Performance Analysis of Smith Predictor and Proportional-Integral-Derivative Controller in Servomotor Speed Control

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Abstract— The work presented in this research report is centred on performance analysis of Smith Predictor and Proportional-Integral-Derivative controller in servomotor speed control application. A controller designed with improved time-delay compensation and method of tuning has made it possible for speed control specifications to be optimally regulated for reliable performance. Servomotor speed control system has proven to exhibit several problems such as time lags due to analysis, measurement, transportation, computation and communication when using conventional controller. This problem leads to increased system dynamic error, decrease stability margin and affects system stability as evident in engineering and industrial process control. Therefore, this heuristic research focuses on hybridization of two controllers to remove inherent transcendental time delay from systems transfer function. This is a comparative study of two different controllers. From the simulation results, non-hybridised controller has a very large settling time of 16.1seconds with less overshoot when a static load disturbance of -1 was used. The rise and peak times showed that the PID controller was suitable to compensate for time delay (≤2seconds) On the other hand, the dynamics of the hybridised controller with large time delay of 94seconds was designed to match with the process model; this successfully eliminated long dead time from the system model. The Smith Predictor hybrid compensated for all iterations of time delay (2≤τ≥94) seconds with ≤1seconds settling time and more over shoot ≤8seconds. Hence, it is recommended that hybrid predictive controllers be improved to ensure large dead time compensation in servomotor speed control to drive industrial and engineering processes reliably.

Key words: Speed Control, Smith Predictor, PID, Servomotor, Time-delay, MatLab/Simulink

I. INTRODUCTION

Feedback maintains a prescribed relationship between the output and the reference input by comparing them and using the difference as a means of control (Ogata, 2007); whenever a close sequence of cause-and-effect relationship exists among variables of a system, a feedback is said to exist. This viewpoint will inevitably admit feedback in a large number of systems that ordinarily would be identified as nonfeedback systems. However, control system theory allows numerous systems, with or without physical feedback, to be studied in a systematic way once the existence of feedback in the sense mentioned previously is established (Kuo and Golnaraghi, 2012). In process control, there are two kinds of typical processes: one can be described by time constant plus time delay models, and the other, by integrator plus time delay models (Chien and Fruehauf, 1990). For a process consisting of a time constant and a time delay, many controllers have been developed. For example, when the time delay is small, a Proportional-Integral-Derivative (PID) controller is commonly used; when the time delay is large, the Smith Predictor (Smith, 1957) is an effective compensator. However, neither the PID nor the Smith Predictor can be used directly for the integrator/time delay process. This heuristic thesis presents several simple techniques for analysing the stability of time-delay systems. It explains the Smith Predictor control scheme for time delay systems and shows how errors in modelling the servomotor parameters can cause instability. Pedagogical investigation of the effects of feedback on the speed control aspect of servomotor performance with Smith Predictor and Proportional-Integral-Derivative controllers will be studied and results of the comparative implementation for both open and closed loop using simulations will be shown.

An open-loop control system utilizes an actuating device to control the process directly without using feedback. It uses a controller and an actuator to obtain the desired response. (Dorf and Bishop, 2010). Closed-Loop control system utilizes an additional measure of the actual output to compare the actual output with the desired output response. The measure of the output is called the feedback. In the field of electrical engineering, Electric motors can be classified by their functions as servomotors, gear motors, and so forth, and by their electrical configurations as DC (direct current) and AC (alternating current motors. Servomotor is a motor used for position or speed control in closed loop control systems. The requirement from a servomotor is to turnover a wide range of speeds and also to perform position and speed (Gopal, 2009). AC and DC servomotors (Sharkawi and Huang, 1989; Ghazy, 2002) are in use in many application; particularly, DC ones are used in computer peripherals and robot manipulators and are characterized by: ability to produce full continuous torque, controlled braking is relatively simple and low cost as compared with similar AC drives at high power and speed control of alternators, control mechanism of full automatic regulators as the first starter, starting systems quickly and correctly. (Stephen, 2005) described some properties of DC servo motors are the same, like inertia, physical structure, shaft resonance and shaft characteristics, their electrical and physical constants are variable. The velocity and position tolerance of servo motors which are used at the control systems are nearly the same. DC motors are well known for their torque-speed characteristics, and their wide operation voltage and current range (Alciatore and Histand, 2007).

II. METHODOLOGY

In this section, the proposed scheme for designing and implementing the real time speed control of the servomotor is described. The procedure to designing speed control of servomotor has been divided four categories or parts which are Mathematical Modelling of Servomotor and Design, Proportional-Integral-Derivative Controller Design, Proportional-Integral-Derivative Smith Predictor Design. Armature self-inductance (L) and resistance (R) has units of Henry (H) and Ohms (Ω). The torque (N.m) at the motor shaft is proportional to the current i(A) induced by the applied voltage (V);

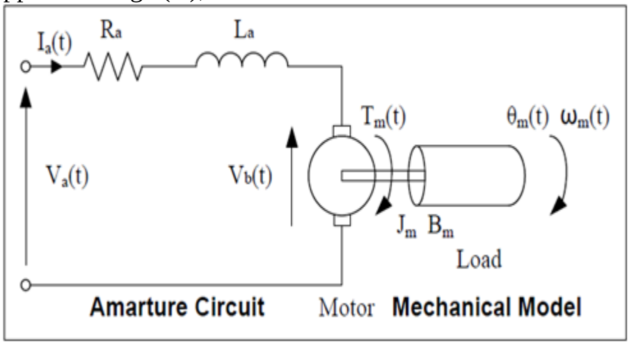

Fig. 1: Servomotor Circuit Schematic Diagram

$\tau = K_m\, i$ (1)

Km is a physical quantity of the motor called the armature constant. Induced or back electromotive force, v_{emf} (V), is a voltage proportional to the angular rate seen at the motor shaft;

$V_{emf} = V_b = K_m\, i$ (2)

K_b is an electromotive force constant, also depends on certain physical characteristics of the motor. Isaac Newton's Second Law of motion is used to derive the mechanical part of the motion equations. It states that the inertial load J ($Kg.m^2$) times the derivative of the angular rate ϖ (rad/sec) equals the sum of all the torques (N.m) about the motor shaft. Refer to (3) shows this;

$J\frac{d\varpi}{dt} = -Bm\varpi + K_m$ (3)

Where $B_m\varpi$ is a linear approximation for viscous friction. The electrical part of the motor equations can be described from Kirchhoff's Law as in equation (3.4);

$\frac{di}{dt} = -\frac{R}{L}i - \frac{Kb}{L}\varpi + \frac{1}{L}\,Va$ (4)

The state space represents a Linear Time Invariant system, given as in equation (7),(8). For an LTI system;

$\dot{x}(t) = Ax(t) + Bu(t)$ (5)

$y(t) = Cx(t) + Du(t)$ (6)

Where;

- x(t)= State vector (n-vector)
- u(t)=Control vector (r-vector)
- A=n×n system matrix
- B=n×r system matrix
- C=m×n output matrix
- D=m×r connection matrix=0

$$\frac{d}{dt}\begin{bmatrix} i \\ \varpi \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{Kb}{L} \\ \frac{Km}{J} & -\frac{Bm}{J} \end{bmatrix}\begin{bmatrix} i \\ \varpi \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_a \quad (7)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} i \\ \varpi \end{bmatrix} + [0]\, v_a \quad (8)$$

From the State-Space representation to Transfer Function realization state of art, equations (5) and (8) can be transformed with the relation in equation (9);(10) below; to give equation (11);

$G(s) = C(sI-A)^{-1}B+D$ (9)

$G(s) = C\frac{adj(sI-A)}{Det(sI-A)}.B+D$ (10)

$G(s) = \frac{K}{(Ra+La)(JmS+Bm)+K^2}$ (11)

Parameters used are described below in Table I.

Parameters	Values
Armature Resistance, R(Ω)	1.0
Armature winding inductance L(H)	0.5
Moment of Inertia of rotor, J(Kgm^2)	0.01Kgm^2/s^2
Damping ratio of mechanical system, B(Nms)	0.1
Electromotive force constant , K	0.01

Table 1: Physical parameters of the DC Servomotor

Fig. 2: Servomotor Speed Control Block Diagram

A. PID Controller Design:

Proportional-Integral-Derivative controller is the most widely used controller structure in many industrial applications because of the following reasons; (Ziegler et'al, 1942), structural simplicity and sufficient ability to solving many practical control problems, simple, robust and familiar to the operator, reduced number of parameters to be tuned.

The design focuses on some well-known PID controller tuning formulas and verification of these in MatLab/Simulink simulation. (Basilio and Matos, 2002); (Ming-Tz & Lin, 2003). The structure of a PID controller in time domain is

$u(t) = K_p\,(e(t)) + \frac{1}{Ti}\int_0^t e(t)d\tau + T_d\frac{de(t)}{dt}$ (12)

Where

u(t)= The control input

e(t)=The difference between the reference signal yr and the output signal y(t). The Complete structure of PID controller is shown in Fig. 3. 6

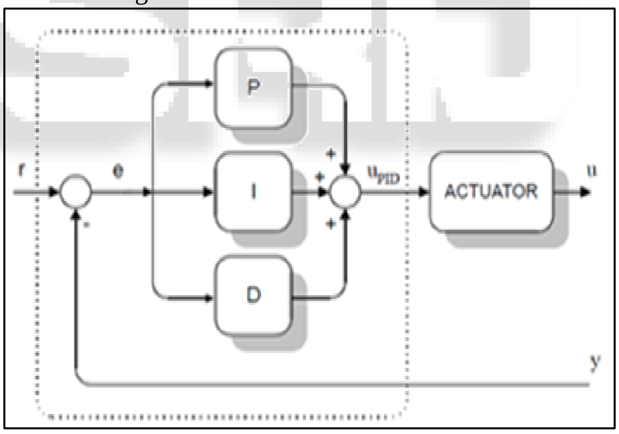

Fig. 2: Simple Structure a PID Controller

$$C(s) = \frac{U(s)}{E(s)} = K_p(1 + \frac{1}{sTi} + sT_d)E(s) = K_p + K_i/s + K_d \quad (13)$$

Where T_i is called the integral time constant or reset time and T_d is called the derivative time constant or rate time. The coefficients K_p, K_i, K_d and T_i, and T_d are related by;

- Proportional gain $=K_p$
- Integral Gain $(K_i) = K_p/T_i$
- Derivative Gain $(K_d) = K_pT_d$

Different manufacturers design controllers in different manner. Basically, there are two topologies mostly used nowadays. The Non-interactive and Interactive PID controller structures

The order of the PID controller is low, but this controller has universal applicability; it can be used in any of SISO systems, example is in linear, nonlinear, time delay systems. Many of the MIMO systems are first decoupled into several SISO loops and PID controllers are designed for each loop. However, for proper use, a controller has to be tuned for a particular process, because each parameter is process dependent. If the PID controller is not properly tuned, it may cause instability to the closed loop system. (Nilesh et'al, 2014).

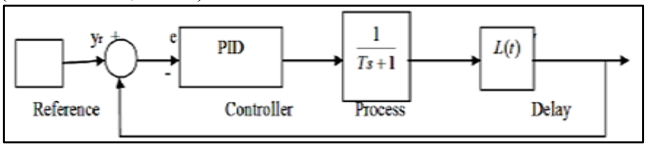

Fig. 3: Block Diagram of a System with Changing Time-delay

Parameter	Rise Time	Overshoot	Steady-State Error	Settling Time
Proportional Gain	Decrease	Increase	Decrease	Small Change
Integral Gain	Decrease	Increase	Remove	Increase
Derivative Gain	Increase	Reduce	No Effect	Decrease

Table 2: Effects of PID Parameters on a System Parameter

B. Classical Smith Predictor:

The Smith Predictor is a model-based controller that is effective for processes with long dead time. It has an inner loop with a main controller that can be simply designed without the dead time. The effect of load disturbance and modelling error are corrected through the outer loop. The Smith Predictor can also be used with significant non-minimum phase dynamics and for higher order systems that exhibit apparent dead time. Modification using a rapid load detector scheme can be applied to further improve the load response of a system. Three modifications of the Smith Predictor for open-loop unstable systems can be of further research interest. This will ensure stability and zero steady-state error to step load disturbances. A design tool very useful to control engineers when it is necessary to design a control system with delay at time response is the Smith Predictor (Ogata, 2009).

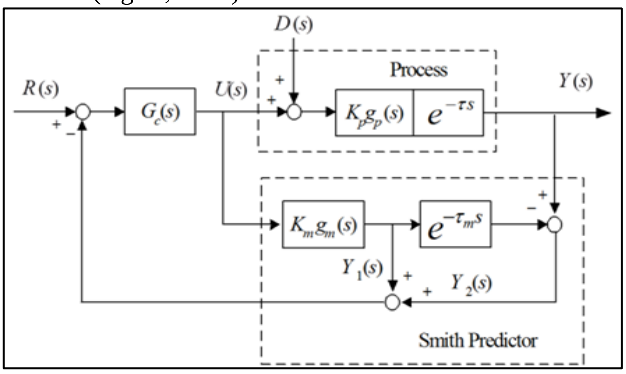

Fig. 4: Smith Predictor Simulink Diagram

Consider a process model described by $G(s) = Go(s)e^{-\tau s}$, where $G_0(s)$ is the delay free part of the system and C(s) is the controller for this, then the closed loop transfer function H(s) will be given as;

$$H(s) = \frac{C(s)Go(s)}{1+C(s)Go(s)} \tag{14}$$

Consider the plant G(s) and a controller $C_{delay}(s)$, then the closed loop transfer function $H_{delay}(s)$ will be;

$$H_{delay}(s) = \frac{Cdelay(s)G(s)}{1+Cdelay(s)G(s)} \tag{15}$$

As equation (14) is having delay(τ), so the response of closed loop H(s) is satisfactory under proper design controller. The objective of Smith Predictor is to eliminate the delay effect by designing a suitable controller C_{delay}. It can be stated as.

$$H_{delay}(s) = e^{-\tau s}H(s) \tag{16}$$

then see that

$$\frac{Cdelay(s)G(s)}{1+Cdelay(s)G(s)} = e^{-\tau s}\frac{C(s)Go(s)}{1+C(s)Go(s)} \tag{17}$$

In equation (14), it is not possible to use the actual plant G(s) and delay in actual closed loop(τ), so replacing it with a model as Ğ(s) of actual plant and estimated closed loop delay (τ̂). Then equation (17) becomes

$$\frac{Cdelay(s)G(s)}{1+Cdelay(s)G(s)} = e^{-\hat{\tau} s}\frac{C(s)\breve{G}o(s)}{1+C(s)\breve{G}o(s)} \tag{18}$$

Solving equation (18), the value of C_{dealy} can be found and is shown in the inner loop of Figure 3.7.

$$C_{delay}(s) = \frac{C(s)}{1+C(s)=C(s)\breve{G}o(s)e^{-\hat{\tau} s}} \tag{19}$$

Moving the delay outside the loop will cause the delay term in the characteristic equation to vanish.

$$1 + C(s)\,\breve{G}o(s) = 0 \tag{20}$$

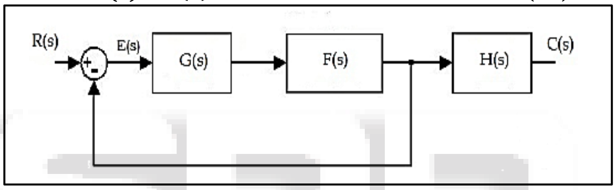

Fig. 5: Smith Predictor Equivalent System

The process activity chart is as seen below;

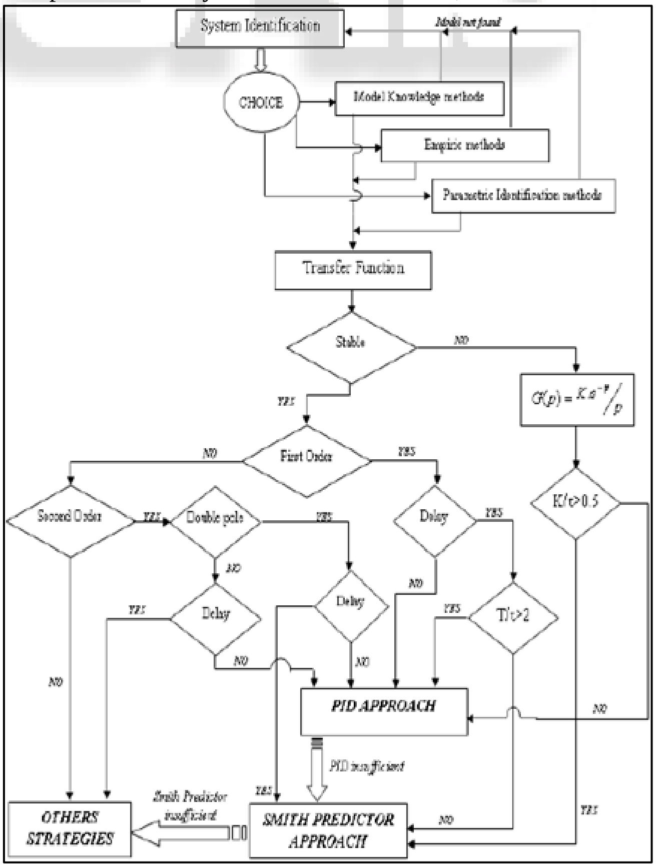

Fig. 6: Process Activity Chart Implementation

In the Continuous simulink block, Fig. 1 is realised as seen below.

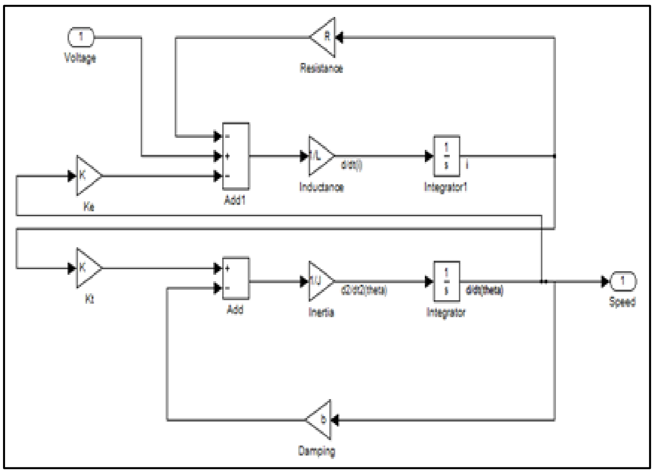

Fig. 7: Servomotor Simulink Design

C. PID Controller Implementation:

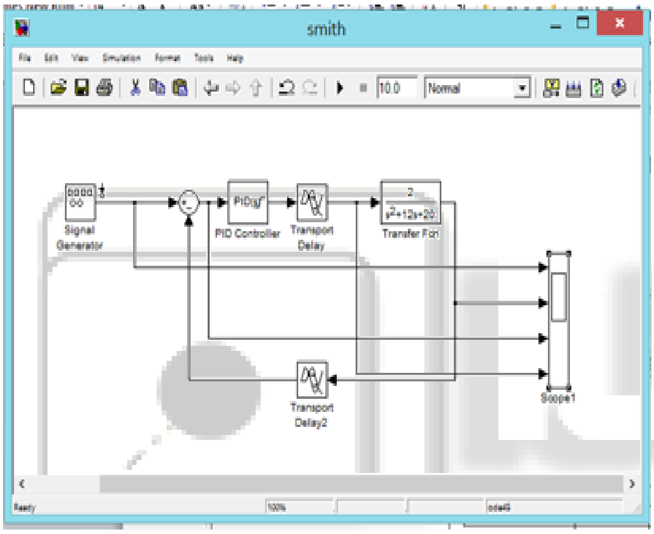

Fig. 8: Servomotor System Model without Smith Predictor

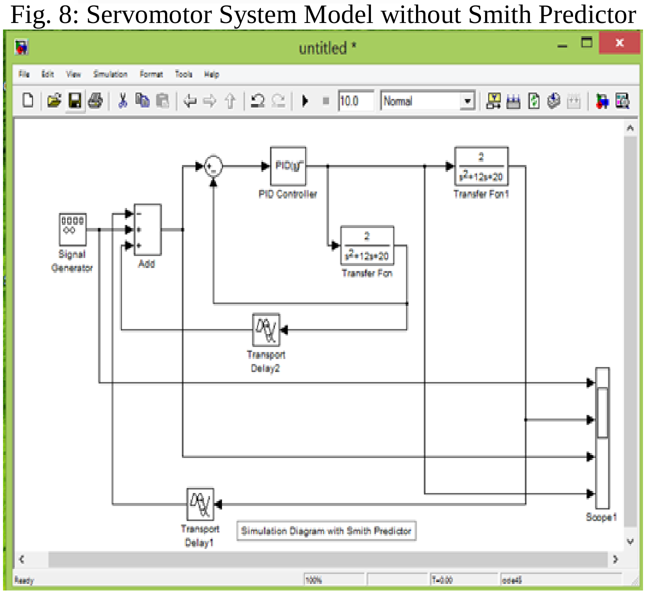

Fig. 9: Simulation Block Diagram with Smith Predictor

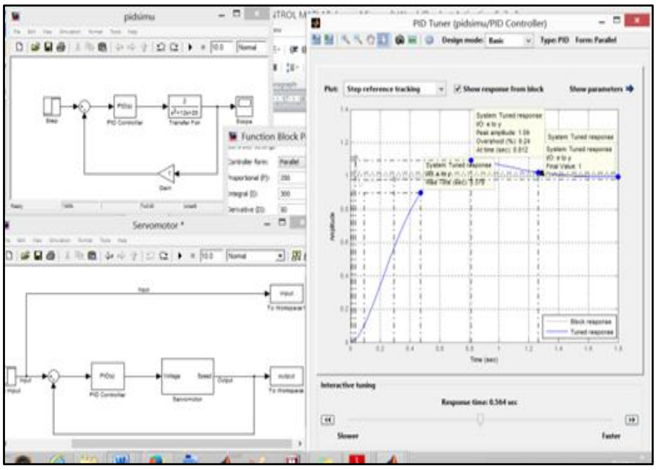

Fig. 10: Simulink Block Diagram of Closed-Loop Speed Control

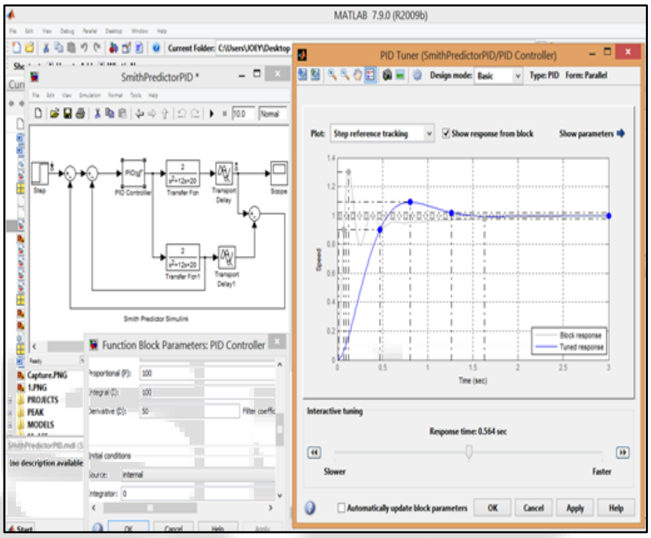

Fig. 11: Simulink Graph Showing Plant and Smith Predictor Response

III. RESULTS AND DISCUSSIONS

Table 3 shows the simulation results of different time delay iterations from 1second up to approximately 94seconds in the performance analysis of Smith Predictor and PID controller in servomotor speed control application.

	Open-Loop Response	Closed-Loop Response Without PID	Closed-Loop Response with PID	PID-Smith Predictor Hybrid Model
Rise Time	1.136	1.017	0.120	0.164
Settling Time	2.065	1.85	16.086	0.440
Settling Time Min.	0.090	0.083	0.88	0.61
Settling Time Max.	0.100	0.091	1.088	0.72
Overshoot	0.000	0.000	8.781	0.015
Undershoot	0.000	0.000	0.000	0.000
Peak Time	5.239	4.640	0.234	0.160

Table 3: Time Response Comparison of the Open-Loop, Closed-Loop, PID Controller and Smith Predictor Responses Characteristics

IV. CONCLUSION

Time-delay has proven to be inevitable in many electrical and mechanical systems and often requires controlling with optimum compensation techniques.

The delay is often expressed as infinite dimension term which prevents applying traditional design method in continuous-time systems. But in discrete time systems, though the delay is expressed as a finite-dimension term, it increases the dimension as well as the system complexity.

From the simulation results, non-hybridised controller has a very large settling time of 16.1seconds with less overshoot when a static load disturbance of -1 was used. The rise and peak times showed that the PID controller was suitable to compensate for time delay (≤2seconds) On the other hand, the dynamics of the hybridised controller with large time delay of 94seconds was designed to match with the process model; this successfully eliminated long deadtime from the system model. The Smith Predictor hybrid compensated for all iterations of time delay ($2 \leq \tau \geq 94$) seconds with ≤1seconds settling time and more over shoot ≤8seconds. Hence, it is recommended that hybrid predictive controllers be improved to ensure large dead time compensation in servomotor speed control to drive industrial and engineering processes reliably.

REFERENCE

[1] Abe, N., Nobuyama E. (2005), 'Control of Delay Systems from Fundamentals to Frontiers #1: Introduction of Time Delay Systems-Transfer Function Approach,' Journal of the Society of Instrument and Control Engineers, Vol 44, no. 11, pp. 799-804.
[2] Abdel, G.A.M., Bensenouci A., (2004), 'Improved Free-Chattering Variable-Structure for a DC Servomotor Position Control', 3rd Saudi Technical Conference, 2: 21-30.
[3] Ananya, R. et'al, (2011), 'MatLab Based Real-Time Control Implementation of DC Servo Motor Using PCI Card', National Institute of Technology, Rourkela
[4] Astrom, K.J., Hagglund, T., 'PID Controllers: Theory, and Tuning, 2nd Edition', ISBN 978-1-55617-516-9
[5] Astrom, K.J. et'al (1994). 'A New Smith predictor for Controlling a Process with an Integrator and Long Dead-Time'. IEEE Transactions on Automatic Control, Vol.39, No.2, pp.343-345.
[6] Basilio, J.C., Matos S.R. (2002), 'Design of PI and PID Controllers with Transient Performance Specification', IEEE Transaction Symposium on Education, 45(4):354-370..
[7] Chapman, S.J. (2004), 'MATLAB Programming for Engineers-International Student Edition', BookWare Companion SeriesTM, Canada.
[8] Edition, McGraw Hill, Higher Education, Australia.
[9] Gopal, M., Nagrath, I.J. (1999), 'Control Systems Engineering 3rd Edition', Wiley Eastern Limited, New Delhi.
[10] Hang C.C., 'Control Systems: Robotics and Automation- Smith Predictor and Its Modifications' Vol II, UNESCO-EOLSS, National University, Singapore.
[11] Kaya, I., Atherton, D.P., (1999). 'A new PI-PD Smith Predictor for Control of Processes with Long Dead Time'. In: Proceedings of the 14th IFAC World Congress, Beijing, China.
[12] Kuo, B.C., Golnaraghi, F.(2012), 'Automatic Control Systems 8th edition', Bhushan Printline, Sahibabad (John Wiley Student Edition), New Delhi, India. ISBN 978-81265-1371-0.
[13] Ming-Tzu, H., Lin, C. (2003), 'PID Controller Design for Robust Performance', IEEE Transaction on Automatic Control, 48(8):1404-1409.
[14] Mohammed, J.A. (2011), 'Modelling Analysis and Speed Control Design Methods of a DC Motor', Eng. &Tech. Journal, Vol. 29, No. 1.
[15] Nobuyama, E., Abe, N. (2005), 'Control of Delay Systems from Fundamentals to Frontiers #2: Introduction of Time Delay Systems-Transfer Function Approach,' Journal of the Society of Instrument and Control Engineers, Vol 44, no. 12, pp. 883-887, (in Japanese).
[16] Ogata, K. (2007), 'Modern Control Engineering, 5th Edition', Prentice-Hall, ISBN-13: 978-0136156734, Page 912.
[17] Siva R. V. et'al, (2013), 'Robust Stabilization of Time-Delay Systems using PID Controller with a Smith Predictor,' IEEE International Conference on Control Application (CCA), part of 2013 IEEE Multi-Conference on Systems and Control, Hyderabad, India.
[18] Smith, O. J. M. (1959). 'A Controller to Overcome Dead Time'. ISA Journal, Vol. 6, No. 2, pp. 28-33.

