

PROPORTIONAL-INTEGRAL-DERIVATIVE ALGORITHM SELECTION FOR CONTROL SYSTEMS

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ABSTRACT

Proportional-Integral-Derivative is a popular control algorithm in feedback control systems. The three common Proportional-Integral-Derivative control algorithms in existence are parallel, series, and ideal. However, the process of selecting an appropriate algorithm for a given plant model has not been rigorously researched as little or no works have been reported in this area. The selection of an appropriate Proportional-Integral-Derivative control algorithm for a set of plant models is reported in this article. The three control algorithms were designed for each of the plant models considered to study the closed-loop step responses for the plants using each of the algorithms. Based on the values of the closed loop step-response performance parameters, an appropriate control algorithm was selected for each of the plants. The process is simple and efficient since the system open-loop transfer function model parameters are the only required to be known. From the results the recommended controller algorithm for the first order with time delay and type 0 second-order systems were parallel/ideal; first-order was series, while type 1 second-order could be any of the three algorithms. The study revealed that the appropriate algorithm for the considered first order with time delay and type 0 second-order systems were parallel/ideal; first-order was series, while type 1 second-order could be any of the three algorithms. It is recommended that the control algorithm parameters should be tuned after selection to improve the system performance.

Keywords: Closed-loop transfer function, First-order system, Open-loop transfer function, PID control algorithm, second-order system

1 INTRODUCTION

Proportional-Integral-Derivative (PID) controller is the backbone of feedback control system as it only requires a few numbers of controller gains and straightforward control law to be tuned and implemented respectively [1, 2]. More so, the controller has predictable controlled system behaviours, simple tuning methods, and digital implementation [3]. Other control algorithms may be considered only when PID algorithm fails under test. This control algorithm is a popular form of feedback control that handles important practical issues and covers more than 90% of the available control loops in industries [4]. PID control algorithm is the candidate for steady-state error reduction and improvement on system transient response [5]. PID control algorithm is more effective for first-order, second-order, or higher-order control systems whose model can be approximated by a first or second-order system model [1, 5]. The controller parameters to be determined are the proportional gain (K_p), integral gain (K_i) and the derivative gain (K_d) that ascertain the stability of the system despite the control actions. Several methods of tuning and obtaining PID controller gains exist in the literature. According to [4], the controller gain values may be determined by first obtaining the system stability region as a function of controller gains and then determining their value that gives the required system response within the region. A graphical method for obtaining PID controllers gains that guaranteed stability for time-delayed higher-order system was presented in [6]. The method can

be applied to yield all stabilizing PID controllers in the K_p , K_i and K_d stability surface and K_i and K_d stability plane for a fixed value of K_p . Simple and efficient PID controller design methodology whereby the controller parameters were solely determined from the plant model parameters was proposed by [7]. The study of the time-domain, frequency-domain, and multi-objective optimal-tuning of PID controller by using different kinds of performance functions for the three control schemes was carried out in [8]. The results showed significant improvement in system performance and maintenance despite variation in the plant dynamics. Proposed by [9] is application of a simple and effective PID controller tuning rules used for a wide range of stable processes for an unstable process by making use of simple desired closed-loop transfer function (CLTF) for the direct synthesis method and simple approximations of the plant time delay. The three commonly used PID control algorithms are parallel, series, and ideal algorithms [10]. The major difference between them is the way the controller gains interact [1, 11]. The techniques of tuning both parallel and series PID control algorithms were presented in [12]. In the control of a pH neutralization system, [13] compared the performance of the three PID controller algorithms based on the time domain performance indices after obtaining the controller parameters using Levenberg-Marquardt's optimization Algorithm. Presented by [14] are both the parallel and ideal forms of PID control algorithm transfer function (TF) and highlight of the functions of each of the controller gain and time parameters. The structures of the TF of parallel and ideal PID control algorithms were given in [11], showing the effects of the individual controller gains and parameters on the controlled system. The TFs of the parallel, series, and ideal PID algorithms with derivative filter were presented in [2]. The effects of PID control algorithm selection and the technique of tuning its parameters on time-delayed systems were reported in [2]. A practical based tuning method using the parallel and series PID controller algorithms with velocity feedback was reported in [15]. The process of selecting an appropriate algorithm among the three for plant control has not been fully exploited [10, 11, 14, 16]. Therefore, an approach of selecting an appropriate PID control algorithm for a given set of systems and the results obtained are presented in this study. Each of these algorithms was modeled and designed for the control of hypothetical first-order, first-order with time delay, type-1 second-order, and type-0 second-order systems. PID controller design method due to [1] where the second-order term within the controller TF becomes distinct after parameters rearrangement was adopted in this study. From this second-order term and the open-loop (OL) characteristic polynomial of the system under control, the PID controller gains were determined. This method of controller design is simple, direct, and enables the designer to determine the appropriate PID controller gains solely from the plant open-loop transfer function (OLTF) parameters. After the design of the controller, the TF for each of the PID controller algorithms and that of the plant to be controlled were cascaded, and then the system CLTF subjected to a step input function one after the other using MATLAB as a simulation tool. The performance parameters for these systems were obtained from the resulting step response. The time-domain performance parameters used are rise time (T_r), time to peak overshoot (T_p), percentage overshoot (PO), settling time (T_s) and steady-state error E_{ss} of the uncompensated and compensated systems dynamic time response. The obtained time-domain performance parameter values form the basis for the selection of the appropriate control algorithm for the plant. The obtained time-domain performance parameters for PID controlled systems were compared with that obtained for uncontrolled systems to know which algorithm is appropriate for a particular plant model.

2 SYSTEM MODEL

The system model used in this study was based on system TF, therefore; there is the need to develop the OLTF for each of the subsystems (plant and controller) and the overall system CLTF. The PID controller design method proposed by [1] was used due to its simplicity and operational effectiveness. It should be noted that [1] applied the method to only parallel PID control algorithm, but it can be extended to other algorithms by expressing their algorithm parameters in terms of their parallel counterparts, as done in this study. The system CLTF of equation 1 was derived using the system block diagram shown in Figure 1.

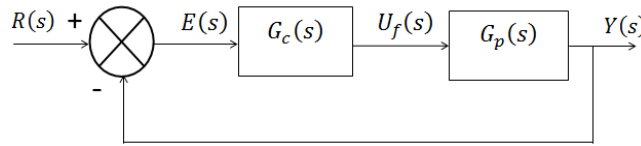


Figure 1. Block diagram of unity feedback control system

$$G_{cl}(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \quad (1)$$

Where, $R(s)$ - Reference input, $E(s)$ - Error signal, $G_c(s)$ - Controller TF, $U_f(s)$ =Control signal, $G_p(s)$ – Plant TF, $Y(s)$ - Actual output.

The models for each of the three PID control algorithms were developed and further simplified to yield the second-order factor. This is necessary as the factor was used for the controller design.

2.1 Parallel Algorithm Model

The TF model for the parallel algorithm version of PID controller is shown in equation 2.

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \quad (2)$$

Rearranging equation 2 yields equation 3 which contains the standard second-order polynomial in s-domain require for the controller design (the term in the parenthesis).

$$G_c(s) = K_d \frac{\left(s^2 + \frac{K_p}{K_d}s + \frac{K_i}{K_d}\right)}{s} \quad (3)$$

According to [1], applying the proposed PID controller design method, the required PID controller gains for the parallel algorithm can be determined by equating the term in parenthesis in equation 3 to the characteristic polynomial of plant OLTf.

2.2 Series Algorithm Model

The TF model for the series PID controller algorithm is given in equation 4.

$$G_c(s) = K_c \left(1 + \frac{1}{T_i s}\right) (1 + T_d s) \quad (4)$$

Where K_c is the gain, T_i and T_d are the integral and derivative times, respectively. Equation 4 was rearranged to bring out the second-order polynomial in s thereby yielding equation 5.

$$G_c(s) = \frac{K_c T_d \left(s^2 + \frac{(T_i + T_d)}{T_i T_d} s + \frac{1}{T_i T_d}\right)}{s} \quad (5)$$

For series algorithm T_i and T_d were determined in terms of K_p , K_i and K_d as shown in equations 6 and 7 by equating equation 5 to equation 3 assuming $K_c=1$.

$$T_d = K_d \quad (6)$$

$$T_i = \frac{K_p - K_i K_d}{K_i} \quad (7)$$

2.3 Ideal Algorithm Model

The TF model for the ideal PID controller algorithm is as shown in equation 8.

$$\frac{U(s)}{E(s)} = K_c \left(1 + \frac{1}{T_i s} + T_d s\right) \quad (8)$$

Rearranging equation 8 gives equation 9.

$$G_c(s) = \frac{K_c T_d \left(s^2 + \frac{s}{T_d} + \frac{1}{T_d T_i}\right)}{s} \quad (9)$$

For ideal algorithm, T_d and T_i were determined by equating equation 9 to 3 when $K_c = 1$ and they are as shown in equations 10 and 11 respectively.

$$T_d = K_d \quad (10)$$

$$T_i = \frac{1}{K_i} \quad (11)$$

3 SYSTEM DESIGN

The following plant models were considered in this study: first-order, first-order with time delay, type 1 second-order, and type 0 second-order systems. To obtain the controller performance evaluation, the three control algorithms were designed for each of the plant models.

3.1 Design of PID Control Algorithm for First-Order System

The design of the three algorithms for first-order system was presented in this subsection.

3.1.1 Design of Parallel PID Control Algorithm for First-Order System

The OLTF and CLTF for first-order system are shown in equations 12 and 13 respectively.

$$G_{pol} = \frac{K}{Ts+1} \quad (12)$$

$$G_{pcl} = \frac{K}{Ts+K+1} \quad (13)$$

where K is the steady state dc gain and T is the system time constant.. To determine the PID controller gains, the characteristic polynomial of the plant OLTF was equated to the second-order polynomial component of equation 3 and K_p was assumed to be 1. Therefore, $K_d = \frac{1}{T}$ and $K_i = \frac{1}{T}$. Substituting the controller gains into equation 2 gives the parallel PID control algorithm TF for this system; which was combined with the plant TF of equation 12 to form the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 14.

$$G_{cl}(s) = \frac{A_1s^2+A_2s+A_3}{B_1s^2+B_2s+A_3} \quad (14)$$

where: $A_1 = KK_d$, $A_2 = KK_p$, $A_3 = KK_i$, $B_1 = A_1 + T$ and $B_2 = A_2 + 1$.

3.1.2 Design of Series PID Control Algorithm for First-Order System

The PID controller parameters for this algorithm were determined by substituting the values of K_p , K_i and K_d into equations 6 and 7 assuming $K_c = 1$. This gives, $T_d = \frac{1}{T}$ and $T_i = \frac{T^2-1}{T}$. Substituting the controller gains and time parameters into equation 4 gives the series PID control algorithm TF for this system. This was then combined with the plant TF of equation 12 to form the system loop TF. The loop TF was substituted in equation 1 to give the system CLTF of equation 15.

$$G_{cl}(s) = \frac{A_1s^2+A_2s+A_3}{s^3+B_1s^2+B_2s+A_3} \quad (15)$$

where: $A_1 = KK_cT_dT_i$, $A_2 = KK_c(T_i+T_d)$, $A_3 = KK_c$, $B_1 = A_1 + T_iT$ and $B_2 = A_2 + T_i$

3.1.3 Design of Ideal PID Control Algorithm for First-Order System

The PID controller parameters were determined by substituting the value of K_p , K_i and K_d into equations 10 and 11 when $K_c = 1$, hence we have $T_d = \frac{1}{T}$ and $T_i = T$. Substituting the controller gains and time parameters into equation 8 yields the ideal PID control algorithm TF for the system. It was combined with the plant TF of equation 13 to form the loop TF. The system CLTF was obtained by substituting the loop TF into equation 1, yielding equation 16.

$$G_{cl}(s) = \frac{A_1s^2+A_2s+A_3}{B_1s^2+B_2s+A_3} \quad (16)$$

where: $A_1 = K_cKT_dT_i$, $A_2 = K_cKT_i$, $A_3 = K_cK$, $B_1 = A_1 + T_iT$ and $B_2 = A_2 + T_i$

3.2 Design of PID Control Algorithm for First-Order System with Time Delay

The design of the three algorithms for first-order system with time delay was presented in this subsection.

3.2.1 Design of Parallel PID Control Algorithm for First-Order System with Time Delay

The TF for first-order system with time delay is as given in equation 17.

$$G_p = \frac{K}{\tau s + 1} e^{-Ls} \quad (17)$$

where: K = steady-state DC gain, τ = system time constant, L = time delay. To get rational TF, first-order pade approximation was used for the approximation of the time delay TF, and the resulting OLTF and CLTF for the system are as shown in equations 18 and 19 respectively.

$$G_{pol} = \left. \begin{aligned} &\frac{a_1 s + a_2}{b_1 s^2 + b_2 s + 2} \\ &\frac{\frac{a_1 s + a_2}{b_1 s + b_1}}{s^2 + \frac{b_2 s + 2}{b_1 s + b_1}} \end{aligned} \right\} \quad (18)$$

$$G_{pcl} = \frac{a_1 s + a_2}{b_1 s^2 + (a_1 + b_2)s + a_2 + 2} \quad (19)$$

Where: $a_1 = -KL$, $a_2 = 2K$, $b_1 = TL$ and $b_2 = 2T + L$. To determine the PID controller gains, the characteristic polynomial of the plant TF of equation 18 was equated to the second-order polynomial of equation 3 and letting $K_p = 1$, Then, $K_d = \frac{TL}{2T+L}$ and $K_i = \frac{2}{2T+L}$. Substituting these controller gains into equation 2 gives the parallel PID control algorithm TF for this system which was combined with the plant TF of equation 18 to form the system loop TF. The loop TF was substituted in equation 1 to give the system CLTF of equation 20.

$$G_{cl}(s) = \frac{A_1 s^3 + A_2 s^2 + A_3 s + A_4}{B_1 s^3 + B_2 s^2 + B_3 s + A_4} \quad (20)$$

where: $A_1 = a_1 K_d$, $A_2 = a_2 K_d + a_1 K_p$, $A_3 = a_2 K_p + a_1 K_i$, $A_4 = a_2 K_i$, $B_1 = A_1 + b_1$, $B_2 = A_2 + b_2$ and $B_3 = A_3 + 2$.

3.2.2 Design of Series PID Control Algorithm for First-Order System with Time Delay

The PID controller parameters were determined by substituting the values of K_p , K_i and K_d into equations 6 and 7, assuming $K_c = 1$, which yields

$$T_d = \frac{TL}{2T+L} \text{ and } T_i = \frac{(2T+L)^2 - 2TL}{2(2T+L)}$$

Substituting these controller gain and time parameters into equation 4 gives the series PID control algorithm TF for this system which was combined with the plant TF of equation 18 to form the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 21.

$$G_{cl}(s) = \frac{A_1 s^3 + A_2 s^2 + A_3 s + a_2}{B_1 s^3 + B_2 s^2 + B_3 s + a_2} \quad (21)$$

where: $A_1 = a_1 K_c T_d T_i$, $A_2 = a_1 (T_i + T_d) + a_2 K_c T_d T_i$, $A_3 = a_1 + a_2 (T_i + T_d)$, $B_1 = A_1 + T_i b_1$, $B_2 = A_2 + T_i b_2$, $B_3 = A_3 + 2T_i$, $a_1 = -KL$, $a_2 = 2K$, $b_1 = TL$ and $b_2 = 2T + L$.

3.2.3 Design of Ideal PID Control Algorithm for First-Order System with Time Delay

The PID controller parameters were determined by substituting the value of K_p , K_i and K_d into equations 10 and 11 assuming $K_c = 1$ which gives

$$T_d = \frac{TL}{2T+L} \text{ and } T_i = \frac{2T+L}{2}$$

Substituting these controller gain and time parameters into equation 8 gives the ideal PID control TF for this system which was combined with the plant TF of equation 18 to form the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 22.

$$G_{cl}(s) = \frac{A_1s^3 + A_2s^2 + A_3s + A_4}{B_1s^3 + B_2s^2 + B_3s + A_4} \quad (22)$$

where: $A_1 = a_1K_cT_dT_i$, $A_2 = a_1K_cT_i + a_2K_cT_dT_i$, $A_3 = a_1K_c + a_2K_cT_i$, $A_4 = a_2K_c$, $B_1 = A_1 + T_ib_1$, $B_2 = A_2 + T_ib_2$, $B_3 = A_3 + 2T_i$, $a_1 = -KL$, $a_2 = 2K$, $b_1 = TL$, $b_2 = 2T + L$

3.3 Design of PID Control Algorithm for Type1 Second-Order System

The design of the three algorithms for type 1 second-order system was presented in this subsection.

3.3.1 Design of Parallel PID Control Algorithm for Type1 Second-Order System

The OLTF and CLTF for a type 1 second-order system are as shown in equations 23 and 24 respectively.

$$G_{pol} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s} \quad (23)$$

$$G_{pcl} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (24)$$

where: ω_n = system natural frequency and ξ = system damping ratio. To determine the PID controller gains for the system of equation 23, the second-order polynomial in equation 3 was equated to the characteristic polynomial of equation 23. If $K_p = 1$, then $K_d = \frac{1}{2\xi\omega_n}$ and $K_i = 0$. Substituting these controller gains into equation 2 gives the parallel PID control algorithm TF for this system which was combined with the plant TF of equation 23 to form the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 25.

$$G_{cl}(s) = \frac{A_1s^2 + A_2s + A_3}{s^3 + B_1s^2 + A_2s + A_3} \quad (25)$$

where: $A_1 = a_1K_d$, $A_2 = a_1K_p$, $A_3 = a_1K_i$, $B_1 = A_1 + b_1$, $a_1 = \omega_n^2$ and $b_1 = 2\xi\omega_n$.

3.3.2 Design of Series PID Control Algorithm for Type1 Second-Order System

The PID controller parameters were determined by substituting the value of K_p , K_i and K_d into equations 6 and 7 which gives

$$K_p = 1, T_d = \frac{1}{2\xi\omega_n} \text{ and } T_i = \infty$$

Substituting these controller gain and time parameters into equation 4 gives the series PID control algorithm TF for this system which was combined with the plant TF of equation 23 to form the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 26.

$$G_{cl}(s) = \frac{A_1s^2 + A_2s + A_3}{s^3 + B_1s^2 + A_2s + A_3} \quad (26)$$

where: $A_1 = K_c a_1 T_d$, $A_2 = K_c a_1$, $A_3 = 0$, $B_1 = A_1 + b_1$, $a_1 = \omega_n^2$ and $b_1 = 2\xi\omega_n$.

3.3.3 Design of Ideal PID Control Algorithm for Type1 Second-Order System

The PID controller parameters were determined by substituting the value of K_p , K_i and K_d into equations 10 and 11 assuming $K_c = 1$ which yielded;

$$T_d = \frac{1}{2\xi\omega_n} \text{ and } T_i = \infty$$

Substituting these controller gain and time parameters into equation 8 gives the ideal PID control algorithm TF for this system which was combined with the plant TF of equation 23 to form

the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 27.

$$G_{cl}(s) = \frac{A_1s^2 + A_2s + A_3}{s^3 + B_1s^2 + A_2s + A_3} \quad (27)$$

Where: $A_1 = K_c a_1 T_d$, $A_2 = K_c a_1$, $A_3 = 0$, $B_1 = A_1 + b_1$, $a_1 = \omega_n^2$ and $b_1 = 2\xi\omega_n$.

3.4 Design of PID Control Algorithm for Type 0 Second-Order System

The design of the three algorithms for type 0 second-order system was presented in this subsection.

3.4.1 Design of Parallel PID Control Algorithm for Type 0 Second-Order System

The OLTF and CLTF for type 0 second-order system are as shown in equations 28 and 29 respectively.

$$G_{pol} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (28)$$

$$G_{pcl} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + 2\omega_n^2} \quad (29)$$

To determine the PID controller gains for the system of equation 28, we proceed by equating the second-order component of equation 3 to the characteristic polynomial of equation 28 and if $K_p = 1$, then $K_d = \frac{1}{2\xi\omega_n}$ and $K_i = \frac{\omega_n}{2\xi}$. Substituting these controller gains into equation 2 gives the parallel PID control algorithm TF for this system which was combined with the plant TF of equation 28 to form the system loop TF. The loop TF was substituted in equation 1 to give the system CLTF of equation 30.

$$G_{cl}(s) = \frac{A_1s^2 + A_2s + A_3}{s^3 + B_1s^2 + B_2s + A_3} \quad (30)$$

where: $A_1 = a_1 K_d$, $A_2 = a_1 K_p$, $A_3 = a_1 K_i$, $B_1 = A_1 + b_1$, $B_2 = A_2 + a_1$, $a_1 = \omega_n^2$ and $b_1 = 2\xi\omega_n$

3.4.2 Design of Series PID Control Algorithm for Type 0 Second-Order System

The PID controller parameters were determined by substituting the value of K_p , K_i and K_d into equations 6 and 7 which gives

$$K_p = 1, T_d = \frac{1}{2\xi\omega_n} \text{ and } T_i = \frac{4\xi^2 - 1}{2\xi\omega_n}$$

Substituting these controller gain and time parameters into equation 4 gives the series PID control algorithm TF for this system which was combined with the plant TF in equation 28 to form the system loop TF. The loop TF was substituted into equation 1 to give the system CLTF of equation 31.

$$G_{cl}(s) = \frac{A_1s^2 + A_2s + A_3}{T_i s^3 + B_1s^2 + B_2s + A_3} \quad (31)$$

Where: $A_1 = a_1 K_c T_d T_i$, $A_2 = a_1 K_c (T_i + T_d)$, $A_3 = a_1 K_c$, $B_1 = A_1 + b_1 T_i$, $B_2 = A_2 + a_1 T_i$, $a_1 = \omega_n^2$ and $b_1 = 2\xi\omega_n$

3.4.3 Design of Ideal PID Control Algorithm for Type 0 Second-Order System

The PID controller parameters were determined by substituting the value of K_p , K_i and K_d into equations 10 and 11 assuming $K_c = 1$ which yielded $T_d = \frac{1}{2\xi\omega_n}$ and $T_i = \frac{2\xi}{\omega_n}$

Substituting these controller gain and time parameters into equation 8 gives the ideal PID control algorithm TF for the system which was combined with the plant TF of equation 28 to form the system loop TF which was substituted into equation 1 to give the system CLTF of equation 32.

$$G_{cl}(s) = \frac{A_1s^2 + A_2s + A_3}{T_i s^3 + B_1s^2 + B_2s + A_3} \quad (32)$$

where: $A_1 = a_1K_cT_dT_i$, $A_2 = a_1K_cT_i$, $A_3 = a_1K_c$, $B_1 = A_1 + b_1T_i$, $B_2 = A_2 + a_1T_i$, $a_1 = \omega_n^2$ and $b_1 = 2\xi\omega_n$

4 SYSTEM SIMULATION

The system closed-loop (CL) step response was plotted for the uncontrolled system and the controlled systems under each of the three PID control algorithms. The simulations were carried out using hypothetical first-order, first-order with time delay, type-1 second-order, and type-0 second-order system models with the following values:

First-order: $K = 2$ and $T = 5$ seconds

First-order with dead time: $K = 2$; $L = 1.5$ seconds and $T = 5$ seconds

Type-1 second-order: $\omega_n = 12$ rad/sec and $\xi = 0.7$

Type-0 second-order systems: $\omega_n = 12$ rad/sec and $\xi = 0.7$

The step responses shown in Figure 2 are for the uncontrolled; parallel, series and ideal PID controlled first-order systems obtained using equations 13, 14, 15 and 16 respectively. The system TFs for the first-order system with dead time shown in equations 19 to 22 are approximate as they are based on approximations of the system time delay TF. To have an exact representation of the system CL response for uncontrolled and controlled systems, the plant TF of equation 17 and the modelled PID control algorithms (parallel, series, and ideal) were created in Matlab, and feedback was used to compute the CL response from input to output. The CL step responses were then plotted for the uncontrolled; parallel, series, and ideal PID controlled systems as shown in Figure 3. For type 1 second-order system, the step response of Figure 4 was obtained by plotting the step responses of the TF using equations 24 to 27. The step response for uncontrolled; parallel, series, and ideal PID algorithm controlled for type 0 second-order system were plotted using the system TFs of equations 29 to 32 respectively and is as shown in Figure 5.

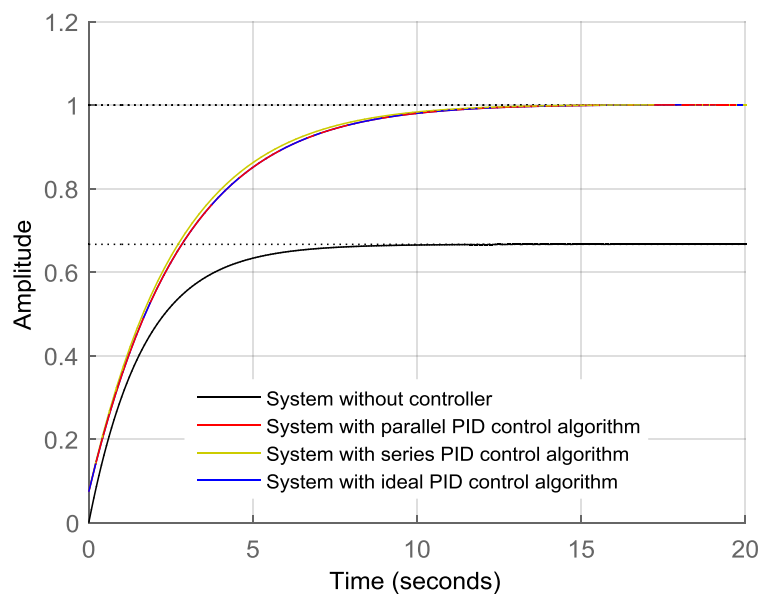


Figure 2. Step responses for uncontrolled and PID controlled first-order systems

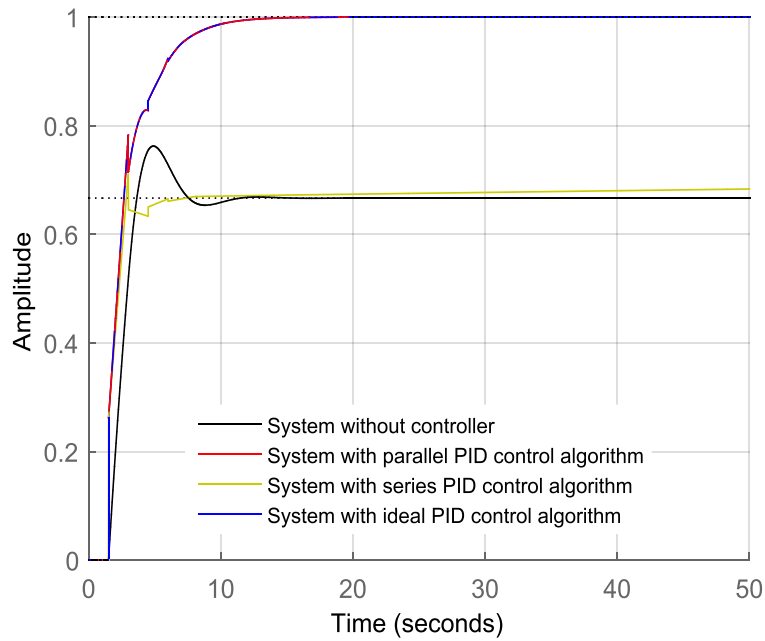


Figure 3. Step responses for uncontrolled and PID controlled first-order systems with delay

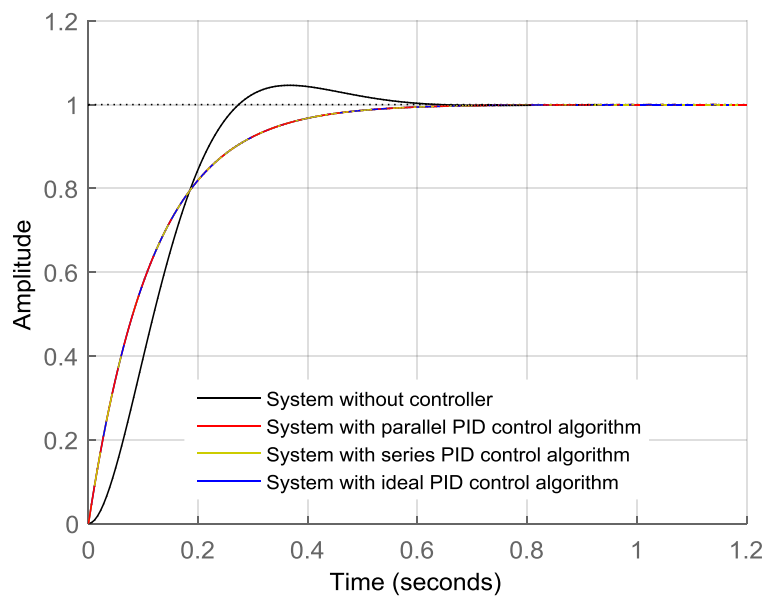


Figure 4. Step responses for uncontrolled and PID controlled type 1 second-order systems

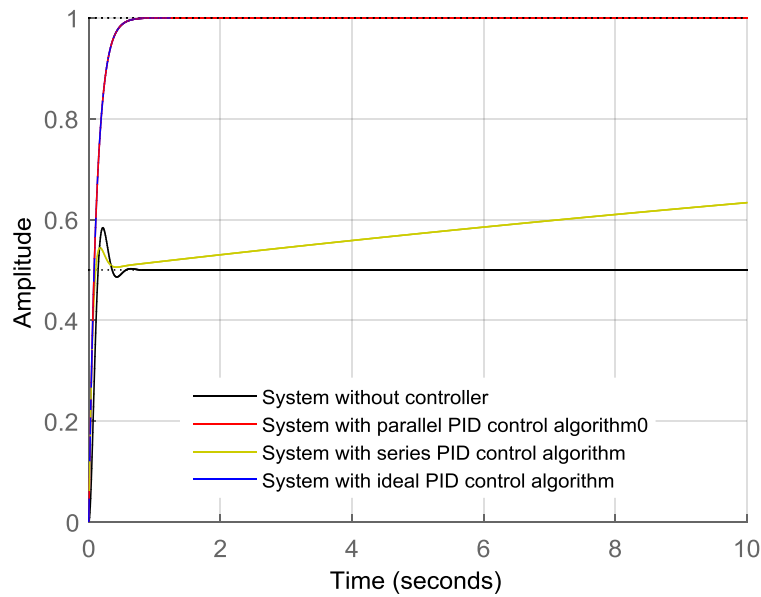


Figure 5. Step responses for uncontrolled and PID controlled type 0 second-order systems

5 RESULTS AND DISCUSSION

The time-domain performance parameters extracted from Figures 2 to 5 are shown in Tables 1 to 4 respectively.

Table 1. Closed-loop time-domain performance parameters for first-order system

Time-domain performance parameters	T_r (sec)	T_p (sec)	PO (%)	T_s (sec)	E_{ss}
System without controller	N/A	N/A	NaN	N/A	N/A
System with parallel PID control algorithm	5.94	15.4	0	10.1	0
System with series PID control algorithm	5.71	14.8	0	9.74	0
System with ideal PID control algorithm	5.94	15.4	0	10.1	0

From Figure 2 the response of the uncontrolled first-order system did not track the reference input as the maximum value attained by this system was 0.667. Therefore, no parameter can be associated with this condition in Table 1. It can be observed from Figure 3 that the response of the controlled systems to step input under any of the PID control algorithms did not start from zero. Rather it started from positive point on the y-axis with an offset of 0.0741 due to the presence of positive zeros whose values are less than that of the poles in the system closed TF. Considering the value of the performance parameters in Table 1, first-order system has the best performance when the series PID control algorithm was used. The performances under parallel and ideal algorithms are the same and next to the best. Therefore, the appropriate PID control algorithm selected for this system was series PID control algorithm.

Table 2. Closed-loop performance parameters for first-order system with time delay

Time-domain performance parameters	T_r (sec)	T_p (sec)	PO (%)	T_s (sec)	E_{ss}
System without controller	N/A	N/A	NaN	N/A	N/A
System with parallel PID control algorithm	4.09	14	0	9.06	0
System with series PID control algorithm	1210	6000	0	2840	0
System with ideal PID control algorithm	4.09	14	0	9.06	0

As shown in Figure 3, the response of the uncontrolled system to unit step input did not track the reference input as the peak value attained by this system was 0.762 at 4.9 s and settled to within $\pm 2\%$ of 0.667 at 7.1 s. Therefore, this system had no direct relationship with the time domain performance parameters since it did not track the reference input. The same results (best performance) were obtained when the system was under the control of either parallel or ideal PID control

algorithms, as can be seen in Table 2. However, the system gave the worst performance when the series PID control algorithm was used. From this analysis, the appropriate algorithm for this system can therefore be selected from either parallel or ideal.

Table 3. Closed-loop time-domain performance parameters for type 1 second-order system

Time-domain performance parameters	T_r (sec)	T_p (sec)	PO (%)	T_s (sec)	E_{ss}
System without controller	0.177	0.367	4.6	0.498	0
System with parallel PID control algorithm	0.257	0.889	0	0.458	0
System with series PID control algorithm	0.257	0.889	0	0.458	0
System with ideal PID control algorithm	0.257	0.889	0	0.458	0

The system unit step response of Figure 4 and the time domain performance parameters of Table 3 show that the uncontrolled system has the best performance with respect to rise time and time to peak overshoot but has the worst percentage overshoot and settling time values. The system performance was the same when the system was under the control of parallel, series, or ideal algorithm and outperforms the uncontrolled system in the area of percentage overshoot and settling time. Therefore, any of the control algorithms can be used for this system.

Table 4. Closed-loop performance parameters for type 0 second order system

Time-domain performance parameters	T_r (sec)	T_p (sec)	PO (%)	T_s (sec)	E_{ss}
System without controller	N/A	N/A	NaN	N/A	N/A
System with parallel PID control algorithm	0.256	1.2	0	0.456	0
System with series PID control algorithm	51.9	180	0	104	0
System with ideal PID control algorithm	0.256	1.2	0	0.456	0

As shown in Figure 5, the system unit step response showed that the response of the uncontrolled system did not track the reference input as the maximum attainable value for this system was 0.584 at 0.214s and it settled to within $\pm 2\%$ of 0.5 at 0.479s. These are not relevant to the time-domain performance parameters since the system does not track the reference input. It is glaring from Tab. 4 that the system with either parallel or ideal algorithm has the same and the best performance while the system with series algorithm has the worst performance. Based on this either parallel or ideal algorithm can be selected for this system.

6 CONCLUSION

The three PID control algorithms were modelled and designed for each of the plants considered. The controller gains were solely determined by the parameters of the plant OLTf. The selection of the appropriate algorithm was based on the values of the time domain parameters obtained from the system CL unit step responses. The study revealed that the appropriate algorithm for the considered first order with time delay and type 0 second-order systems were parallel/ideal; first-order was series, while type 1 second-order could be any of the three algorithms. It is recommended that the control algorithm parameters should be tuned after selection to improve the system performance.

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