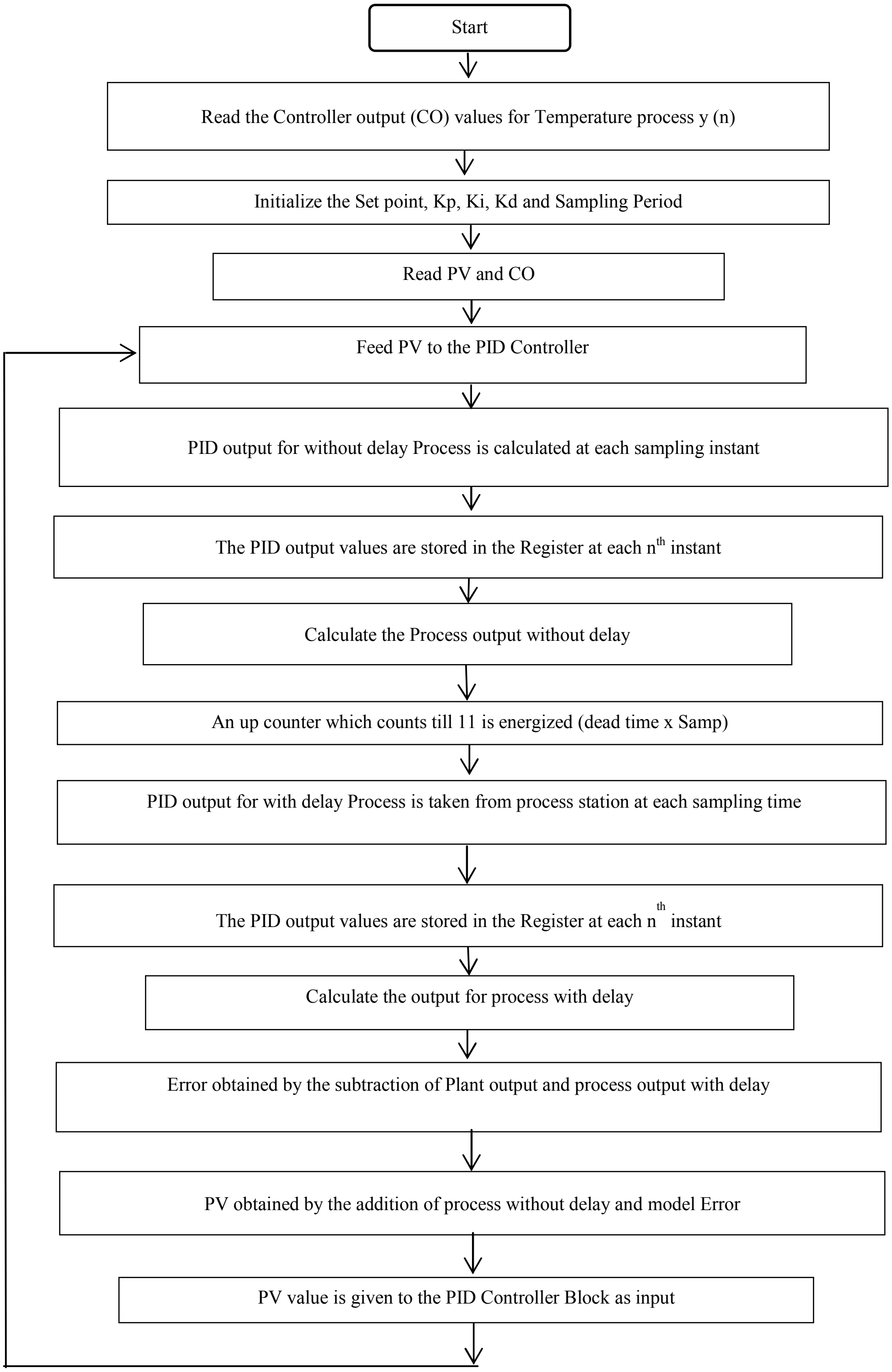

Fig. 5: Flowchart for control program

The effects of load disturbance and modelling error are corrected through an outer loop. $G_c(s)$ is the transfer function of the controller in continuous domain. $G_p(s)$ is transfer function of the plant, $e^{-\theta ds}$ is Dead time of the plant. $G_{pm}(s)$ represent the transfer function for the model of the plant, $e^{-\theta dms}$ is the dead time of the plant model. The closed loop transfer function without DTC would be (Hamamchi *et al.*, 2001):

$$\frac{C(s)}{R(S)} = \frac{G_C(S)G_P(S)e^{-\theta ds}}{1 + G_C(S)G_P(S)e^{-\theta ds}} \tag{8}$$

And the closed loop characteristic equation is:

$$1 + G_C(S)G_P(S)e^{-\theta ds} = 0 \tag{9}$$

The time delay item $e^{-\theta ds}$ in characteristic equation could produce phase lag and make the system unstable. Then the closed loop transfer function with DTC is:

$$\frac{C(S)}{R(S)} = \frac{G_C(S)G_P(S)e^{-\theta ds}}{1 + G_C(S)G_P(S) + G_C(S)G_P(S)e^{-\theta ds} - G_C(S)G_{Pm}(S)e^{-\theta dms}} \tag{10}$$

In the case of $G_p = G_{pm}$ and $\theta_d = \theta_{dm}$, the transfer function can be written as:

$$\frac{C(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-\theta ds}}{1+G_c(s)G_p(s)} \tag{11}$$

The corresponding characteristic equation is:

$$1 + G_c(s)G_p(s) = 0 \tag{12}$$

It can be observed that the time delay is eliminated in the characteristic Eq. (12) which will improve the control performance significantly. From the Eq. (12), the Fig. 3 is equivalently transformed to Fig. 4 as follows:

Design and development of DTC Using PLC: The open loop transfer function obtained from the temperature process station is given as in Eq. (13); K= 0.61234, τ = 10.06, td = 56 sec, Where K is the process gain, τ is the time constant and td is the delay time. The transfer function obtained from this process parameters are, (Balaji and Vijayakumar, 2009):

$$G_p = \frac{0.61234\, e^{-56s}}{10.06s+1} \tag{13}$$

Transfer function in Eq. (13) can be converted into discrete form using Z-transformation. The control equation for DTC for temperature process in discrete-time domain from Eq. (10) is:

$$m_1(n) = 0.06086\, u(n) + 0.0550\, u(n-1) + 0.0497\, u(n-2) + 0.0449\, u(n-3) + 0.0406\, u(n-4) + 0.0367\, u(n-5) \tag{14}$$

where, $m_1(n)$ represents the Plant model output without delay. The control action at the n^{th} and $(n-1)^{th}$ sampling instants represented as u(n) and u(n-1) as in Eq. (14). The output from the temperature process station (4-20 mA) is given as input to the PID controller. The DTC is designed based on the discrete transfer function as in Eq. (14) and the control program is written in PLC using the ladder logic functions. The output of the heater-furnace system is read through the analog input module of the PLC. In each sampling time (5 Sec), the output of the DTC is compared with the output of the heater-furnace system. The error generated from the comparison is summed up with the model output from the inner loop. The error output is taken as the measured value or process variable and given to the PID controller. The velocity-form of PID (VFPID) controller is developed in PLC. In this form, instead of the actual value of the controller output signal, its change from the preceding sampling instant is computed.

The tuning of VFPID for the heater-furnace system is done using process reaction curve method (Balaji and Vijayakumar, 2009). The PV (Process Variable) is given as input to the PID controller and the above steps are repeated up to the process station reached the given set point. Figure 5 the step-by-step procedure implemented in developing the control program for the proposed DTC with PID controller is shown.

RESULTS AND DISCUSSION

The results obtained and the performance measures of the proposed DTC with PID controller is presented and compared with the results of the conventional VFPID controller. The proposed DTC with PID controller is implemented in real time for reducing the effects of dead time in heater-furnace system.

Simulation results: The heater-furnace system is a slow responding process as compared with that of a flow or level process. Therefore VFPID controller is preferred over the position-form PID (PFPID) controller. The open-loop tuning method called process reaction curve method is used to tune the gain values of the PID controller, (Balaji and Vijayakumar, 2009). The Simulink diagram of VFPID and DTC with PID controllers are shown in Fig. 6. The simulation result of the tuned VFPID controller is compared with the simulation result of the proposed DTC with PID controller.

Figure 7 shows the simulation results for conventional PID (VFPID) and DTC with PID which are taken to ensure the correctness of the controller design for the heater-furnace system with mathematical model. It is evident from the response shown in Fig. 7, that the DTC with PID has performed better in steady-state conditions. The overshoot posed by VFPID is completely eliminated in the simulated response of proposed DTC with PID controller. Figure 8 shows the error between the process model and actual heater-furnace system.

Real-time results for VFPID: Figure 9 shows the response of the VFPID controller with Dead time and overshoot. It is seen that VFPID controller takes long time to reach set point and has a high overshoot.

The Peak overshoot is about 6.25°C and the rise time is 9 min. The Output of the VFPID controller takes

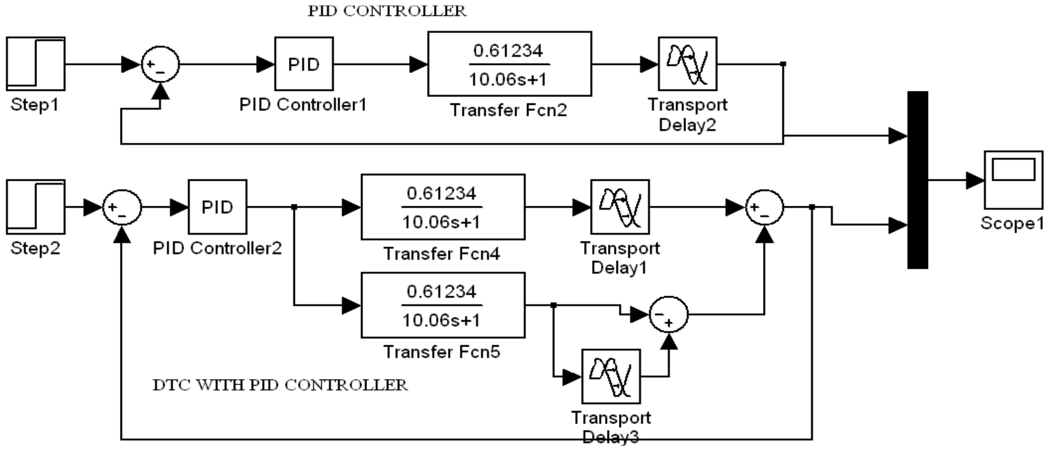

Fig. 6: Simulink diagram for PID and proposed DTC with PID for heater-furnace system

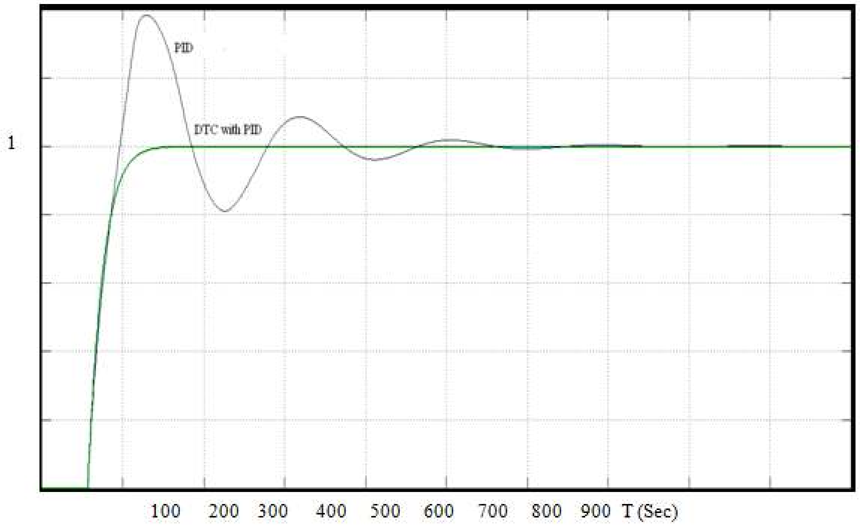

Fig. 7: Response of VFPID and DTC with PID for temperature process

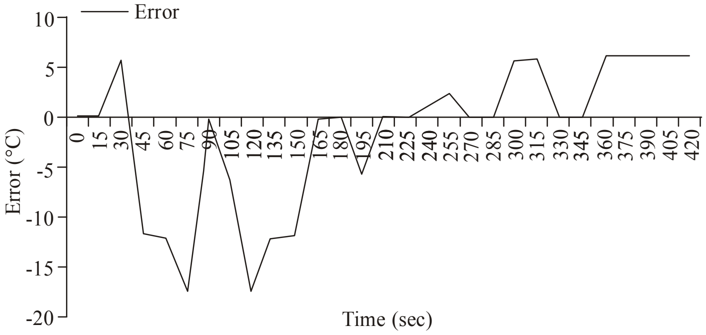

Fig. 8: Error between the actual system and system model

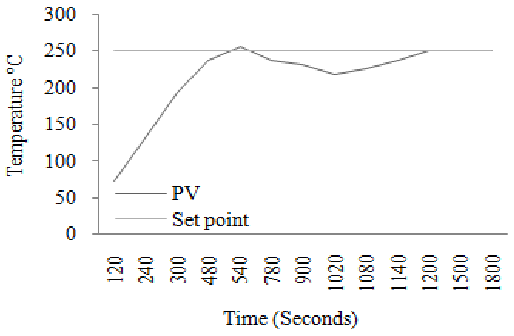

Fig. 9: Response of VFPID controller

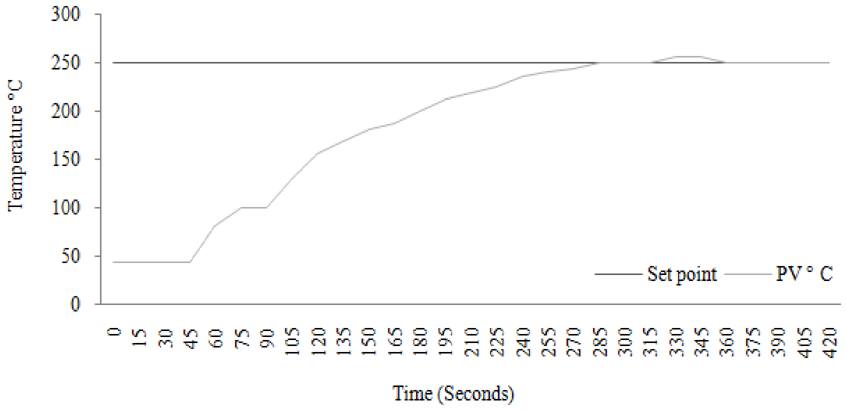

Fig. 10: Response of DTC with PID

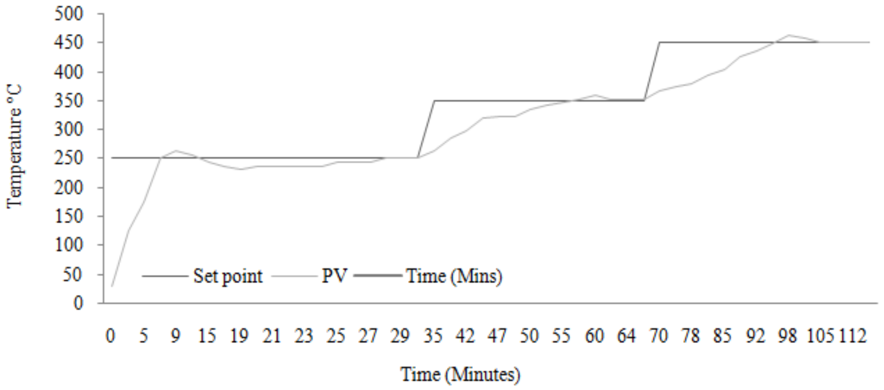

Fig. 11: Servo-regulatory response for VFPID

Table 1: Performance comparison of time domain specifications of DTC with PID and VFPID

Type of controller	Rise time (Min)	Peak (°C)	Over shoot (%)	Settling time (Min)
DTC with PID	4	256.0	2.68	6
VFPID	9	256.0	2.40	20

20 min to reach the set point. The parameters of PID controllers are Kp = 4; Ki = 0.001; Kd = 0.1; Sampling time, Ts = 5 sec.

Real-time results for DTC with PID: The online results obtained on implementing the DTC with PID for the heater-furnace system is shown in Fig. 10. It is observed that there is a significant reduction in overshoot and settling time.

Though a peak overshoot of about 6.0°C has occurred the rise time is just 4 min which indicate that the response of DTC with PID is faster than VFPID. This is because of the fact that the DTC with PID has eliminated the effects of dead time. The settling time of

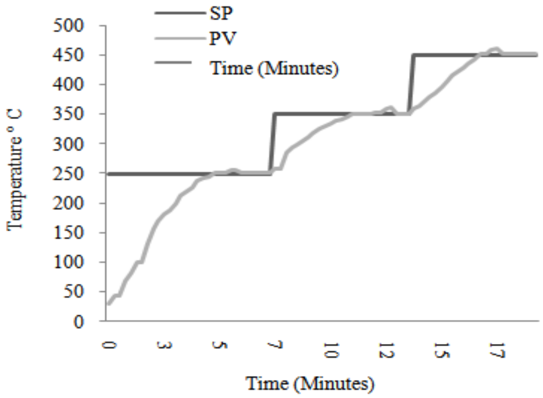

Fig. 12: Servo-regulatory response for DTC with PID controller

the proposed DTC with PID is about 6 min which is much faster than the VFPID controller. The parameters for PID controller are Ts = 5 sec; Kp = 4; Ki = 0.001; Kd = 0.1.

The time domain specifications such as rise time, settling time, overshoot time and peak time are obtained from the results.

Table 1 compares the results of VFPID controller and DTC with PID controler. It is evident from the time-domain specifications that the use of DTC with PID for heater-furnace system has performed better than the VFPID controller.

Figure 11 and 12 shows the set point tracking capability of the VFPID controller and DTC with PID controller respectively. The initial set point 250°C is tracked by both controllers. The set point change of about 100°C is applied to both controllers once the initial set point is reached.

The settling time of VFPID is from 20 to 30 min in all the three cases, where as the DTC with PID takes much lesser time around 7 min to track the set point changes.

CONCULSION

The effect of dead time in the steady response can be eliminated by DTC. In the present work, the proposed DTC with PID has eliminated the long delay time in the heater-furnace system. The control program for VFPID and DTC with PID is developed using GE Fanuc Versamax PLC and interfaced with the heater-furnace system. The results of the steady state response and servo-regulatory response indicate the DTC with PID controller has performed better than the conventional VFPID in time-domain specifications. However the overshoot of 6°C observed in VFPID is not minimized in DTC with PID also. This induces further work to design a more robust controller which minimizes the overshoot meanwhile eliminating the effects of dead time.

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