Modified Cascade Controller Design for Unstable Processes With Large Dead Time

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ABSTRACT In this article, a simple controller design with the fractional order calculations applies to unstable cascade processes with a significant time delay. Series cascade control system consists of two loops in which the inner loop is designed using the IMC principle based on the synthesis method. The primary controller is designed with the FOPI-FOPD controller to ensure stable and satisfactory closed-loop performances for the unstable processes. For the primary controller, five tuning parameters are involved, which tuned using the centroid of the convex stability region method. Different examples are given to illustrate the superiority of the proposed design over some existing designs. Results obtained from simulation reveals that with the proposed control design, enhanced closed-loop control performances are obtained for nominal and perturbed conditions.

INDEX TERMS Series cascade control, unstable time-delay process, fractional-order PI/PD, internal model control, convex stability region.

I. INTRODUCTION

Many of the industries are dealing with unstable processes. Unstable poles in the unstable process, in many cases, provide extreme overshoot and more substantial settling time [1]. In such a case, the standard PID controller is not suitable for standard tuning methods. Hence, many authors have been studied during the past decades about the various control methods of the unstable process with larger delay time. Some researchers have compensated the unstable process adequately with Smith delay compensation. However, the Smith predictor does not apply to the unstable process with the substantial delay time [2]–[4]. As pointed out by many researchers, a particular cascaded structure has often pro-

vided an enhanced closed-loop performance than the standard feedback control. The cascade control structure consists of the primary and secondary loops, where the fast dynamics are handled by the secondary loop and slow dynamics are handled by the primary loop. Cascade controller design is a special control structure which deals with the stable and unstable process (plural) with delay time effectively [5]–[10]. The inner and outer loops of the cascade control structure are employed with Proportional–Integral–Derivative (PID) controllers which are low order controllers. Two different strategies such as a series cascade control system (SCCS), a parallel cascade control system (PCCS), are extensively used for stable and unstable industrial processes to achieve enhanced closed-loop performance respectively. Proportional-Integral (PI) controller is often used in the primary loop and the proportional (P) control is used as a secondary controller in

The associate editor coordinating the review of this manuscript and approving it for publication was Chao-Yang Chen.

the secondary loop of cascade controller design. Enhanced SCCS design is used [11]–[18] for unstable and integrating process with three controllers and one filter for obtaining the closed-loop performances. In the design of controllers to the unstable process, it is common to use a set point filter []. The filter constant is optimized to obtain the desired performances with the unstable process using various optimization algorithms. Zafer Bingul applies differential evaluation for optimizing the filter constant and analyzed the robustness of the design by obtaining the compelling performances from the unstable process [19]. In [20], the generalized predictive cascade design is proposed for the stable, unstable, and integrating system using filtered smith predictor design. The design of the many cascade control systems is not simple. Two controllers of cascade structure are desirable in the practical aspects even when unstable system has a longer delay time. Recently, PI-PD control structure is proposed by many authors for an unstable system with more substantial delay time. Many tuning methods for the PI-PD control structure is reported for an unstable process [21]–[25]. The improved performance is obtained using the PI-PD structure than the PID controller design for both the stable and unstable systems with substantial delay. This article attempts to use the advantages of PI-PD control design as a primary controller to SCCS for an unstable system with a large delay. The PI-PD controllers have a broad prospect, but there are limitations in controller tuning. The concept of PI-PD combined with the cascade structure for the stable and unstable process with the larger dead-time will provide the expected closed-loop response when the proper tuning methods are used. However, with the tuning methods of PI-PD controllers, there some severe problems pointed out in the chemical process due to uncertainties and larger delay time [26]–[33]. superior performance is reported recently with fractional controller design over the integer design.

Recently, many researchers applied the fractional calculus for modeling and controlling of industrial process systems when the controller parameters such as integration and the differentiation are described via fractional-order equations. Recently, with a revival of interest in the area of fractional calculus, fractional order integral and differential are used and it played a vital role in control system design. The FOPID controllers are also used for many practical applications like motion control, robotics, electric power systems and many time-delay processes in recent days [34], [35]. Varieties of design procedures are applied to FOPID controllers design and obtained desired performances even when the system has load disturbances and uncertainties of the plant model. Many researchers dealt with optimization algorithms like GA, PSO, Grey Wolf Optimizer [36] to find the optimum parameters of PID and FOPID controllers. In [37], the authors applied swarm intelligence for obtaining optimum parameters of the FOPID controller which helps to obtain the desired performances from the unstable processes. The combination of both FO and smith predictor scheme is applied in many industrial applications like furnace, water irrigation system,
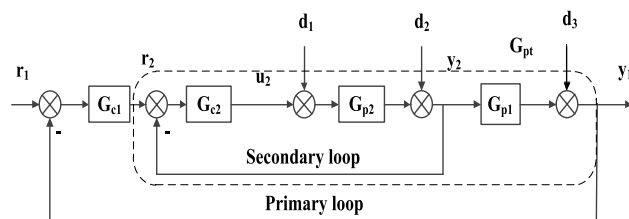

FIGURE 1. Basic series cascade control structure.

and others [38]–[41]. The guaranteed results are obtained using the combination of fractional-order system and smith predictor system. The advantages of controller design with the combination of fractional order calculation and the cascade controller design are reported in the recent research. The IMC controller was also modified with fractional calculus and the improved response was obtained from Second-Order plus Dead Time (SOPDT) processes in [42]–[46]. Based on suggestion from the literature, series cascade control system is designed for an unstable system with a substantial dead time. In this article, the SCCS is designed with the FOPI-FOPD control structure and the robust stability conditions of the unstable system are given. In the proposed SCCS design, set-point tracking and disturbance rejection are done by FO-IMC. Simulation results illustrate the improved performances and robustness of the design than the other related work reported in the literature.

This article is organized as follows: In Sec 2, fractional-order calculations to PI-PD controller and FO-IMC design is introduced. The system description and statement of the problem are discussed in section 3. Section 4 discusses the comparative results with some the selected examples from the literature and finally, the conclusion is displayed in section 5.

II. THEORETICAL DEVELOPMENTS

Many process industries have cascade structures. Most of the secondary processes of the cascade structure are stable, whereas the primary process may be stable or unstable and with or without dead time. In this work, a stable secondary process is considered with the stable/integrating/unstable primary process. The proposed design is represented pictorially in Fig. 1

III. CONTROLLER DESIGN

The controller design for both primary and secondary loop is essential to the system. The secondary controller is designed before the primary controller. Fig. 2 shows the block diagram of the modified cascade control structure to the plant model. The FO-IMC based controller is designed to the secondary loop. FO-PI/FO-PD controller is designed to the primary loop so that effective and stable performance can be obtained for the unstable process [49]–[52].

A. FRACTIONAL-ORDER CALCULUS

The generation of non-integer order for the integral and derivative operators is given in [1]. Caputo's definition, Riemann–Liouville and Grünwald–Letnikov are some of the
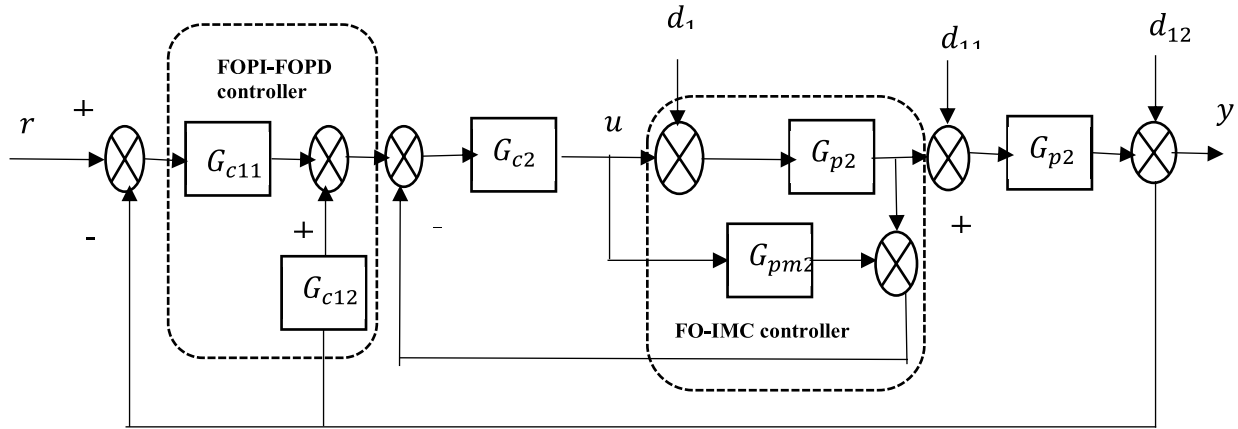
FIGURE 2. Proposed cascade loop for the unstable time-delay process.

definitions that are often used in the literature [39]. Caputo's definition is used widespread and it is given in Eq (1)

$$a_{b^r}^D f(t) = \frac{1}{\mu(v-r)} \int_a^b \frac{f(\tau)}{(t-\tau)^{r-v+1}} d\tau,$$
$$\text{for } (v-1 < r < v), \quad a = 0 \quad (1)$$

and $\frac{d^v}{dt^v} f(t)$, $r = v$ for $(v-1 < r < v)$ since v is larger than or equal to r and $\mu(z)$ is Euler's gamma function.

The Laplace Transform of the Riemann-Liouville definition of the fractional derivative is given in Eq (2)

$$\mathcal{L}\left\{o_b^{D^r} f(t)\right\} = s^r \mathcal{L}\{f(t)\} - \sum_{k=0}^{n-1} s^{r-k-1} f(t)|_{t=0} \quad (2)$$

for $(v - 1 < r < v)$. For zero initial condition, $\mathcal{L}\left\{o_b^{D^r} f(t)\right\} = s^r \mathcal{L}\{f(t)\}$.

An input-output derivative in the Caputo definition is Caputo fractional derivative (Podlubny 1999b) is the main interest to the authors to use Caputo's definition in this article.

Generally, the integer-order derivative is similar to the Laplace Transform of the fractional derivative, which helps the fractional calculus to work with non-integer order in the fractional controller design. The above calculation has been used for solving the fractional order calculation and the fractional-order modeling, and control toolbox from MATLAB is further used in this article for obtaining the numerical results.

B. FO-IMC CONTROLLER DESIGN FOR THE SECONDARY PROCESS

Internal Model Control (IMC) design, which was developed by Morari and co-workers [43] and it is used in many controller applications recently. The direct synthesis model of the IMC design provides the analytical controller parameters to the process model Eq (3)- Eq (6) by using the assumed process model. The IMC approach has the advantage that it allows model uncertainty and a tradeoff between performance

and robustness to be considered more systematically.

$$G_{Cs}(s) = \frac{G_{IMC}(s)}{1 - G_{IMC}(s)G_{m_2}(s)} \quad (3)$$

$$\frac{y_2(s)}{r_2(s)} = \frac{G_{c_2}(s)G_{p_2}(s)}{1 - G_{c_2}(s)G_{m_2}(s) + G_{c_2}(s)G_{p_2}(s)} \quad (4)$$

$$\frac{y_2(s)}{d_2(s)} = \frac{1 - G_{c_2}(s)G_{m_2}(s)}{1 - G_{c_2}(s)G_{m_2}(s) + G_{c_2}(s)G_{p_2}(s)} \quad (5)$$

$$\frac{y_2(s)}{r_2(s)} = G_{IMC}(s)G_{p_2}(s) \quad (6)$$

Assume $G_{p_2}(s)$ is the secondary process model which is used as an internal model and $G_{IMC}(s)$ is the internal model controller. Then, the IMC controller is designed in the following steps with Eq (7)- Eq (10):

Step 1:

$$G_m(s) = G_m^-(s)G_m^+(s) \quad (7)$$

In Eq (7), $G_m^+(s)$ contains any time delays and right-half plane zeros. $G_m^+(s)$ must have a steady-state gain equal to one

Step 2:

The controller is specified as

$$G_{IMC}(s) = \frac{1}{G_m^-(s)} f(s) \quad (8)$$

where f(s) is pass filter with the steady-state gain is equal to one.

$$f(s) = \frac{1}{(1 + \tau_c(s))^a} \quad (9)$$

The desirable close-loop constant τ_c and positive integer a are chosen in such a way to make the controller realizable.

For FO-IMC,

$$f(s) = \frac{1}{(1 + \tau_c s^{1+\gamma})^a}, \quad 0 < \gamma < 1 \quad (10)$$

where γ is a fractional number.

C. PRIMARY CONTROLLER DESIGN

The primary controller is designed using fractional order calculus. The FOPI-FOPD controller structure in the primary loop is tuned based on fraction order calculus to stabilize the process model. For the effective primary controller design, the overall primary process model is required, which is obtained from the r2 to y1 of the cascade control structure. For the overall primary model, the perfect secondary loop transfer function is required that is identified by the secondary loop controller design.

$$G_{pp_1}(s) = \frac{y_1(s)}{r_2(s)} = G_{ps_1}(s)\, G_{p_1}(s) \qquad (11)$$

where, $G_{ps_1}(s)$ is a secondary process model and $G_{pp_1}(s)$ a primary process model. In this article, the primary process is given in Eq (12), and Eq (13) has been considered as,

$$G_{p1}(s) = \frac{K(1-zs)}{\tau s - 1} e^{-\theta s} \qquad (12)$$

$$G_{p1}(s) = \frac{K}{\tau s - 1} e^{-\theta s} \qquad (13)$$

Let us assume the obtained secondary loop process model has the structure of Unstable First Order Plus Time Delay (FOPTD) process,

$$G_{ps_1}(s) = \frac{k_{s1} e^{-\theta_s s}}{\tau_{s1} s - 1} \qquad (14)$$

The primary process is designed to complete the model $G_{pp_1}(s)$, which is a second-order process and it is derived by substituting Eq (13),(and) Eq (12) into Eq (14) to obtain as Eq (15) and Eq (16),

$$G_{pp1}(s) = \frac{k_{s1} e^{-(\theta_s + \theta_{p1})s}}{(\tau_{s1} s - 1)(\tau_c s^{1+\gamma} + 1)} \qquad (15)$$

$$G_{pp1}(s) = \frac{k_{s1}(1-zs) e^{-(\theta_s + \theta_{p1})s}}{(\tau_{s1} s - 1)(\lambda s^{1+\gamma} + 1)} \qquad (16)$$

Note: The primary process model in this article is considered as an unstable first order plus dead time and first-order plus positive zero with dead time model, However, the processes with two unstable poles can be properly identified as a first-order system and the method proposed can be applied since the two unstable poles of the system makes the entire process into the third-order system.

The transfer function of the FOPI-FOPD controllers are proposed here for the primary loop controller design. The basic transfer function model of an FO-PI is given by

$$G_{C_1}(s) = K_p \left(1 + \frac{K_I}{s}\right)^r \qquad (17)$$

The model of the FO-PI in Eq (17), consists of the proportional gain K_p, the integral gain K_I and the fractional-order r. The range of the order considered in this article is (0, 2).

The transfer function of an FO-PD is given in Eq (18)

$$G_{C_2}(s) = K_p (1 + K_d s)^\rho \qquad (18)$$

The fractional-order of the FO-PD control is ρ with the range of (0,2) is used and proportional, and derivative gains of the transfer function model are K_p and K_d.

3.4 Selection guidelines for filter tuning parameter τ_c

Many simulation cases, it is observed that the phase margin and gain margin are reduced with the increase in τ_c. Higher value of τ_c leads to poor performance, and lower values lead to small tolerance to delay mismatch. For the practical design of the controller, the (value of) τ_c is selected between 0.5 to 2 in this article.

IV. PROBLEM STATEMENT AND SYSTEM DESCRIPTIONS

The cascade controller modified with the primary PI-PD controller structure for the stable and unstable primary process is introduced in this section.

A. CENTROID OF CONVEX STABILITY

The centroid of convex stability method is used in this article for the computation of stabilizing the PI-PD controllers for processes with time delay using the stability boundary locus. The method used here stabilizes the values of PI-PD controllers in the k_f-k_i plane and k_f-k_d plane for a given system by achieving user specified gain and phase margins for time delay systems. The equations of the planes and straight lines can be derived using the stability boundary of the stabilizing regions obtained in the k_f-k_i plane for fixed values of k_d and k_f-k_d plane for fixed values of k_f. The method used here provides many advantages when applied to the control systems with time delay of any order including unstable time delay systems. This is an effective method in terms of computing the stability region. The basics of the stabilization of PI controller are given in [32].

In this article, the parameters of the FOPI-FOPD controller are generalized to the unstable system and it can be obtained by the graphical method. Three points in the proposed method are in-center point, Fermat point, and geometry method in convex stable region used to tune the FOPI-FOPD controller parameter. The major steps involved in the design are: Initially, the internal loop FOPD controller is designed for the open loop unstable system. In the $k_d - k_f$ plane, the stability boundary locus is obtained using characteristic polynomial of the internal loop closed loop. Next, the in-center coordinate points of the convex stability region are computed. Afterwards, the desired locus of FOPI controller is obtained by embedding PD controller parameters into the transfer function. Then, the outer loop ferment point of convex stability region is obtained which are the FOPI controller parameters. The method proposed needs only a simple geometric calculation so that the FOPI-FOPD controller parameters are obtained in the stable region to ensure the closed-loop stability. The parameters can be obtained by computing the triangle points such as vertex V and two corner points C1 and C2. The convex stability region of the PD controller can be described as a triangle by these points. According to the coordinates of the above points, the in-center of the PD

controller can be calculated. The basics concepts are further extended to fractional order design.

B. FOPI-FOPD BASED MODIFICATION OF PRIMARY LOOP

The disturbance and the secondary loop output affect the primary process where the unstable primary process can be stabilized using the PD controller of the modified structure. The reference inputs to the primary (Gc1) and secondary controller Gc2 are r1 and r2.

In the Fig (2), the inner loop is modified with FO-IMC controller for disturbance rejection whereas, the FOPI-FOPD controller designed in the primary loop is used for stabilizing the system so that the desired performances can be obtained [53]. The primary loop FOPI-FOPD controller is designed using Fractional order calculus like the secondary FO-IMC controller calculations.

The secondary loop of the cascade design is used for disturbance rejection of both the stable and unstable process. The action of the secondary loop is much faster than the primary loop so that the disturbance rejections of the process can be performed effectively. It helps to eliminate or reduce the steady-state disturbances of the primary loop.

In equation (15), the process model is designed. The perfect primary process model can be taken from (15) and is given in Eq (19),

$$G_p(s) = \frac{k_p e^{-\theta_p s}}{(\tau_{s1} s - 1)(\tau_p s^{1+\gamma} + 1)} \tag{19}$$

where, $\theta_p = (\theta_s + \theta_{p1})$ and $\tau_c = \tau_p$. Further re-written the eq (19) by assuming the $\tau_2 = -\tau_p$, $\tau_{s1} = \tau_1$ and $k_p = -k$ and obtain the following equations Eq (20)- Eq (21) as,(kp is not changed?)

$$G_p(s) = \frac{k_p e^{-\theta_p s}}{(\tau_1 s - 1)(\tau_2 s^{1+\gamma} - 1)} \tag{20}$$

$$G_p(s) = \frac{k_p(1 - zs) e^{-\theta_p s}}{(\tau_1 s - 1)(\tau_2 s^{1+\gamma} - 1)} \tag{21}$$

The general structure of the primary process and the primary controller is given as,

$$G_p(s) = \frac{N(s)e^{-\tau s}}{D(s)} \tag{22}$$

$$C_{p1}(s) = K_p + \frac{K_i}{s^\alpha} = \frac{K_p s^\alpha + k_i}{s^\alpha} \tag{23}$$

$$C_{p2}(s) = K_f + K_d s^\beta = \frac{(k_f + 100k_d) s^\beta + 100k_f}{s^\beta + 100} \tag{24}$$

where α and β are the fractional order of the integral and derivative parts respectively. k_f, k_p are the proportional gain for the PD and PI controller respectively, and the derivative and integral gains are k_d and k_i. The fractional calculation is to tune the FOPI-FOPD controller of the primary controller, which ensures the stability of the system. The proper selection brings the closed-loop cascade system to be stable.

For the model calculation let us consider Eq (25) and Eq (26),

$$C_{p1}(s) = \frac{N_1(s)}{D_1(s)} \tag{25}$$

$$C_{p2}(s) = \frac{N_2(s)}{D_2(s)} \tag{26}$$

The internal feedback loop characteristic equation can be further written as Eq (27),

$$\nabla_2(s) = D(s) D_2(s) + N(s)N_2(s)e^{-\tau s} \tag{27}$$

Based on the convex stability region method the inner loop controller design is stabilized by substituting $s = j\omega$ and it becomes as,

$$\nabla_2(j\omega) = D(j\omega) D_2(j\omega) + N(j\omega) N_2(j\omega)$$
$$* (\cos(\tau\omega) - j\sin(\tau\omega)) \tag{28}$$

where, $e^{-\tau j\omega} = (\cos(\tau\omega) - j\sin(\tau\omega))$. Finally splitting the Eq (28) into the real and imaginary part and equate to 0 then we can obtain the unknown parameters of k_f and k_d.

$$\nabla_2 = Re_2 + Im_2 = 0 \tag{29}$$

The Re_2, Im_2 are the real and Imaginary part of the decomposed PD controller Eq (29) which is a function of the unknown parameters k_f and k_d and frequency variable. The stability region can be found by plotting the values of k_d and k_f in the $k_f - k_d$ region, which is the convex stability region by the corner and cusp points of the k_d and k_f values.

Step 1: Calculate control parameters of k_d and k_f by obtaining the centroid of convex stability of $k_f - k_d$ region for PD controller parameters.

$$K^C{}_d = \frac{\sum_{i=1}^{n} K_{di}^{cu} + \sum_{i=1}^{m} K_{di}^{cp}}{n + m} \tag{30}$$

where, $K^C{}_d$, K_{di}^{cu}, K_{di}^{cp} are the derivative controller parameter of PD controller, cusp points and corner points of the coordinates in $k_f - k_d$ plane respectively.

$$K^C{}_f = \frac{\sum_{i=1}^{n} K_{fi}^{cu} + \sum_{i=1}^{m} K_{fi}^{cp}}{n + m} \tag{31}$$

where, $K^C{}_f$, K_{fi}^{cu}, K_{fi}^{cp} are the derivative controller parameter of PD controller, cusp points and corner points of the coordinates in $k_f - k_d$ plane respectively. The k_d and k_f control parameters are considered to minimize the inner loop combination of $G_p(s)$ and $C_{p2}(s)$ as Eq (32), and the final form of the reduced model is as,

$$G(s) = \frac{N(s)}{D(s)} = \frac{G_p(s)}{1 + C_{p2}(s) G_p(s)} \tag{32}$$

Step 2: Now again do the same procedure for PI controller where the centroid of convex stability of $k_p - k_i$ the region is obtained to calculate the controller parameters of k_p and k_i for the PI controller. For obtaining it, substitute $s = j\omega$ in Eq (33) and obtain the characteristics equation by equating the denominator of the model to 0.

$$\nabla_1(s) = D(s) D_1(s) + N(s)N_1(s)e^{-\tau s} \tag{33}$$

After substituting $s = j\omega$ and obtaining the characteristics equation, the decomposed model with the real and imaginary parts separated is given as,

$$\nabla_1 = Re_1 + Im_1 = 0 \qquad (34)$$

Re_1, Im_1 are the real and Imaginary part of the decomposed PI controller in Eq (34) which is a function of the unknown parameters k_p, k_i and frequency variable. The stability region can be found by plotting the values of k_i and k_p in the $k_i - k_p$ region which is the convex stability region by corner and cusp points of the k_p and k_i values.

Step 3: By using the Eq (30) and Eq (31), the centroid can be found for the PI controller and the stability region can be obtained by plotting the $k_i - k_p$ region. Eq (35) and Eq (36) are obtained using the controller parameters $K^C{}_p$ and $K^C{}_i$ with the cusp and corner points of r and s as,

$$K^C{}_p = \frac{\sum_{i=1}^r K_{pi}^{cu} + \sum_{i=1}^s K_{pi}^{cp}}{n + m} \qquad (35)$$

and

$$K^C{}_i = \frac{\sum_{i=1}^r K_{fi}^{cu} + \sum_{i=1}^s K_{fi}^{cp}}{n + m} \qquad (36)$$

C. GUIDELINES FOR SELECTING CLOSED-LOOP TIME CONSTANT

The closed-loop time constant α plays a vital role in setpoint tracking and load disturbance rejection performance. Smaller values of α yields better servo and regulatory performance, but degraded robust stability. On the other hand, increasing α improves system robustness at the cost of closed-loop performance. Hence, the choice of time constants is a trade-off between performance and robustness. As discussed in section-3, using the model reduction techniques, the higher-order transfer functions can be approximated as $P_t(s) = (K_t e^{-\theta_t s})/(1 + \tau_t s)$. Eventually, the PI-PD control structure shown in Figure 2 reduces to a unity feedback structure with a PI controller in series with a FOPTD transfer function, as shown in Figure 3.
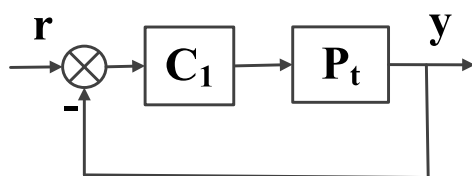

FIGURE 3. The reduced form of FOPI-FOPD control structure.

The loop transfer function of the system shown in Figure 3 is,

$$L(s) = C_1(s) P_t(s) \qquad (37)$$

Substituting C_1 and P_t in Eq (37) which gives Eq (38) as,

$$L(s) = K_c \left[1 + \frac{1}{T_i s} \right] \frac{K_t}{(1 + \tau_t s)} e^{-\theta_t s} \qquad (38)$$

The maximum sensitivity of the system can be obtained from Eq (39) is given by

$$M_S = \left\| \frac{1}{1 + C_1(s) P_t(s)} \right\|_\infty \qquad (39)$$

To study the variation in the maximum sensitivity (M_S) concerning process dynamics and α, an FOPTD process model with transfer function $G_p(s) = (K_t e^{-\theta_t s})/(1 + \tau_t s)$ is considered. Assuming $K_t = \tau_t = 1$, the time delay $'\theta_t'$ is varied and the corresponding M_S values can be obtained. An analytical expression relating α and M_S is obtained using a curve fitting toolbox of MATLAB as given in Eq (40),

$$\alpha = \theta_t \left(\frac{M_s - C}{A} \right)^{\frac{1}{B}}$$
$$0.01 \le \left(\frac{\theta_t}{\tau_t} \right) \le 8 \qquad (40)$$

The plant model P_m that is used for obtaining the controller settings is only an approximation of the actual plant dynamics P. Hence, it is necessary to assume the time constant α such that the closed-loop system is robust to uncertainties in estimated process dynamics. The condition in Eq (41) is used for closed-loop robust stability given in [16]:

$$\|l_m(s) T_d(s)\| < 1 \quad \forall \omega \in (-\infty, \infty) \qquad (41)$$

where, T_d is the closed-loop complementary sensitivity function and l_m is the process multiplicative uncertainty which is given by

$$l_m(s) = \left| \frac{P(s) - P_m(s)}{P_m(s)} \right| \qquad (42)$$

If uncertainties exist in process gain, time delay and time constant of the primary process model Eq (42), α should be selected such that the following condition in Eq (43) is satisfied:

$$\|T_d\|_\infty < \left| \frac{[(\tau - \Delta\tau) s + 1]}{(\tau s + 1)\left(1 + \frac{\Delta K}{K}\right) e^{-\Delta\theta s} - ((\tau - \Delta\tau) s + 1)} \right|,$$
$$\forall \omega > 0 \quad (43)$$

where ΔK, $\Delta\theta$, and $\Delta\tau$ represent uncertainties in gain, time delay, and time constant of the primary process model. In the following chapter, different applications with an unstable system are considered for simulative performances to examine the proposed design.

V. SIMULATION RESULTS

To examine the proposed design, three examples are considered where the primary process is unstable with time delay. The designed techniques in this research are considered to obtain the benefit of the design in closed-loop performances. Integral Absolute error (IAE) and Integral Squared Error (ISE) are the performance indices considered for comparing the proposed deign with the existing methods. The smoothness of the control signal is evaluated by finding the total variation of the manipulated variable.

TABLE 1. Performance analysis for Example 1.

	Nominal model			Perturbed model		
	Proposed	Method 1	Method 2	Proposed	Method 1	Method 2
IAE	12.41	13.08	15.32	16.25	16.96	20.10
TV	21.48	34.26	23.56	24.65	42.58	28.92

The steps are,

- The transfer function for the primary and secondary process is considered as given in Eq.14 and Eq.16.
- Design the FO-IMC based secondary controller using Eq.18
- Design the pre-filter for overshoot minimization according to Eq.10 by selecting τ_c
- Design the FOPI-FOPD based primary controller using feedback controller characteristic equation Eq.27 and Eq.28 and obtain the overall model of the primary loop according to Eq.38
- Check the closed-loop stability of the system using Eq.41 by satisfying the condition Eq. 43 and evaluate the closed loop performances.

The above steps are applied to the following examples and the closed loop performances are compared using simulation.

Example 1: The unstable time delay cascade process studied in [8,9,14,20] is considered here where the unstable primary process model and stable secondary process model are given by Eq (44) and Eq (45),

$$G_{p1}(s) = \frac{e^{-0.339s}}{5s - 1} \tag{44}$$

$$G_{p2}(s) = \frac{e^{-0.6s}}{2.07s + 1} \tag{45}$$

In this article, the perfect comparison is considered using the methods discussed by Kaya [10] and Tan *et al.* [12]. For a fair and perfect comparison, the method proposed in this article is a simple cascade control scheme with the PI-PD designed outer loop and the IMC structure of an inner loop. The primary control loop is designed using fractional order calculation and the methods considered for the comparison also have modified cascaded loop with two or more additional controllers with the modified Smith predictor. The inner loop controller is designed by considering the $\lambda = 0.5$, $\gamma = 0.2$, $a = 1$, and $\theta_{m2} = 0.3$ then the secondary IMC controller is obtained from the eq (10). With this IMC controller, the primary loop can be designed by using eq (20). The maximum sensitivities of the inner and outer loops are assumed as 2 and 1.6 respectively (The sensitivity M_s and α are obtained by curve fitting toolbox using MATLAB and n this article it is recommended). The chosen fractional order parameters $\alpha = \beta = 0.2$ (As suggested in [27] the values are taken), for the PI-PD primary controller is further used to obtain the PD

and PI centroid controller parameters. The parameters of the centroid PD controller and PI controller are obtained as per the steps 1,2 and 3 of the parameter calculation. Accordingly, the proposed methods yield the parameters are $K_f = 4.312$, $K_d = 3.124$, $K_p = 2.1525$, $K_i = 3.478$.

The methods taken for comparison have different tuning parameters for each controller. Unit step change disturbance is given to the proposed design and [3], [5]. In [3], the secondary controller is obtained as $G_{c2}(s) = \frac{(2.07s+1)}{(0.3s+1)}$, and further, the values are considered for the tuning is, $K_c = 0.478$. $\tau_i = 0.99$, $\tau_d = 0.213$, $\gamma = 6.821$, $\beta = 0.567$ to design the primary controller with the designed filter for the setpoint is $F = \frac{1}{(6.8s+1)}$. In the other example, [5] is considered and the secondary controller is designed by considering the parameters as $K_c = 9.16$, $\tau_i = 2.9$, $\tau_d = 4.46$, $\beta = 0.234$ and for the disturbance rejection case, $K_c = 4.86$, $\tau_i = 0.85$, $\tau_d = 2.479$, $\gamma = 0.467$, $\beta = 0.02$ with the setpoint filter of $F = \frac{1}{(5.74s+1)}$. The above methods with the mentioned parameters are used for the analysis of the performance of the controller design methods. The effective comparison, setpoint changes are given as disturbance during 350s. The observations are made continuously as shown in Fig. (4) and Fig (5). The detailed observations on the response plot are expressed, the better performances of the design proposed over the other methods which are considered. The figures show that the proposed method gives better performance). The robustness of the design is further analyzed with the existence of +/−20% perturbation in the secondary loop gain and time delay, and are observed in Fig (6) and Fig (7). The performance indices, IAE and TV are calculated for the nominal and perturbed models and are given in Table 1. The observations also listed in table where the quantitative comparison is tabulated in terms of Integral Absolute error (IAE) and Total Variation (TV). The comparative closed-loop evaluation concerning Eq (46)-Eq (47) records in table.1

$$IAE = \int_0^\infty e(t)dt \tag{46}$$

$$TV = \sum_{n=0}^N |u_{n+1} - u_n| \tag{47}$$

Example 2: In this example, the work in [7], an isothermal continuous stirred tank reactor, is considered in Eq (48)-(49) where the primary process is unstable, and the secondary process is stable.

$$G_{p1}(s) = \frac{3.433e^{-20s}}{103.1s - 1} \tag{48}$$

$$G_{p2}(s) = \frac{e^{-0.5s}}{3s + 1} \tag{49}$$

The inner loop controller is designed by considering the $\lambda = 0.5$, $\gamma = 0.2$, $a = 1$, then the secondary IMC controller is obtained from the eq (10). For this unstable primary process, the centroid of the convex region is calculated by using the procedure and the obtained parameters for PD region is $K_f = 4.312$, $K_d = 3.124$ by considering the fractional parameters $\alpha = \beta = 0.2$. using the centroid PD parameters into the
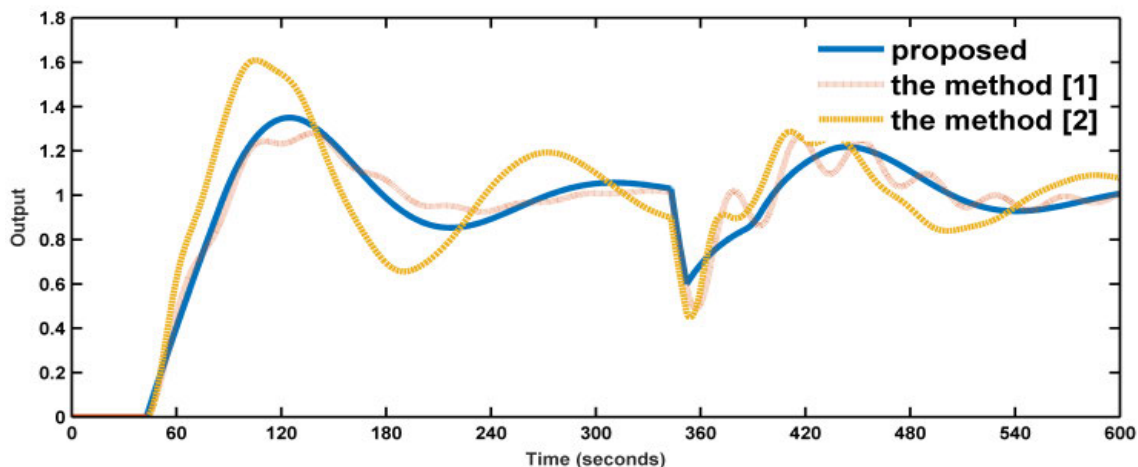
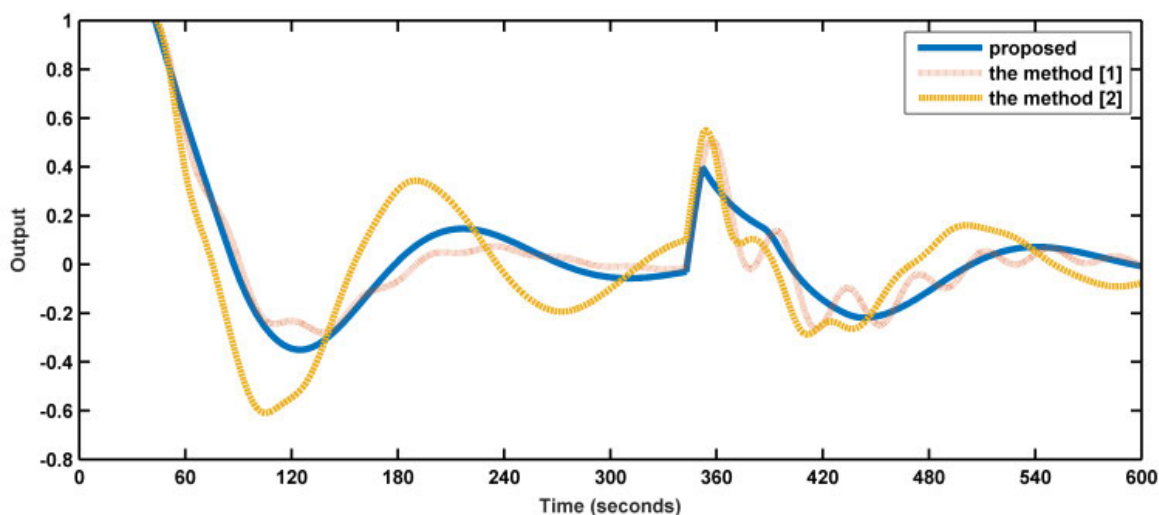**FIGURE 4. Closed-loop nominal performances for Example. 1.**

FIGURE 5. Controller performances (nominal) for Example.1.

inner loop of the system from y1 to r1 which is reduced into to single transfer function model. Reduced transfer function further used to find the stability region of the K_p-K_i plane to find the PI parameters for the outer loop. Using the steps for finding the stability region PI controller parameters, we can obtain the controller parameters $K_p = 4.312$, $K_i = 3.124$. Thus, the obtained controller parameters of the PI-PD primary controller with the inner loop IMC parameters, the performance of the design is analyzed and compared. For the comparison, [6] and [7] are considered. Reference [6] yields the controller parameter $K_c = 4.86$, $\tau_i = 0.85$, $\tau_d = 2.479$, $\gamma = 0.467$, $\beta = 0.02$ with the setpoint filter of $F = \frac{1}{(5.74s+1)}$. A step magnitude 5 at t = 150 is considered and for the robustness of the design, +/− 20% uncertainty is considered in GC1 and 10% in time delay of primary and secondary process. The detailed observations on the response plot are expressed, the better performances of the design

proposed over the other methods which are considered. The improvements in the proposed design 9.2% and 15.35% are observed at the nominal condition over the other methods such as method 1 and method 2. The responses observed for the comparison is shown in Fig (8)-Fig (11) for both nominal and perturbed systems. The comparative closed-loop evaluation is recorded in table.2.Furthermore, regulatory response of the proposed design performance criterion is comparable with that of [7] as seen in table.2.Although, it is observed from Fig. 8 that the tuning strategies reported in [7] yields oscillatory responses if there is perturbation in the process parameters. One-point worth mentioning is that the tuning strategies reported in [7] fails to give robust closed-loop responses.

Example 3: In this example, the study has been considered in [8] is taken for the comparison where the primary process model is unstable and secondary is a stable model is
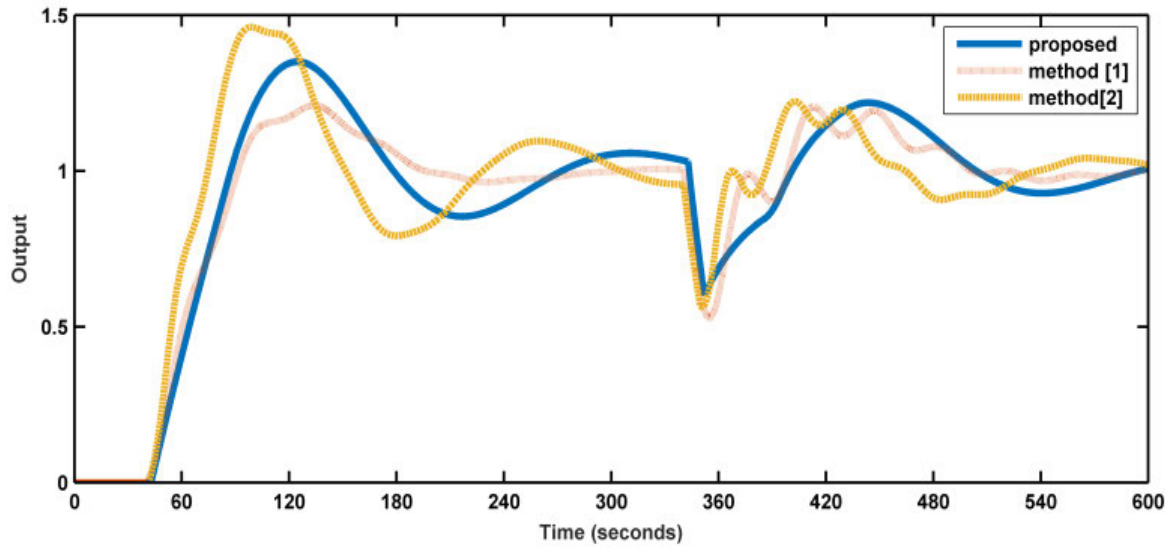
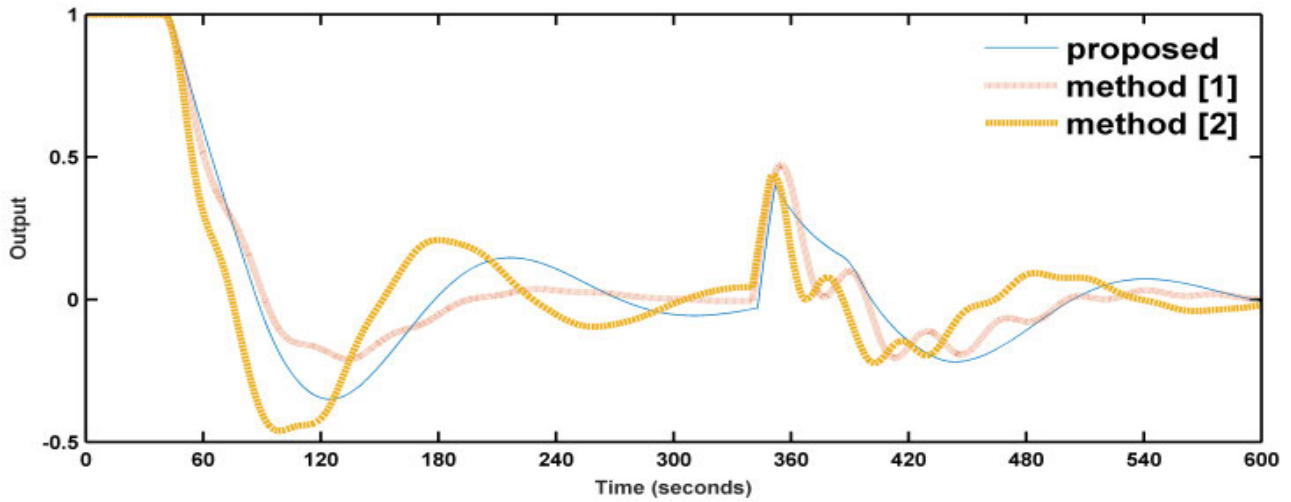**FIGURE 6.** Closed-loop (perturbed) performances for Example.1.

FIGURE 7. Controller performances (perturbed) for Example.1.

TABLE 2. Performance analysis for Example 2.

	Nominal model			Perturbed model		
	Proposed	Method 1	Method 2	Proposed	Method 1	Method 2
IAE	60.85	88.21	61.02	31.35	42.06	34.68
TV	0.327	0.291	0.399	0.275	0.596	0.511

TABLE 3. Performance analysis for Example 3.

	Nominal model			Perturbed model		
	Proposed	Method 1	Method 2	Proposed	Method 1	Method 2
IAE	14.42	23.28	32.12	21.51	26.36	30.14
TV	9.35	11.21	9.59	15.24	16.32	29.65

considered as,

$$G_{p1}(s) = \frac{e^{-3s}}{10s - 1} \qquad (50)$$

$$G_{p2}(s) = \frac{2e^{-2s}}{s + 1} \qquad (51)$$

The proposed method has the controller parameter for the process model (50) and (51). The chosen is $\lambda = 0.5$, $\gamma = 0.2$, $a = 1$ and $\theta_{m2} = 0.3$.

After the internal IMC controller design, the primary controller is designed with the selected fractional order parameters $\alpha = \beta = 0.2$. The centroid convex regions of PD are obtained from the PD stability region and further reduced the complete model into a single transfer function model to obtain the PI stability region. After the reduction, the obtained parameters are further used for the effective cascaded controller design for the primary unstable process. The obtained
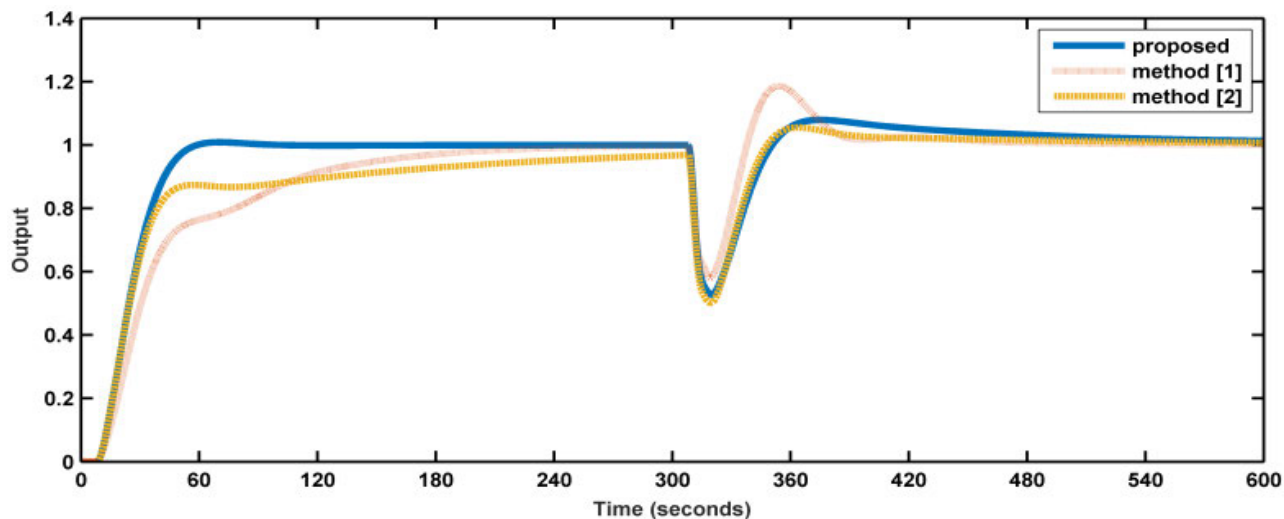
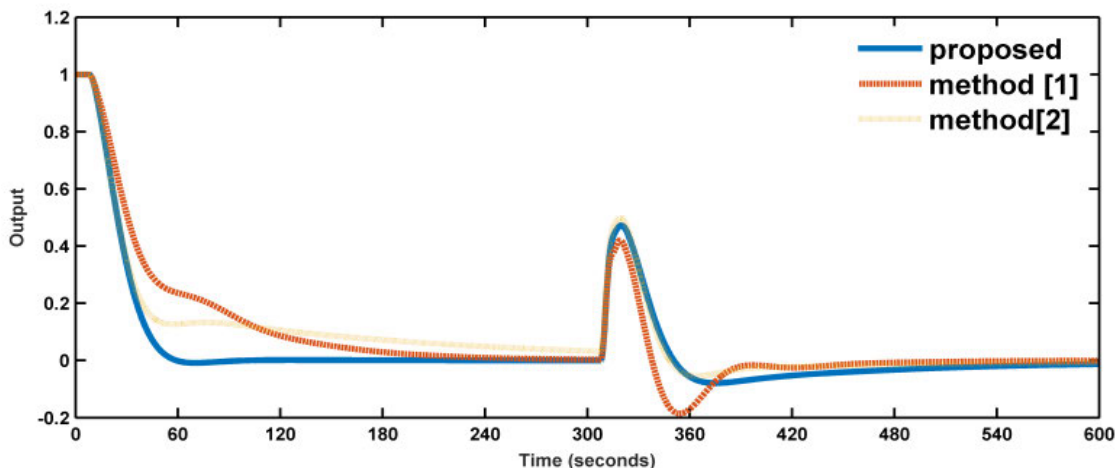**FIGURE 8.** Closed-loop nominal performances for Example.2.

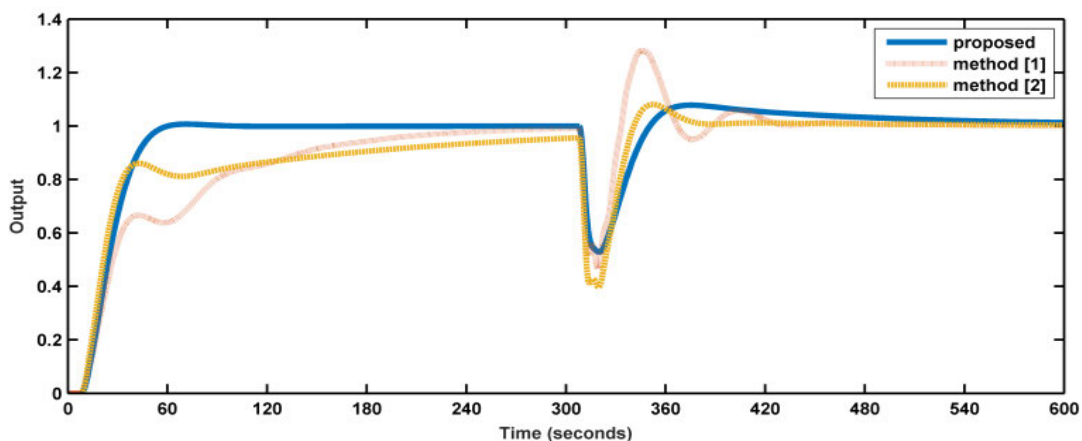**FIGURE 9.** Controller (nominal) output for Example.2.

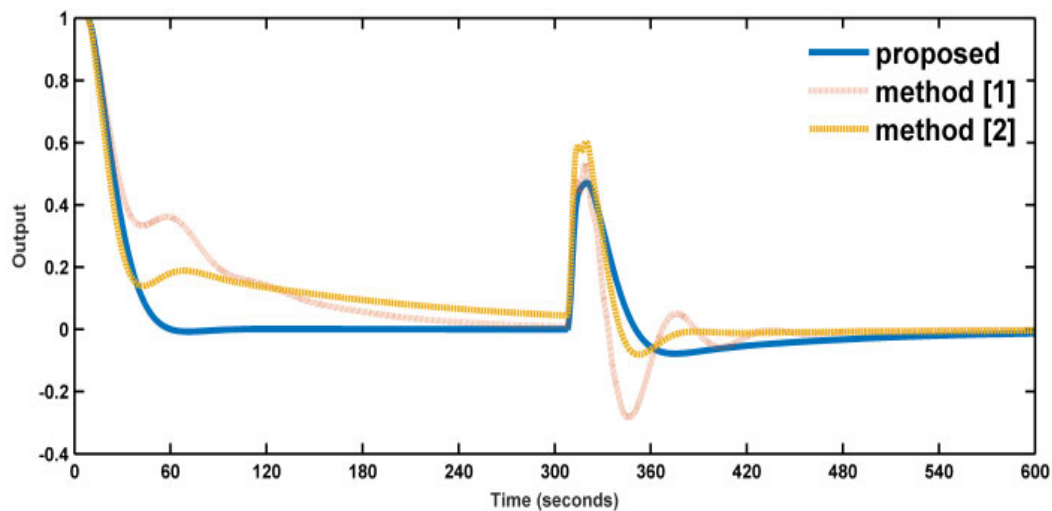**FIGURE 10.** Closed-loop (perturbed) performances for Example.2.
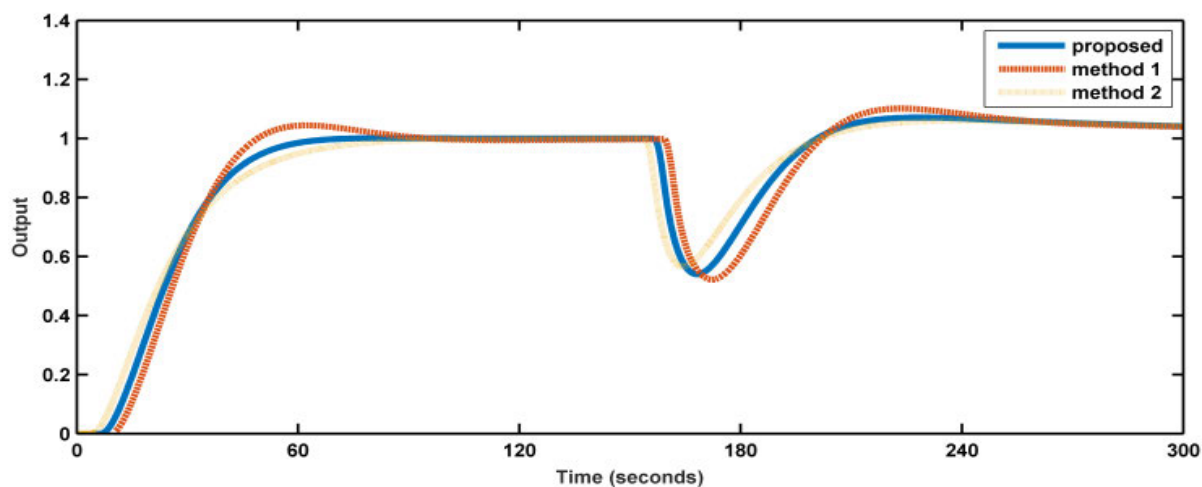
FIGURE 11. Controller (perturbed) output for Example.2.

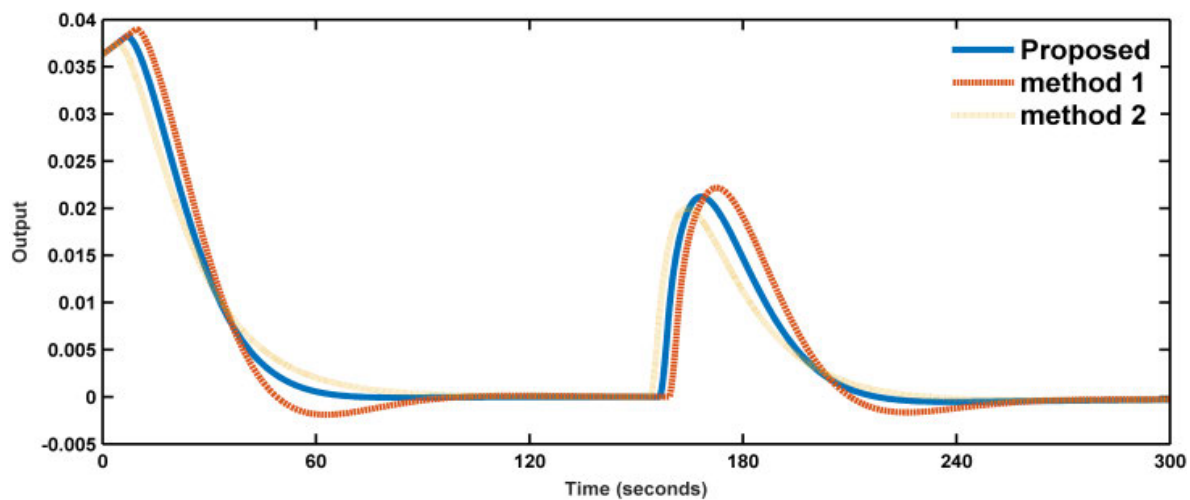**FIGURE 12.** Closed loop (nominal) performances for Example.3.

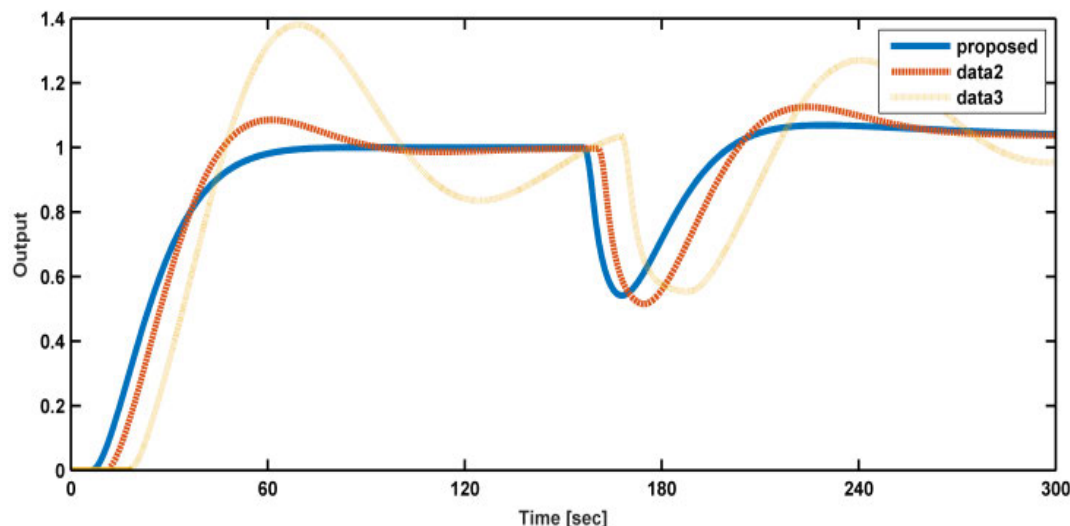**FIGURE 13.** Controller (nominal) output for Example.3.

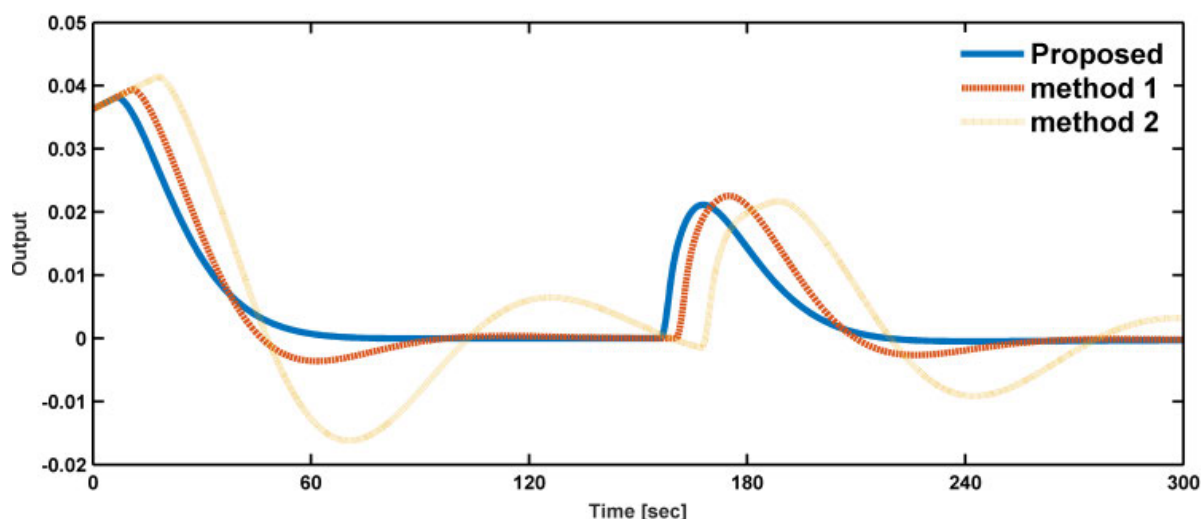**FIGURE 14.** Closed-loop (perturbed) performances for Example.3.

FIGURE 15. Controller (perturbed) output for Example.

parameters are $K_f = 4.312$, $K_d = 3.124$, $K_p = 4.312$ and $K_i = 3.124$. For Rao et al predictive method, tuning parameters are $K_{cs} = 2.79$, $K_{ds} = 8.59$, $K_{is} = 0.09$, $\beta_s = 1.65$ and $\lambda_s = 5$. For [22], tuning parameters $K_{cs} = 0.12$, $\tau_{is} = 5.5$, $\tau_{ds} = 1.728$, $\beta = 0.88$ and $\alpha = 72.25$ are considered with the setpoint filter of 72.25. With all the methods and proposed methods are simulated for the performance comparative analysis. The setpoint step change is given at $t = 1s$ and the disturbance at $t = 350s$ is given and the resulting response is plotted in Fig (12) and Fig (13) for the nominal model and Fig (14) and Fig (15) for the perturbed model. The plotted response is exploiting the performances of all three methods and the observation is highlighted that the proposed design has an improved response over the other in terms of quick disturbance rejection and fast response. The comparative closed-loop evaluation is recorded in table 3 and it shows the improvements of the proposed design at nominal

condition about 26.2% and 38.4% are observed over the other examples.

Nowadays, disturbance rejection analysis is a more essential part to deal with than the tracking performances analysis. Hence, the design proposed in this study is apt for engineering applications due to its better regulatory performance. However, in practical scenarios, noise may exist in the sections of final control element, the process or from measuring instruments, and this makes the proposed design struggle to provide robust performances. The detailed analysis reported that the proposed design methods for the unstable primary process with dead time effectively control and stabilize. In the disturbance rejection case, the proposed design effectively reacts to reject the disturbance quicker than the other methods. The proposed design Once again shows that the fractional-order controllers often enhance the speedy response to the stabilized control system, as highlighted in the literature study.

The proposed control method will be useful for the stabilization, disturbance rejection, and delay compensation of unstable systems with long dead time.

VI. CONCLUSION

The simple series cascaded controller for unstable process with the dead-time is designed with fractional-order controllers. The simple design includes the inner loop fractional-order IMC controller and the primary FOPI-FOPD controllers for the outer loop. The essential advantage of FO helps to recover the response when the disturbance occurs. Due to the advantages of fractional order controllers, fractional-order internal model controllers and FOPI-FOPD controllers are designed for disturbance rejection and setpoint tracking performances. The proposed design is simple and more suitable for any cascade unstable system possessing time delay. The proposed controllers yield small values of integral absolute error, integral squared error, and settling time compared with the other researcher's works. Another advantage of the proposed method is that it is robust to parameter variations and the proposed predictive control scheme provides good performance under system uncertainties compared with literature methods. The superiority of the proposed controllers is illustrated by controlling simple and uncertain processes. Simulation results demonstrate robust stabilization, better (tracking) control performance, and disturbance rejection of the closed-loop systems via the proposed controllers. The proposed control method will be useful for the stabilization, disturbance rejection, and delay compensation of unstable systems with long dead time.

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