Performance Comparison of Dead-time Compensation Schemes for Processes with Dead-Times

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ABSTRACT

A dead time that is typically connected to the industrial operations' input and output. A particular kind of control device designed to deal with time delays is called a dead-time compensator (DTC). DTCs can now be found in commercial control systems as standard modules. Numerous DTC techniques have been proposed and effectively applied in real-time under computer control. This work presents a comparative analysis of the Proportional Integral Derivative (PID), Smith Predictor (SP), Predictive PI (PPI), and Proportional Delayed Integral (PDI) controllers as they relate to processes that have a dead time. Using the Integral Absolute Error (IAE) and Total Variation (TV) in manipulated variable criterion for the First Order Plus Dead-Time (FOPDT) model with different dead-time values, the effectiveness of these control systems is assessed. Further, the robustness metrics such as gain margin and phase margin are computed and compared. Also, the schemes are validated in the level control process and the results are presented. In this work, the outcomes of this comparison study have been analysed in detail and presented with numeric examples.

Keywords: Dead-Time; Smith Predictor; PID Controller; PPI Controller; PDI Controller; Dead-time Compensation.

1. Introduction

PID is the most widely used and fundamental algorithm for feedback control [1]. PID tuning is difficult if there is a large amount of dead time in the operation. A loop with a high dead-time, for example, will respond with an excessive oscillation if the PID is aggressively tuned. Slowly tuned PIDs, on the other hand, will not work well for loops with limited dead time. Furthermore, it is unsuitable to use the derivative of the measured signal for prediction when dealing with systems that have a considerable dead time. Thus, in systems where dead time is dominating, the derivative component is often disconnected.

Smith, 1957 [2] was among the first articles to address dead time in particular. The dead-time compensator that was described there has been referred to in the literature as the Smith predictor, and the term has evolved to mean dead-time compensator in general. Smith demonstrated how a plant's design issue with dead time may be simplified to a plant design issue without dead time. A DTC that fixed part of the model's and controller's parameters concurrently was reported in Hägglund, 1996 [3], reducing the number of parameters from five to three. The disregard for complexity is still very frequent. In Normey- Rico et al., 1997 [4], a filtered PPI controller was suggested. Explored in [5, 6] are the dead-time compensation capabilities of the widely used Internal Model Control (IMC) scheme.

The literature contains numerous DTC systems that are based on various process types and closed loop goals. Dead-time compensators (DTCs) are primarily of two types: those that are obtained by merely inserting a time delay element into the integral feedback loop of a PI/PID [13–17] controller, or those that are constructed as the Smith predictor and their modified schemes [6–12]. Time delay is specifically used in the controller's architecture by the Proportional Delayed Integral (PDI) controller [13]. PID dead-time controllers have settings for distributed processes and incorporate a time delay component into the integral feedback circuit of PID controllers. A comparison of PID and dead-time compensating controllers' performances is shown in [17].

In this work, comparison study between the PID controller, Smith Predictor (SP), Predictive PI (PPI) controller and Proportional Delayed Integral (PDI) controller has been performed. Dead-time compensation schemes are discussed in section 2 and comparative analysis has been presented in section 3 followed by conclusions in section 4.

2. Dead-time Compensation Schemes

2.1 PID Controller

A common feedback loop controller used in industrial control applications is PID. The PID controller comes in three varieties. The standard or "non-interacting" form, the series or "interacting" form, and the parallel form are what we mean by these terms. The ideal form, where terms don't interact in time, is the standard form. The PD and PI controllers are connected in series using the series or "interacting" algorithm, which is exactly how earlier pneumatic and certain analogue controllers functioned. It is the most constrained of the three forms. The parallel form is the most versatile and "mathematician's" form out of the three. The parameters have little physical interpretation in this form.

Complex zeros are allowed in the standard form, which is advantageous when regulating oscillatory systems. The parallel form also permits pure integral or proportional action. The most intuitive form to tune is supposedly the series form. The generic transfer function for a parallel form of PID controller (shown in Figure 1.) is

$$G_c(s) = K_P + \frac{K_I}{s} + K_d s \qquad (1)$$

Where, K_P, K_I, K_d are proportional, Integral and Derivative gain respectively.

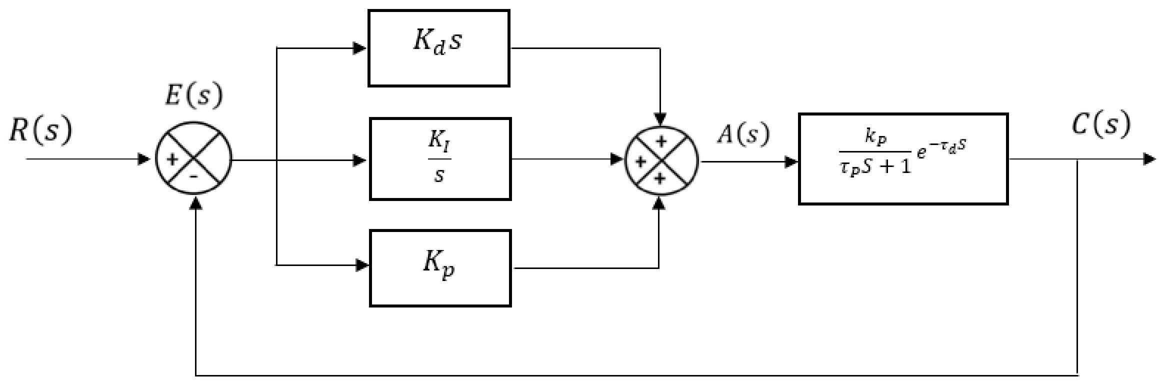

Figure 1: PID controller in closed loop system

The controller output is dependent on both the past values of the controller output and the present value of the error. Many methods are proposed in the literature regarding tuning of PID controller parameters. PID controller tuning based on Internal Model Controller (IMC) method is quite popular due its single parameter tuning, and it is given in the table 1.

2.2 Smith Predictor

Since the qualitative behaviour of the controlled process is determined by a PI/PID controller is insufficient for processes with dead time. To remove the process dead-time from the controlled system's characteristic equation, Smith presented a control strategy using a PI/PID controller that is shown in Figure 2. The Smith's modification allows the PI/PID controller to be applied for processes with significant dead-time. An IMC based tuning algorithm is used for PID parameter tuning and it is given in the Table 1.

The closed loop transfer function of the Smith predictor scheme between the setpoint *r* and output *y* is

$$G_{cl}(s)=\frac{G_c(s)G_p(s)}{1+G_c(s)\left[G_{m0}(s)-G_m(s)+G_p(s)\right]} \tag{2}$$

In case of perfect modelling, the closed loop transfer function can be written as

$$G_{cl}(s)=\frac{G_{cp}(s)G_p(s)}{1+G_{cp}(s)G_{m0}(s)} \tag{3}$$

where , $G_{cp}(s) = K_P + \frac{K_I}{s} + K_d s$, $G_p(s) = \frac{k_P}{\tau_P S+1} e^{-\tau_d S}$, $G_{m0}(s) = \frac{k_P}{\tau_P S+1}$

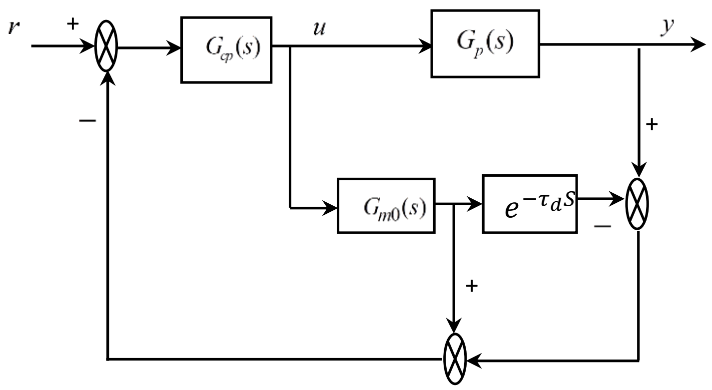

Figure 2: Smith Predictor

2.3 Predictive PI controller (PPI) Controller

With a unique tuning rule, the PPI is a type of Smith predictor. In industrial systems, the PPI controller can be used in place of the PID controller for processes that have a lot of dead time.

The controller may be readily added as an extra feature to the current PID controllers because its structure is comparable to that of a PID controller in reset configuration.

In addition, the PPI controller uses low-order approximations of the process dynamics, like the FOPDT model, for its design, and it is computationally simple and easy to implement. These approximations can adequately explain the behaviour of a large variety of processes, and there are currently numerous industrially validated methods for creating such models from plant data. The FOPDT transfer function is given by

$$G_p(s) = \frac{k_P}{\tau_P S+1} e^{-\tau_d S} \quad (4)$$

where the process model parameter k_P, τ_P and τ_d are the process gain, time constant and dead-time respectively.

The PPI controller transfer function is given by:

$$G_c(s) = k_c \left(\frac{T_i s+1}{T_i s+1-e^{-\tau_d s}} \right) \quad (5)$$

The PPI controller is developed using the FOPDT model. The controller parameter tuning relations for the PPI controller is given in Table 1.

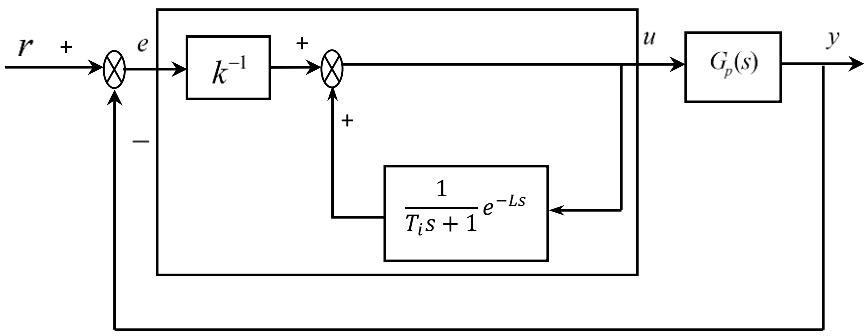

Figure 3: Predictive PI Controller.

2.4 PDI Controller

By generating phase lead, a PID controller reduces the proportional-integral PI control system's overshoot and increases its robustness. On the other hand, the derivative term intensifies the high frequency interference and could result in strong control measures. As an alternative, the derivative term can be substituted without signal differentiation by adding a time delay or a low pass filter to the integral term, which also exhibits phase lead for a specific frequency range. It increases control system bandwidths without significantly raising peak amplitude ratios. It is possible to utilize this controller for processes with dead times and noisy environments because there is no explicit distinction of process output signals. The PDI controller is shown in Figure 4. The tuning relations for PDI Controller is given in the Table 1.

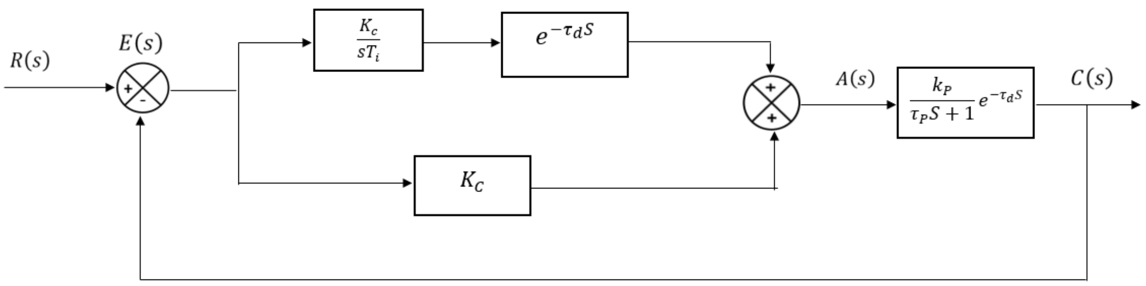

Figure 4: PDI Controller

The PDI controller transfer function is shown in Equation (6)

$$G_c(S) = K_c\left(1 + \frac{e^{-\tau_d s}}{sT_i}\right) \quad (6)$$

Table 1: Controller Tuning Relationships for Various Control Schemes

Control Scheme	Tuning Relationship
PID Controller	$K_c = \frac{\tau_p + \frac{\tau_d}{2}}{k_p(\lambda+\tau_d)}$ $T_i = \tau_p + \frac{\tau_d}{2}$ $T_d = \frac{\tau_p + \tau_d}{(2\tau_p+\tau_d)}$
Smith Predictor	$K_c = \frac{\tau_p + \frac{\tau_d}{2}}{k_p(\lambda+\tau_d)}$ $T_i = \tau_p + \frac{\tau_d}{2}$ $T_d = \frac{\tau_p + \tau_d}{(2\tau_p+\tau_d)}$
PPI Controller	$K_c = \frac{1}{k_P}$ $T_i = \begin{cases} \tau_p, if \frac{\tau_d}{\tau_p} > 3 \\ \frac{\tau_p}{4}, otherwise \end{cases}$

PDI Controller	$K_c = a_1 + \sqrt{2\, a_0\, a_2}$ $T_i = \frac{a_1}{a_0} + \sqrt{2\frac{a_2}{a_0}}$ $\theta_F = \sqrt{2\frac{a_2}{a_0}}$ $\lambda = \frac{\tau_p}{3}$ $a_0 = \frac{1}{k_P(\lambda+\tau_d)}$ $a_1 = a_0(\tau_p + \frac{\tau_d^2}{2(\lambda+\tau_d)})$ $a_2 = a_0(\frac{3\tau_p\tau_d^2-\tau_d^3}{6(\lambda+\tau_d)} + \frac{\tau_d^4}{4(\lambda+\tau_d)^2})$

3. Comparison Analysis

The different control schemes discussed in the previous section is implemented for FOPDT process model with various values of dead-time. The process gains and time constant is fixed as unity (k_P = 1 and τ_P = 1). This analysis is done to explore the effect of process dead-time on the closed loop performance of the control schemes. The obtained controller parameters are shown in Table 2.

Table2: Controller parameters of various control schemes for dead-time process

Control Schemes	Case :1 ($\tau_d = 3$)	Case: 2 ($\tau_d = 5$)	Case :3 ($\tau_d = 7$)
PID Controller	Ti = 2.5 Td = 0.6 Kc = 0.0794 $\lambda = 2.2$	Ti = 3.5 Td = 0.7143 Kc = 0.1077 $\lambda = 3.6$	Ti = 4.5 Td = 0.7778 Kc = 0.1343 $\lambda = 5$
Smith Predictor	Ti = 2.5 Td = 0.6 Kc = 0.0794 $\lambda = 2.2$	Ti = 3.5 Td = 0.7143 Kc = 0.1077 $\lambda = 3.6$	Ti = 4.5 Td = 0.7778 Kc = 0.1343 $\lambda = 5$
PPI Controller	Kc = 1 T_i = 0.25	Kc = 1 T_i = 1	Kc = 1 T_i = 1
PDI Controller	$a_0 = 0.3$ a_1 = 0.7050 a_2 = 0.5467 Kc = 1.2778 Ti = 4.2592 $\theta_F = 3.6625$	a_0 = 0.1875 a_1 = 0.6270 a_2 = 0.7370 Kc = 1.1527 Ti = 6.1476 $\theta_F = 2.8038$	a_0 = 0.1364 a_1 = 0.5919 a_2 = 0.9146 Kc = 1.0914 Ti = 8.0035 $\theta_F = 3.6625$

3.1 Performance Metrics

The closed loop performance of the control schemes is valued using IAE Criterion. IAE is commonly used to assess the performance of a system or controller by considering the integral (accumulated) value of the absolute difference between the desired setpoint and the actual system output. Mathematically, IAE is expressed as

$$IAE = \int_0^\infty |r(t) - y(t)|\, dt \quad (7)$$

Total Variation (TV) in controller is output is considered as the control effort required to achieve the desired closed loop responses. The minimum value indicates the less control effort i.e. control energy is utilized. The TV of the controller output u is evaluated as

$$TV = \sum_{k=1}^{\infty} |u(k+1) - u(k)| \quad (8)$$

3.2 Robustness Metrices

The robustness metrics used to assess the closed loop system's robustness to predicted model parameter uncertainty are the Gain Margin (GM) and Phase Margin (PM). The system's stability increases with increasing GM. The amount of gain that can be changed without the system becoming unstable is known as the gain margin. The Bode plot can be used to immediately read the gain margin. To do this, find the vertical distance at the frequency where the Bode phase plot = 180° between the x-axis and the magnitude curve on the Bode magnitude plot.

The GM is provided by the solution of the following set of equations:

$$\angle G(j\omega)H(j\omega)|_{\omega=\omega_g} = -\pi \quad (9)$$

$$A_m = \frac{1}{|G(j\omega)H(j\omega)|} \quad (10)$$

The phase crossover frequency, as used in classical language, is defined as the frequency ωg at which the Nyquist curve has a phase of $-\pi$.

The system's stability will increase with increasing PM. The amount of phase that can be changed without causing the system to become unstable is known as the phase margin. Usually, it is stated as a phase in gradations. The Bode plot can be used to directly read the phase margin. To accomplish this, find the vertical separation at the frequency where the Bode magnitude plot = 0 dB between the phase curve (on the Bode phase plot) and the x-axis. The gain crossover frequency is this point.

The phase margin can be found by

$$|G(j\omega)H(j\omega)|_{\omega=\omega_c}=1 \quad (11)$$

$$\Phi_m = \angle G(j\omega)GP(j\omega) + \pi \quad (12)$$

where the gain crossover frequency is defined as the frequency ωc at which the amplitude of the Nyquist curve is one.

3.3 Simulation Analysis

The setpoint change was made by the unit step input in the reference signal. The closed loop response of all four control schemes for FOPDT process with dead-time $\tau_d = 3, 5, \& \ 7$ values are shown in Figure 5, 7, & 9 respectively. The corresponding controller response is shown in Figure 6, 8, &10 respectively. The obtained performance and robustness metrices are presented in Table 3.

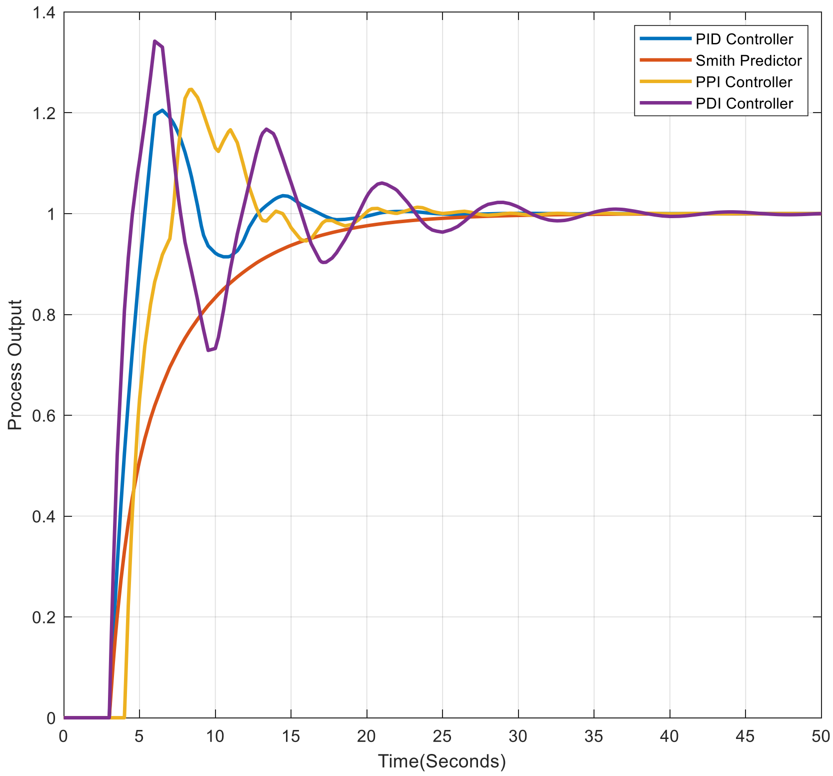

Figure 5: Setpoint tracking response of FOPDT process having dead-time $\tau_d = 3$

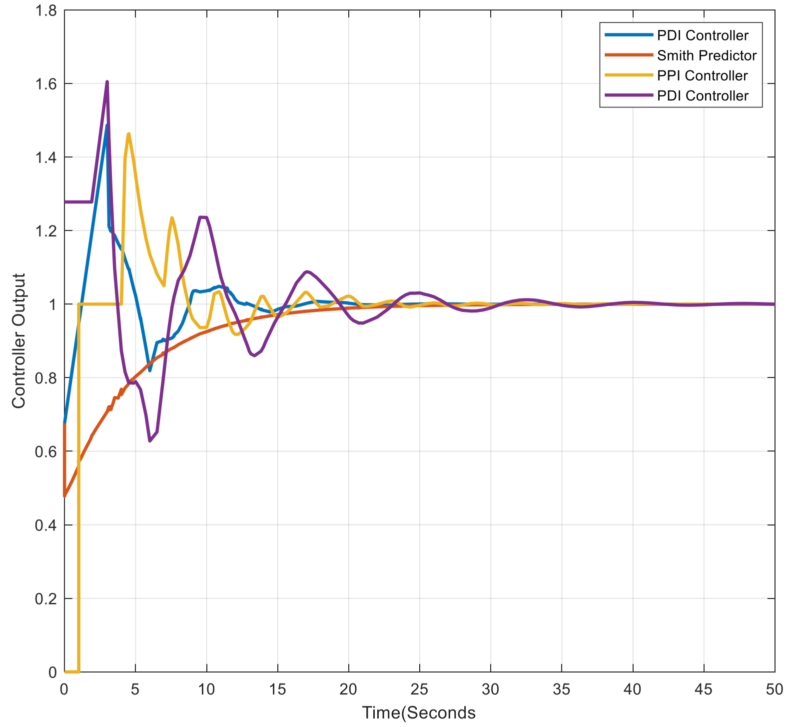

Figure 6: Controller response of FOPDT process having dead-time $\tau_d = 3$

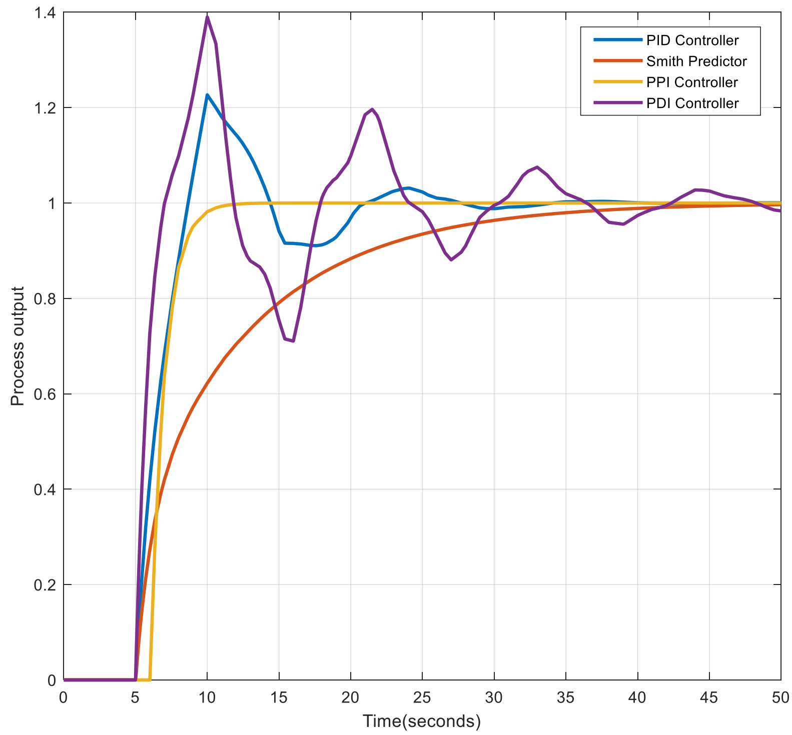

Figure 7: Setpoint tracking response of FOPDT process having dead-time $\tau_d = 5$

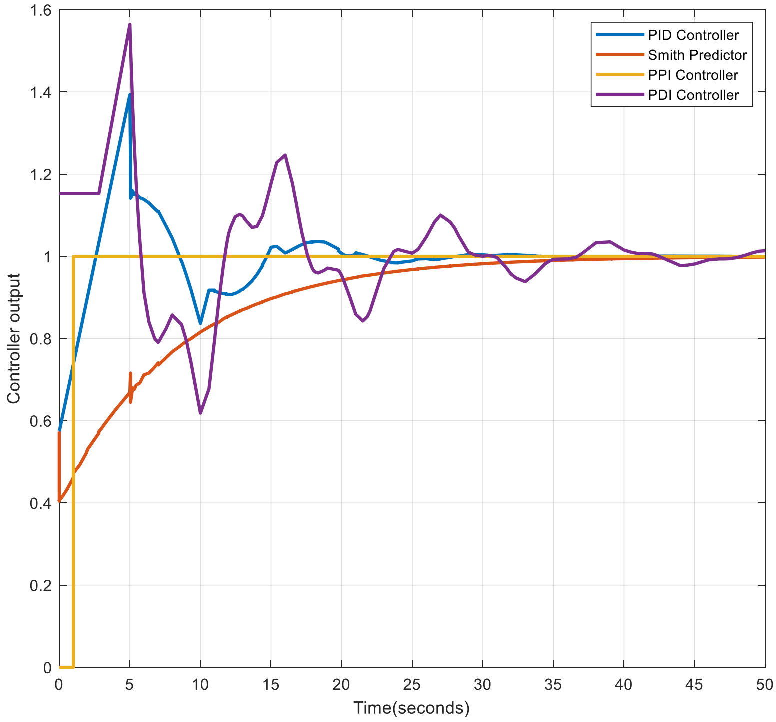

Figure 8: Controller response of FOPDT process having dead-time $\tau_d = 5$

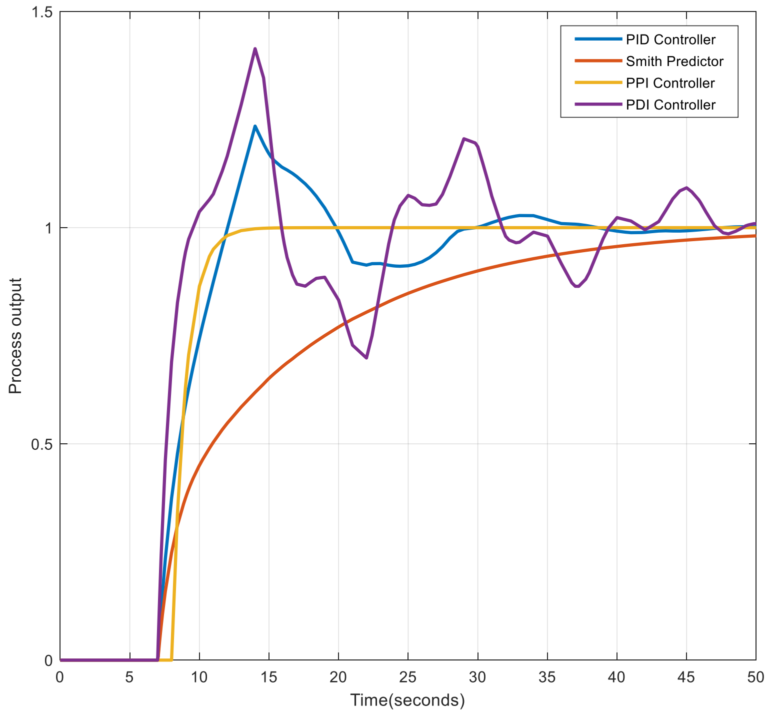

Figure 9: Setpoint tracking response of FOPDT process having dead-time $\tau_d = 7$

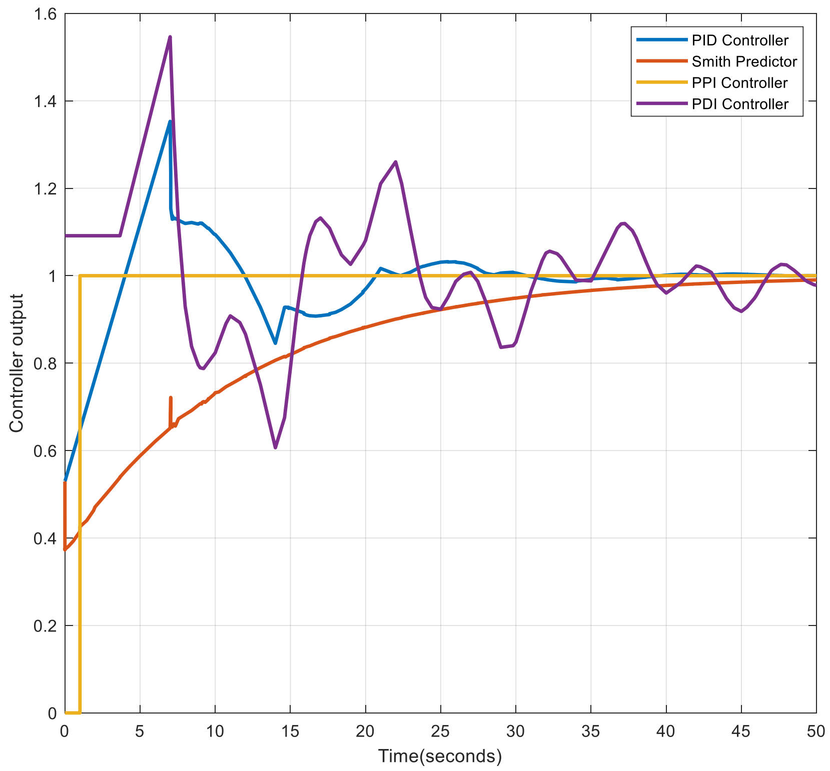

Figure 10: Controller response of FOPDT process having dead-time $\tau_d = 7$

Table 3: Performance and Robustness Comparison of Different Control Schemes

	Control Scheme	IAE	TV	GM	PM
Case: 1 ($\tau_d = 3$)	PID Controller	4.859	9.489	5.64	63.1
	Smith Predictor	3.7	6.67	5.64	63.1
	PPI Controller	4.985	13.31	6.84	48.8
	PDI Controller	5.804	11.09	3.03	60.6
Case: 2 ($\tau_d = 5$)	PID Controller	7.731	10.35	5.54	62.7
	Smith Predictor	6.1	6.957	5.54	62.7
	PPI Controller	6.026	11	6.64	61
	PDI Controller	9.028	12.35	3.02	60.5
Case: 3 ($\tau_d = 7$)	PID Controller	10.6	11.88	5.5	62.5
	Smith Predictor	8.5	7.092	5.5	62.5
	PPI Controller	8.026	11	6.31	60.5
	PDI Controller	12.13	16.47	2.39	60.5

It is inferred that the smith predictor scheme shows better response with low IAE value for less dead-time process compared to other control schemes. PPI control scheme shows better response with high dead-time process. The Smith predictor scheme gives improved phase margin compared to PPI controller for all dead-time values. Also, the Smith predictor scheme gives lower TV value, and this makes as the good choice for energy saving. The PPI controller gives higher gain margin compared to Smith predictor. The PDI controller gives higher IAE value and low gain margin compared to all other schemes. The Smith predictor is suitable for less dead-time values and PPI scheme is recommended for high dead-time values. The simulation results reveals that the Smith predictor shows improved and have good robustness.

4. Validation of the Control Schemes on the Level Control Process

The above discussed control schemes are validated in real-time level control process. The level control set-up shown in Figure 11 consists of a level tank fitted with level transmitter calibrated to measure level, and Variable Frequency Drive (VFD) with diaphragm pump for flow manipulation. These units are installed in support housing that is intended to be a stand-alone model, together with the required plumbing and fitting. ACE 2007 wireless data acquisition system is used as an interfacing unit to interface the system with PC / laptop. The process parameters are controlled through computer by manipulating cold water flow to the process tank through VFD The Piping and Instrumentation (P&I) diagram is shown Figure 12. The level inside the tank is measured and controlled.

The input change is typically standardized to a step change to systematically define the transitory reaction of an output to a change in the input. The process dynamics are typically characterized using the simplest step input change pattern. The most basic transient reaction is the first order lag with dead-time, in which the output reacts to a step change in the input after dead-time.

Anadolu Psikiyatri Dergisi || ISSN: 1302-6631 || Volume 25; Number 6
https://doi.org/10.5281/zenodo.14214567

Figure 11: Level Control Set-up

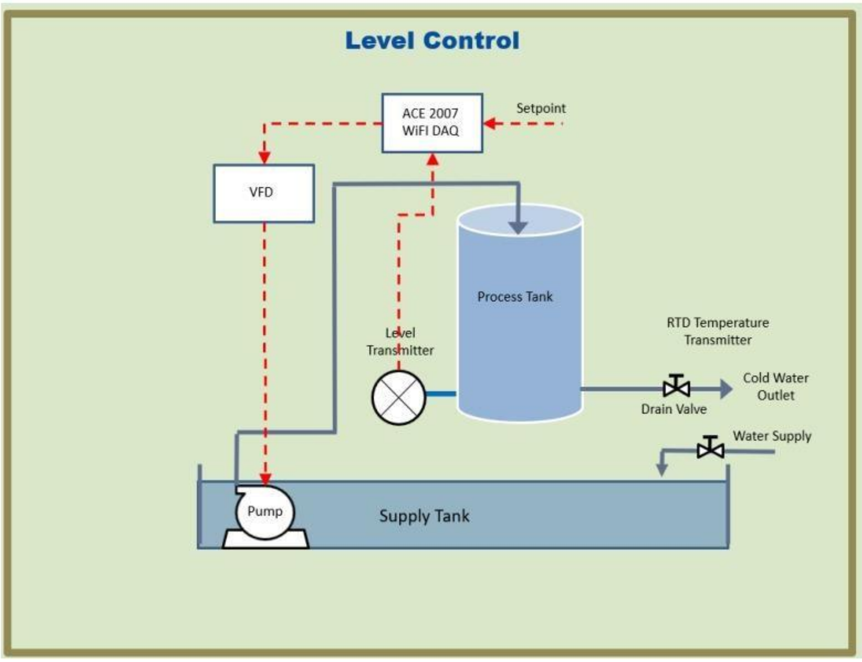

Figure 12: Schematic Diagram of Level Control Set-up

4.1 Process Model Identification

At the first step the FOPDT process model parameters are obtained for the level control process. A step change in manipulated variable is applied and the corresponding level response is recorded. The recorded input and output response data used for identification is shown Figure 13. The process gain, or k_P, is defined as the ratio of the change in the input to the change in the output. The first order time constant τ_p is equal to the amount of time it takes for the output to reach 63.2% of its final value.

The non-responsive period is taken as the process dead-time τ_d. A first order plus dead-time (FOPDT) model is identified from the input and output responses. The obtained process model is given below:

$$G_P(s) = \frac{0.6}{91s + 1} e^{-28s}$$

The identified process model and actual process output is compared in Figure 14. It is inferred that the identified process model has exactly matching the actual level process dynamics.

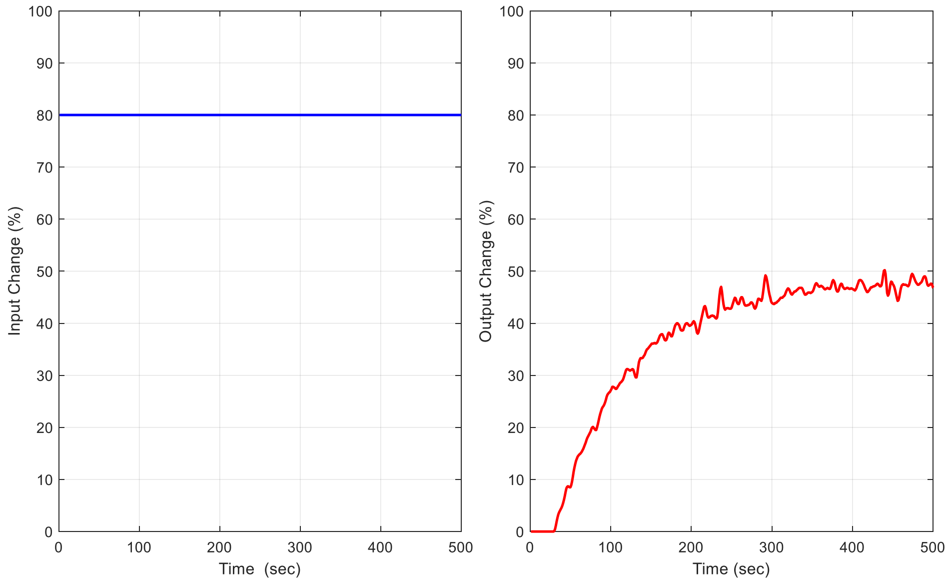

Figure 13: Input and Output Data for Process Model Identification

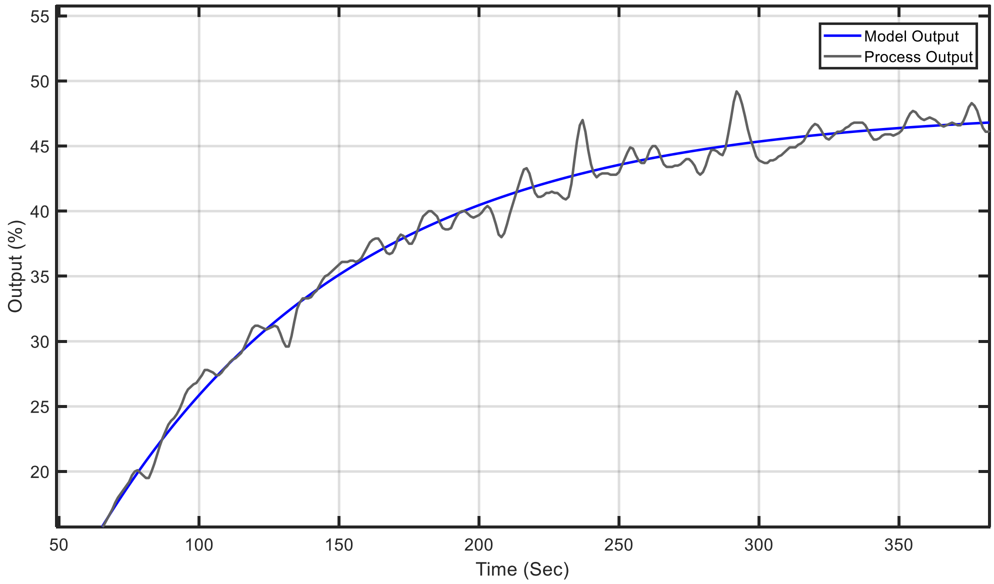

Figure 14: The identified process model output and process output

The controllers are designed for this model, and it is presented in Table 4. A setpoint change was performed to evaluate the controller performances. The resultant closed loop response is presented in Figure 15. Their subsequent manipulated variable is reported in Figure 16. The calculated IAE and TV values also reported in Table 4.

Table 4: Controller parameters and performance measure for level control process

Control Schemes	**Parameters**	**IAE**	**TV**
PID Controller	Ti = 105 Td = 0.5667 Kc = 3 $\lambda = 30.33$	3190	156.3
Smith Predictor	Ti = 105 Td = 0.5667 Kc = 3 $\lambda = 30.33$	2331	150.5
PPI Controller	Kc = 1.67 $T_i = 22.75$	5275	209.4

As like the simulation results the Smith predictor scheme is outperformed. The additional dead-time compensation in this scheme improves the total response as compared to PID controller. The IAE and TV values is low compared to other control schemes.

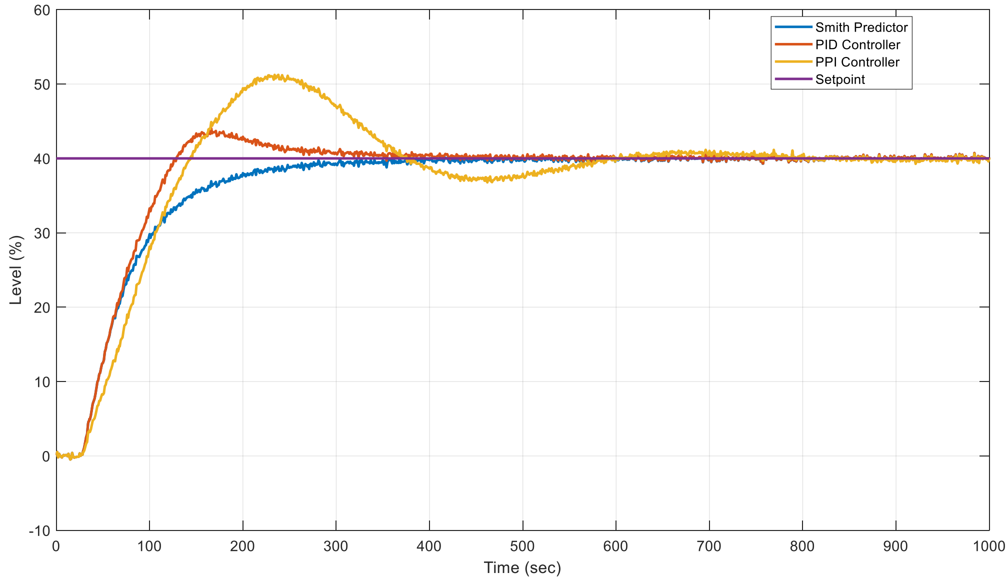

Figure 15: Setpoint tracking response of level control process

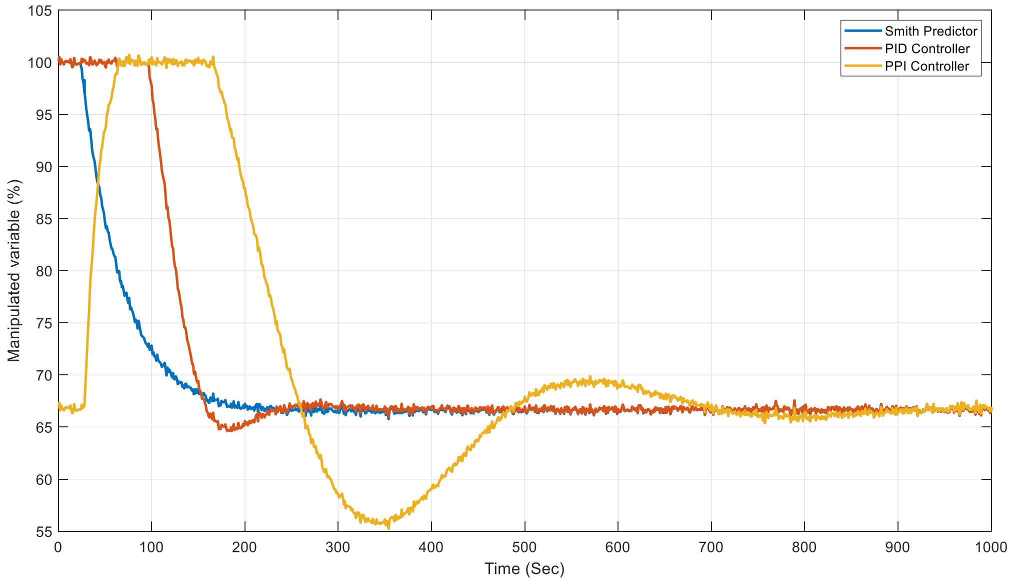

Figure 16: Manipulated variable response for level control process

5. Conclusions

The dead-time compensation schemes performance and robustness are evaluated for various values of dead-times. It can be concluded that the PPI (Proportional-Integral) controller outperforms the Smith predictor in large-delay scenarios, while the Smith predictor performs better in small-delay scenarios. Overall Smith predictor scheme shows better performance with good robustness level. The PDI controller performance is poor when compared to all other control schemes. The PID controller gives moderate performance level. This conclusion has arrived from analysing various performance metrices (IAE, TV) and robustness metrices (GM, PM). This conclusion can have significant implications for real-world control systems design and implementation, as it provides guidance on selecting the appropriate control strategy based on the characteristic time delay of the process being controlled.

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