AN IMPROVED PERFORMANCE FRACTIONAL ORDER CONTROLLER FOR CASCADE CONTROL SYSTEM DESIGN

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Abstract- When the manipulated and disturbance variables affect the primary and secondary output simultaneously; the parallel cascade control is suggested. This paper proposes control tuning rules for parallel cascade controller systems using fractional-order proportional-integral (FOPI) based on fractional calculus. For stable, unstable, and integrating process models with time, the modified parallel cascade control structure Smith Predictor (SP) is addressed. Based on the Smith predictor, an enhanced cascade control scheme is implemented to regulate a class of time-delayed unstable processes. There are three controllers in the PCCS control structure: two for the primary loop and one for the secondary loop. Fractional Order Internal Model Control (FO-IMC) principles are used in the design of the secondary loop controller. Based on a modified Smith predictor control structure, the same process is used to design the primary loop set point tracking controller and disturbance rejection controller. The frequency domain technique will be used in the proposed controller to tune both the primary and secondary controllers, improving the performance of the servo mechanism and the regulatory mechanism for step input changes in set point and disturbance, respectively. To verify the effectiveness of the suggested strategy, this approach will be used to integrate unstable processes.

Key words – *Fractional calculus, Fractional order PI controller, parallel cascade, smith predictor, FO-IMC, frequency domain tuning.*

I. INTRODUCTION

Industrial processes frequently employ cascade control. This is implemented in order to lessen disruption and enhance the closed-loop system's servo response. Both manipulated and disturbance variables influence the primary output through the secondary output in the traditional cascade control structure, which is essentially composed of the primary (outer) and secondary (inner) loops. The manipulation and disturbance variables (d and u_2) simultaneously affect the primary and secondary output (y_1 and y_2). These real-world application scenarios served as the basis for the proposal of the parallel cascade control. In order to address the reflux flow rate (manipulated variable) and feed flow or composition (disturbance) affecting the purity of the overhead product (primary output) and the tray temperature (secondary output), Luyben first introduced parallel cascade control structure (PCCS) [1].

In controller designs for the inner and outer loops of the cascade control, PI/PID controllers are still frequently utilized, despite the development of numerous sophisticated control techniques. Nonetheless, the intricacy of the control structure and the tuning process continue to restrict the amount of works pertaining to parallel cascade control. A straightforward approach was presented in Ref. [2] for unstable processes, wherein the secondary and primary loops were treated as proportional-integral (PI) and proportional-controller (P), respectively.

In Ref. [3], a modified PCCS was proposed to handle integrating, unstable, and stable processes. In order to stabilize the unstable/integrating processes, the authors used a proportional derivative (PD) controller. For the secondary loop, they designed the controller using the internal model control (IMC) approach. The literature's available tuning rules might not provide a good servo performance if the primary process has a significant time delay, which is a drawback of the cascade control scheme. For the outer loop, many researchers suggested using a time-delay compensator, or Smith predictor [4].

Initially, for stable processes with a large time delay, Rao et al. [5] combined PCCS and the Smith predictor and achieved satisfactory closed-loop performances. The authors also included a set point filter for the secondary loop, and the authors continued to use the IMC approach for the inner loop and direct synthesis for the outer loop. The PCCS for a class of time-delayed, stable, and integrating processes was enhanced by several authors. The integral squared error (ISE) index was also used to incorporate the set-point filter into the PID controllers, which were designed using a loop shaping technique. A modified Smith predictor was also implemented in the primary loop to improve the servo performance.

A unified method for fine-tuning a cascade scheme's controllers for unstable, integrating, and stable processes was put forth by the authors. In order to support the controlled systems' robustness, the Kharitonov theorem was used. Fractional-order calculus has received more attention lately from control engineers as well as academics for modelling and control problems since it offers greater flexibility and computational power advancement.

Bode made an early mention of using a fractional structure in a feedback loop, which is expanded upon. But for decades, this concept remained a straightforward idea without any real substance. A standard PID controller was considered to be generalized when proposed the fractional-order PID controller (FOPID), also known as $PI^{\lambda}D^{\mu}$, which involves a fractional-order differentiator (μ) and integrator (λ). The two additional parameters (λ and μ) of this kind of controller allow it to perform better than traditional PID controllers for both integer- and fractional-order processes. Additionally, fractional-order controllers have been shown to offer increased robustness and to be a novel approach to resolving a variety of industrial control issues in other works.

The tuning rules of the FOPID controller have been the subject of extensive research, primarily in single-input single-output (SISO) systems, as reported in a variety of literature types. Very few studies use fractional-order controllers for other complex control systems, like cascade structures; for example, in and, but the authors are only interested in the parallel cascade systems. Furthermore, some of the literature that was available was unable to solve the servomechanism problem for the primary loop with a large time delay. To increase the system's performance, this work proposes tuning guidelines for a cascade control scheme that uses a fractional-order PI controller.

For this type of system, most classical PID controllers must choose between servomechanism and regulator issues, as was indicated in the introduction section. As a result, the purpose of this paper is to suggest an analytical method of fractional-order PI controller tuning for enhancing a cascade scheme with stable processes plus time delays in terms of both disturbance rejection and set-point tracking. Both the fractional-order controller's robustness and the tuning rules' flexibility make it reasonable.

Included in the control structure will be the Smith predictor, which removes a delay term from a closed-loop system's characteristic equation. Although they only took into account the integer-order PID controller, other authors also used this compensator to address time delays in parallel cascade control structures. Our inner loop design strategy is primarily grounded in the ideas of the direct synthesis method. The proposed fractional-order PI tuning rules for the outer loop can be directly derived by combining the frequency domain with the direct synthesis method.

The proposal's structure is set up as follows: The example of an IMC-based centralized control system is covered in Section II. The frequency response approach centralized control arrangement design is shown in Section III. Case study simulation and projected algorithm justification are shown in Section IV. A summary is shown in Section V.

II. BASICS OF FRACTIONAL ORDER CALCULUS

The FOC dates back to the beginning of time, but up until recently; it was only used in mathematics. With its large "memory" and noisy behaviour, FOC differential conditions are a suitable apparatus to divide problems of fractal aspect, and many real frameworks are better modelled with them.

The natural concept of FOC is as old as IOC, and Leibniz's letter to L'Hopital provides a detailed description of it. Analytically, the FOC generalization is expressed as follows:

$$D^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_a^t (d\tau)^{-\alpha} & \alpha < 0 \end{cases} \tag{1}$$

With $\alpha \in R$

The account of FOC as per the Riemann-Liouville is expressed as:

$$ {}_aD_c^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d}{dt^n} \int_c^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau, \qquad n-1 < \alpha < n \tag{2}$$

Where, the fractional operator denotes the derivative of the fractional, '-' stands for the integral of the fractional, and $\Gamma(.)$ corresponds to the Euler's gamma function through a positive α.

In S-(frequency) domain it is expressed as given in Eqn. (3):

$$L\left\{ {}_aD_c^{\alpha} f(t) \right\} = s^{\alpha} F(s) \tag{3}$$

For an LTI system, it can be written as:

$$\sum_{i=0}^{n} D_0^{\alpha_i} y(t) = \sum_{i=0}^{m} b_i D_0^{\lambda_i} u(t) \tag{4}$$

Where, the information and result are denoted by u(t) and y(t), respectively: The fractional operators are represented by αi and λ_i, while the steady coefficients of the framework are a_i and b_i.

As a result, the SISO framework appears as follows in the S-domain:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{b_m s^{\lambda_m} + b_{m-1} s^{\lambda_{m-1}} + b_{m-2} s^{\lambda_{m-2}} + L + b_0 s^{\lambda_0}}{a_n s^{\alpha_n} + a_{n-1} s^{\alpha_{n-1}} + a_{n-2} s^{\alpha_{n-2}} + L + a_0 s^{\alpha}} \tag{5}$$

It is evident that simulating a fractional order framework is difficult due to the order of s in Equation (4). Most general applications make use of the Oustaloup frequency calculation with constrained numbers of poles and zeros. $s\alpha$, the FO operator, was estimated within the frequency range [ωb, ωh].

$$s^{\alpha} \cong s^{\alpha}_{[\omega_b, \omega_h]} \approx K \sum_{k=-N}^{N} \frac{s + \omega_k'}{s + \omega_k} \tag{6}$$

Pole, zero, and the gain in Eqn. (6) can be found as follows:

$$K = \omega_h^{\alpha}$$

$$\omega'_k = \omega_b \left(\frac{\omega_h}{\omega_b}\right)^{(k+N+0.5-0.5\alpha)/(2N+1)}$$

,

$$\omega_k = \omega_b \left(\frac{\omega_h}{\omega_b}\right)^{(k+N+0.5+0.5\alpha)/(2N+1)}$$

III. REPRESENTATION OF IMC BASED CENTRALIZED CONTROL SYSTEM

A structure similar to the one in Fig. 1 is used to control cascade processes. G_{p1} and G_{p2} are the names of the two processes in the block diagram. Figure also displays the inner and outer loop controller blocks. For each of the two loops, the disturbances are represented by the numbers d_1 and d_2. The overall output of the control loop is y_1, and the control structure input, or set point, is r_1.

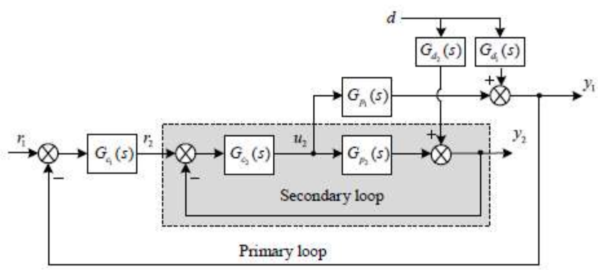

Fig.1. Cascade control of two different processes G_{p1} and G_{p2}

From the Fig.1 the transfer function of process can be expressed as:

$$G_p(s) = \frac{G_{p1}(s)}{1+G_{c2}(s)\left(G_{p2}(s)-\tilde{G}_{p2}(s)\right)+G_d G_{p1}(s)} \tag{7}$$

Let us assume that $G_{p2}(s) = \tilde{G}_{p2}(s)$ is perfect model,

Therefore, the process model will be reduced using block diagram approach as,

$$G_p(s) = \frac{G_{p1}(s)}{1+G_d G_{p1}(s)} = G_{pm}(s)e^{-\theta_p s} \tag{8}$$

In the above structure the G_{p1} process is considered in the different forms as first order stable/unstable and second order stable.

$$G_{p1}(s) = \frac{K_1}{\tau_1 s+1} e^{-\theta_1 s} \tag{9}$$

$$G_{p1}(s) = \frac{K_1}{\tau_1 s-1} e^{-\theta_1 s} \tag{10}$$

$$G_{p1}(s) = \frac{K_1}{s\left(\tau_1 s+1\right)} e^{-\theta_1 s} \tag{11}$$

And the process G_{p2} is used in the form of

$$G_{p2}(s) = \frac{K_2}{\tau_2 s+1} e^{-\theta_2 s} \tag{12}$$

IV. DESIGN OF CONTROLLER IN FREQUENCY DOMAIN

The general PI controller operation can be analytically expressed as:

$$u(t) = K_C e(t) + K_I D_t^{-\lambda} e(t) \quad \text{for} \quad \lambda > 0 \tag{13}$$

Similarly, the fractional order PI controller is written as follows.

$$G_C(s) = K_C + \frac{K_I}{s^{\lambda}} \tag{14}$$

To convert the FOPI controller to the frequency domain, simply replace s = jω in equation (14):

$$G_C(j\omega) = K_C + \frac{K_I}{(j\omega)^{\lambda}}$$

The term fractional power can be written as follows:

$$(j\omega)^{\lambda} = \omega^{\lambda}\left[e^{j\left[\frac{\pi}{2}+2n\pi\right]}\right]^{\lambda} = \omega^{\lambda}\left[e^{j\left[\frac{\pi}{2}\lambda+2n\lambda\pi\right]}\right]$$

Where, $n = 0, \pm 1/\lambda, \pm 2/\lambda, ... \pm m/\lambda$. Ultimately, the following equation can be used to rewrite it:

$$(j\omega)^{\lambda} = \omega^{\lambda}(\cos\gamma_1 + j\sin\gamma_1), \quad \gamma_1 = \frac{\pi\lambda}{2} \tag{15}$$

Equation (16) is the result of changing (15) into (14) and creating a complex equation to represent the FOPI controller in the frequency domain.

$$G_C(j\omega) = \left(K_C + \frac{K_I \cos\gamma 1}{\omega^{\lambda}}\right) - j\left(\frac{K_I \sin\gamma 1}{\omega^{\lambda}}\right) \tag{16}$$

A) Inner Loop Controller design:

The inner loop controller will be designed using the direct synthesis (DS) method. It is possible to compute the inner loop's closed-loop transfer function (from the input r_2 to the output y_2):

$$\frac{y_2}{r_2} = \frac{G_{c2}(s)G_{p2}(s)}{1+G_{c2}(s)G_{p2}(s)} \tag{17}$$

From the above equation, it is computed as,

$$G_{c2} = \frac{1}{G_{p2}(s)} \frac{y_2/r_2}{1-y_2/r_2} \tag{18}$$

Assuming that the intended closed-loop response π and the process model are known beforehand, Gp_2 In terms of set point changes, $(y_2/r_2)_d$ is regarded as the closed-loop transfer function. As a result, the optimal controller is achieved by rewriting:

$$G_{c2} = \frac{1}{\tilde{G}_{p2}(s)} \frac{(y_2/r_2)_d}{(1-y_2/r_2)_d}$$

In general, the transfer function model is expressed as:

$$\left(\frac{y_2}{r_2}\right)_d = \frac{e^{-\theta_2 s}}{\tau_{c2}+1} \tag{19}$$

In the above equation, it shows the first process with dead time. The time delay, and time constant values may be obtained from the equation. Using Taylor approximation for the delay term, the feedback controller is obtained:

$$G_{c2}(s) = \frac{1}{G_{p2}(s)} \frac{e^{-\theta_2 s}}{(\tau_{c2}+\theta_2)s} \tag{20}$$

Think about the inner process model's FOPDT:

$$\tilde{G}_{p2}(s) = \frac{K_2}{\tau_{c2}+1} e^{-\theta_2 s} \tag{21}$$

Equation (21) can be substituted into equation (20) to obtain the PI controller for the inner loop:

$$G_{c2}(s) = \frac{\tau_2}{K_2(\tau_{c2}+\theta_2)}\left[1+\frac{1}{\tau_2 s}\right] \tag{22}$$

B) Outer loop Controller design:

The following formula is used to determine the primary process model's equivalent transfer function.

$$G_p(s)e^{-\theta_p s} = \left(\frac{y_2}{r_2}\right)_d \tag{23}$$

$$G_{p1}(s) = \frac{e^{-\theta_2 s}}{\tau_{c2}s+1} \frac{K_1 e^{-\theta_1 s}}{\tau_1 s+1}$$

The control loop in question pertains to the fractional-order PI controller. The first order plus delay time system's (FOPDT) relative dead time parameter is used to determine the fractional order λ, as per the guidelines given by,

$$G_p(s) = \frac{K_1}{(\tau_{c2}s+1)(\tau_1 s+1)}$$

However, only the free-delay process model is utilized to derive the analytical tuning rules for the outer loop because of the Smith predictor scheme. The following is how to get the optimal feedback controller:

$$G_{c1}(s) = \frac{1}{\tilde{G}_p(s)} \frac{(y_1/r_1)_d}{1-(y_1/r_1)_d} \tag{24}$$

Fractional-order form is used in this control loop to select the desired closed loop response.

$$\left(\frac{y_1}{r_1}\right)_d = \frac{e^{-\theta_p s}}{\tau_{c1}s^{\gamma}+1}$$

$$G_{c1} = \frac{1}{K_1} \frac{(\tau_{c1}s+1)(\tau_{c2}s+1)}{1+\tau_{c1}s^{\gamma}-e^{-\theta_p s}} \tag{25}$$

The complete design steps of proposed centralized control system are given below.

Step 1: Consider the cascade processes as $G_{p1}(s)$ and $G_{p2}(s)$.

Step 2: Approximate the two processes and design controller in inner loop using direct synthesis method and outer loop controller using frequency response approach.

Step 3: Choose the robustness factors like gain margin and phase margin to design the controller in corresponding loop.

Step 4: Design Fractional order controller by selecting the appropriate values of λ and μ.

Step 5*:* A demonstration of the anticipated unified control is evaluated with respect to the essential of integral over the working time, that is, the requirement of IAE (Integral Absolute Error) and ISE (Integral Square Error), as provided by Equations (25 and 26). The control algorithm is better displayed the lower these IAE and ISE estimations are [6, 7].

The expressions are:

$$IAE = \int_0^{\infty} (|E_1(t)| + |E_2(t)|)dt \tag{26}$$

$$ISE = \int_0^{\infty} (E_1^2(t) + E_2^2(t))dt \tag{27}$$

V. SIMULATION RESULTS

Example 1: Consider the transfer function of cascade processes [8] as given by Eqn. (28) and (29)'

$$G_{p1}(s) = \frac{e^{-4s}}{20s+1} \tag{28}$$

$$G_{p2}(s) = \frac{1}{10s+1} \tag{29}$$

The corresponding controller's designed for the cascade control systems using the frequency response approach are given as:

$$G_{c1}(s) = 2.89 + \frac{0.3624}{s^{0.9}}$$

$$G_{c2}(s) = 0.758\left(1+\frac{0.4257}{s^{0.9}}\right)$$

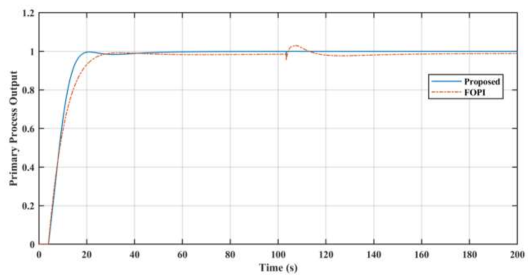

Fig.2. Closed loop servo and regulatory response of example1

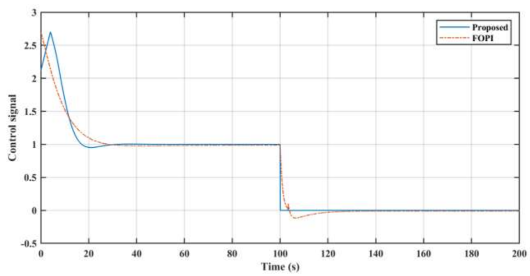

Fig.3. Control signals of Example 1

The proposed approach is compared with the method of FOPI controller and the corresponding closed loop response is shown in Fig 2 and 3 respectely. The proposed frequency response approach is design for gain margin 3db and phase margin 65 degrees. Comapring to the FOPI the present approach is provided better response. To validate the effectiveness the dicturbance is applied at 100s and observed the corresponding response. The controller signal is also displayed in Fig.3. The overshoots and settling are improved in the current method.

The IAE and IAE values are noted for the simulation of example 1 and listed in Table 1. These values shows the improvement in the performance of current method.

Table 1: Performance Index of Example 1

Control Method	Nominal Model			Perturbed Model		
	IAE	ISE	TV	IAE	ISE	TV
Proposed	5.8921	1.7589	1.2356	4.9658	2.0612	3.9587
FOPI	6.1723	2.7231	3.6211	6.6548	2.8601	4.3013

Example 2: Consider the transfer function of cascade processes as given by Eqn. (30) and (31).

$$G_{p1}(s) = \frac{e^{-4s}}{20s - 1} \tag{30}$$

$$G_{p2}(s) = \frac{2e^{-2s}}{20s + 1} \tag{31}$$

The corresponding controller's designed for the cascade control systems using the frequency response approach are given as:

$$G_{c1}(s) = 2.0175 + \frac{0.5137}{s^{0.9}}$$

$$G_{c2}(s) = 1.6667\left(1 + \frac{1}{s}\right)$$

The proposed approach is compared with the method of FOPI controller and the corresponding closed loop response is shown in Fig 4 and 5 respectely. The proposed frequency response approach is design for gain margin 3db and phase margin 65 degrees. Comapring to the FOPI the present approach is provided better response.

To validate the effectiveness the dicturbance is applied at 125s and observed the corresponding response. The controller signal is also displayed in Fig.5. The overshoots and settling are improved in the current method.

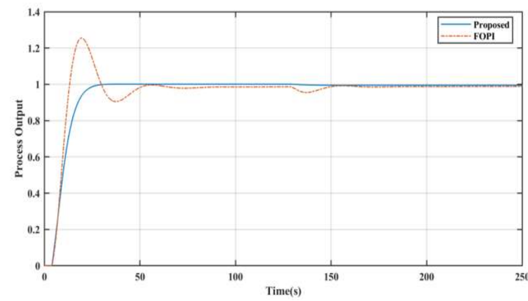

Fig.4. Closed loop servo and regulatory response of example 2

The IAE and IAE values are noted for the simulation of example 2 and listed in Table 2. These values shows the improvement in the performance of current method.

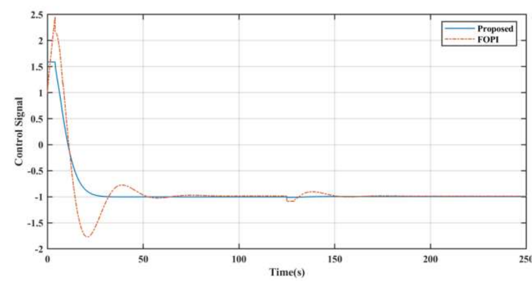

Fig.5. Control signal of example 2

Table 2: Performance Index of Example 2

Control Method	Nominal Model			Perturbed Model		
	IAE	ISE	TV	IAE	ISE	TV
Proposed	7.0568	3.5892	2.0015	7.5682	3.0125	3.7742
FOPI	8.9633	4.0985	2.3717	11.1245	4.2856	4.5196

Example 3: Consider the transfer function of cascade processes as given by Eqn. (32) and (33).

$$G_{p1}(s) = \frac{e^{-6.5672s}}{s(3.4945s + 1)} \tag{32}$$

$$G_{p2}(s) = \frac{2e^{-2s}}{s + 1} \tag{33}$$

The corresponding controller's designed for the cascade control systems using the frequency response approach are given as:

$$G_{c1}(s) = 0.0477 + \frac{0.0038}{s^{0.9}}$$

$$G_{c2}(s) = 0.02(1 + 3.283s)$$

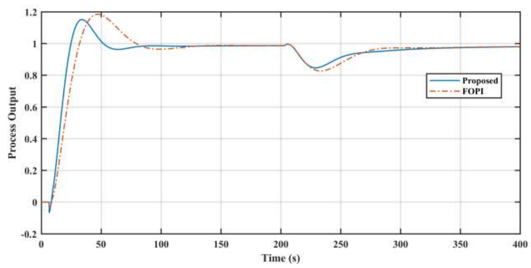

Fig.6. Closed loop response of example 3

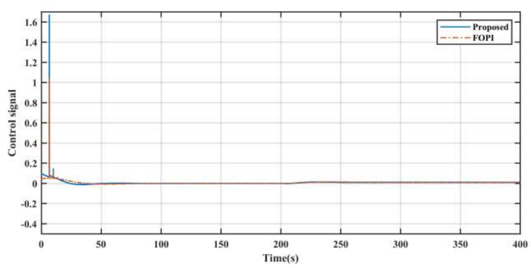

Fig.7. Closed loop response of fisrt output (Y_2) of HOP

The proposed approach is compared with the method of FOPI controller and the corresponding closed loop response is shown in Fig 6 and 7 respectely. The proposed frequency response approach is design for gain margin 3db and phase margin 65 degrees. Comapring to the FOPI the present approach is provided better response. To validate the effectiveness the dicturbance is applied at 200s and observed the corresponding response. The controller signal is also displayed in Fig.7. The overshoots and settling are improved in the current method.

The IAE and IAE values are noted for the simulation of example 3 and listed in Table 3. These values shows the improvement in the performance of current method.

Table 3: Performance Index of Example 3

Control Method	Nominal Model			Perturbed Model		
	IAE	ISE	TV	IAE	ISE	TV
Proposed	14.257	5.125	0.092	16.257	6.145	0.024
FOPI	17.952	7.579	0.185	18.59	7.99	0.203

VI. CONCLUSIONS

In this paper a parallel cascade control system is proposed for three different processes. The cascade control system has two loops i.e., inner and outer loops. In general it is used for disturbance rejection in industrial control applications. To enhance the performance of this scheme a fractional order controller is used. In addition to the FO-IMC controller a modified smith predictor is used to reduce the effect of delays in the loop. The two loop controllers are designed using direct synthesis approach and frequency response approach respectively. To improve the set point tracking and disturbance rejection a robust specifications of gain margin and phase margin are chosen in the proposed algorithm. To prove the effectiveness of algorithm three different processes have been simulated in MATLAB environment and corresponding responses also reported in the paper. In order to study the regulatory response of the proposed approach a unit step disturbance is applied at a specific time and observed the response of each process considered in the paper. Compare to other related approaches, the present method gives the better improved response. It is applicable to stable, unstable, integral and higher order processes with time delay also.

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