# Intelligent metaheuristic algorithm based FOPID controller for CSTR system

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**ABSTRACT**

The purpose of this research is to assess a continuous stirred-tank reactor (CSTR) system's performance. To enhance its performance, a fractional-order proportional-integral-derivative (FOPID) controller was employed, necessitating the tuning of independent control parameters. For this purpose, a sine-cosine algorithm (SCA) was introduced to optimize these parameters. The FOPID controller, tuned using the SCA, provides a powerful combination that addresses the complexities of the CSTR system. The fractional-order nature of the FOPID controller allows for superior tuning and robustness, offering enhanced flexibility in adjusting the system's response characteristics and improving overall control performance. The SCA, known for its effective exploration of the search space through sine and cosine functions, ensures that the controller parameters are optimally selected to enhance the system's performance by achieving an optimal fitness function. To showcase the effectiveness of the proposed SCA-tuned FOPID controller, comparisons were drawn with other optimization techniques designed for the CSTR system. The study presents time-domain characteristics and frequency responses of the proposed controller. The simulation results demonstrated that the SCA-FOPID controller significantly outperforms the other designed controllers, achieving a 54.07% reduction in the integral of time absolute error (ITAE) compared to genetic algorithm (GA), an 18.64% reduction compared to grey wolf optimizer (GWO), and a 34.79% reduction compared to differential evolution (DE). These significant reductions in ITAE underscore the effectiveness of this approach, highlighting the superior performance and robustness of the SCA-tuned FOPID controller in optimizing the CSTR system.



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## 1. INTRODUCTION

In chemical engineering, a continuous stirred tank reactor (CSTR) is a popular reactor design for carrying out continuous chemical processes. It is made out of a tank or vessel that is used to continually feed reactants in and take products out. The reactor has an agitator or stirrer that makes sure the reactants are well mixed and have a consistent composition throughout the reaction [1], [2]. As the temperature has an impact on reaction rates, product selectivity, and safety in CSTRs, it is an essential parameter. To manage the jacket temperature and keep it at the intended setpoint, controllers such as proportional-integral-derivative (PID) controllers can be used. The controller continuously monitors the temperature inside the reactor and adjusts the heating or cooling provided by the jacket to keep the temperature within the desired range [3]. PID controllers [1], are commonly used due to their simplicity, effectiveness, and widespread availability. More advanced control strategies, such as model-based control or adaptive control, can also be employed in complex CSTR systems to achieve better control performance. In order to get desired system responses, PID controller parameters must be effectively tuned. However, finding the optimal settings can pose a considerable challenge, varying across different industrial applications. In recent times, there has been a shift towards utilizing meta-heuristic optimization algorithms as a preferred choice over conventional methods like Ziegler–Nichols [1], [2], [4], Cohen–Coon [5], and trial-error-tuning approaches [6]. This shift is attributed to the limitations of these traditional methods, which often fall short of attaining the optimal results sought in diverse industrial scenarios. Similar to other industrial applications, evolutionary algorithms have been used by researchers to tune PID controllers for the CSTR system. Genetic algorithm (GA) [1], [7]–[9] particle swarm optimization (PSO) [1], [10], artificial bee colony (ABC) [3], Modified ABC [11], firefly algorithm (FF) [12], biogeography-based optimization (BBO) algorithm [12], hybrid BBO-FF algorithm [12], and fuzzy based PID controller [13] have all been utilized to fine-tune PID controller parameters specifically for the CSTR system. The fractional-order proportional-integral-derivative (FOPID) controller offers greater design flexibility in various engineering applications and has been used in CSTR systems to improve generator voltage quality. Unlike the traditional PID controller, the FOPID controller requires tuning five independent parameters, making it a more complex control system to design. This added complexity is due to the two additional parameters introduced by the fractional-order component. This increased tunability allows for more precise control but also demands a thorough understanding of the system and control theory to get the intended outcome. The process of tuning these parameters within the CSTR system has seen the application of GA [14], [15], PSO [11], [14], cuckoo search (CS) [11], state of matter search (SMS) [11], and hybrid contractor safety management system-elite opposition-based learning (CSMS-EOBL) [11], algorithms. Across these studies, researchers collectively aim to improve the response of the CSTR system by focusing on enhancing its transient response characteristics. This involves refining parameters, for example, minimizing steady-state error, peak time, rising time, settling time, and percentage overrun. Despite this shared objective, they have chosen various algorithms because no single algorithm guarantees finding the optimal controller parameters for the CSTR system. In essence, different algorithms can lead to the discovery of improved controller parameters, thereby yielding a superior response from the CSTR system. In the exploration of methods to improve the CSTR system's response, researchers have diversified their approach by considering various objective functions within the optimization algorithms mentioned earlier. Error-based objective functions like integral of time absolute error (ITAE) [1]–[4], integral of absolute error (IAE) [2], integral of time-weighted squared error (ITSE) [2], integral of squared error (ISE) [2], [5], and mean square error (MSE) [3], [6], [7] have been prominent in CSTR system studies. Moreover, custom-defined objective functions, encompassing a blend of percentage overshoot, settling time, peak time, rise time, and steady-state error have also found application in optimizing the CSTR system [8]. Among these, the widely utilized ITAE objective function was introduced in [4]. This particular objective function is frequently used by researchers, as it provides a standardized basis for comparing their innovative approaches with established methodologies present in the existing literature.

The proposed approach is applied to the temperature control of CSTR. Although extensive literature exists on various control methods for CSTR, its highly nonlinear nature and complex dynamic properties make it a challenging task. As a result, traditional control methods often struggle with this complexity. In recent years, optimization-based control has become more favored over conventional or intelligent controllers. To address this challenge, the sine cosine algorithm (SCA) is introduced as the solution. In this paper, SCA is employed in the controller design process due to its ability to avoid local minima, explore diverse regions of the search space, and effectively converge towards the global solution. This makes it superior to other well-known optimization algorithms. Previous studies have often tested control strategies under ideal or minimally disturbed conditions, more work is needed to develop disturbance-rejection techniques and controllers that are robust against a wide range of uncertainties in CSTR operations.

The SCA-FOPID controller is suggested in this study to enhance the system's frequency response and transient response. This paper's primary contribution can be summed up as follows: i) The SCA algorithm is used to tune the proposed controller settings; this is the first time this approach has been applied to choose the best parameter in CSTR investigations and ii) By comparing the suggested controller's performance to other well-known control strategies reported in the literature, it seeks to validate the efficacy of the controller using the SCA algorithm.

The paper's following sections follow this structure: section 2 outlines the model of the CSTR system under study. Section 3 outlines the suggested procedures for controller design. Section 4 analysis of the SCA's performance. Section 5 presents simulation results and a discussion. Lastly, section 6 provides the paper's conclusion.

## 2. MODEL OF CSTR

The exothermic CSTR [9], [16] is a widely used chemical system in various industries. The model of CSTR is taken from [10], which has been validated through an actual experimental setup. It has been extensively discussed in the literature. Figure 1 shows this reactor operates with a single exothermic and irreversible reaction, specifically the conversion of reactant A into product B (A→B). The reactor is assumed to always maintain perfect mixing. Reagent A is continuously introduced into the reactor at a constant volumetric flow rate, while the product stream B is also continuously removed at the same volumetric flow rate. The density of the liquid remains constant, and consequently, the volume of the reacting liquid remains constant as well. To illustrate the system, refer to the accompanying diagram depicting the reactor and the cooling jacket that surrounds it.

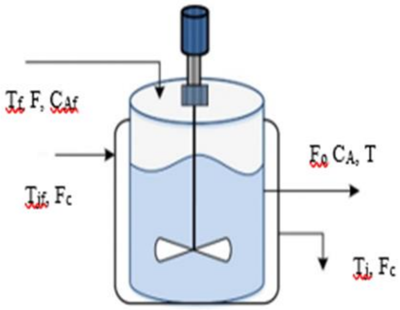


Figure 1. CSTR system

Fundamental concepts of mass balance and energy conservation are used to model the nonlinear CSTR system. A concentration in the vessel over time is given by (1). The initial term involving V as the reactor volume and F as the volumetric flow rate represents the disparity in concentration between the input and the stream. The subsequent term, indicating the reaction rate per unit volume, adheres to the Arrhenius rate law, expressed as (2). Here, the activation energy is denoted by E, the Boltzmann ideal gas constant is denoted by R, T is the reactor's temperature, $K_0$ is a nonthermal constant, and according to the rate law, the relationship between the reaction rate and absolute temperature is exponential. Similarly, the temperature change per unit of time can be approximated in (3) by assuming constant volume in the reactor and applying the energy balance concept.

$$\frac{dC_A}{dt} = \frac{F}{V}\left(C_{Af} - C_A\right) - r(t) \quad (1)$$

$$r(t) = k_0 e^{-E/RT}\, C_A \quad (2)$$

$$\frac{dT}{dt} = \frac{F}{V}\left(T_f - T\right) - \frac{\Delta H}{\rho C_P} r(t) - \frac{UA}{\rho C_P V}\left(T - T_j\right) \quad (3)$$

In this equation, the impact of changes in the inlet feed stream temperature ($T_f$) and jacket coolant temperature ($T_j$) is depicted by the first and third terms respectively. The second term denotes the effect on the reactor temperature induced by the chemical reactions occurring within the vessel. Specifically, ΔH represents the heat of the reaction per mole, $C_p$ stands for the heat capacity coefficient, ρ represents the density coefficient, U denotes the overall heat transfer coefficient, A signifies the area allocated for heat exchange, specifically the interface area between the coolant and the vessel. The CSTR Model's parameter values are listed in Table 1 [16].

Table 1. Parameter for CSTR system

| Parameter | Values | Unit |
|---|---|---|
| F/V | 1 | 1/h |
| R | 1.985875 | kcal/(kmol-K) |
| ΔH | -5960 | kcal/kmol |
| E | 11843 | kcal/kmol |
| $K_0$ | 34,930,800 | 1/h |
| $\rho C_p$ | 500 | kcal/($m^3$-K) |
| UA | 150 | kcal/(K-h) |

## 3. METHODS

In this section, it is explained the results of the research and at the same time is given in this study, the proposed controller is utilized to regulate the temperature of a CSTR. Additionally, the parameters of the proposed controller are fine-tuned using the SCA metaheuristic algorithm. A traditional PID controller requires the tuning of three distinct parameters, whereas the FOPID controller involves the adjustment of five different parameters. Figure 2 illustrates the specific parameters that need tuning for each controller. The fitness function is used to minimize ITAE for tuning the proposed controller [1], ITAE is defined as (4).

$$ITAE = \int_0^T t|e(t)|dt \tag{4}$$

### 3.1. FOPID controller

In a traditional PID controller, there are three main components i.e., PID. A FOPID [12]–[15], [17]–[19] controller extends this concept by introducing fractional calculus into the controller design. Instead of using integer order differentiation and integration, it employs fractional order differentiation and integration to fine-tune the control action. This allows for more flexibility in control system design and can be particularly useful in systems with complex dynamics or non-integer-order behavior. The equation denoted as (5) illustrates the general transfer function of an FOPID controller, while the associated block diagram is depicted in Figure 2.

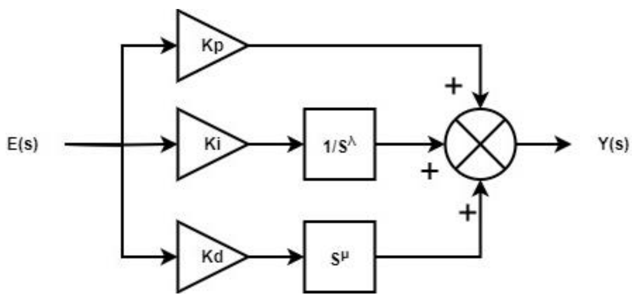


Figure 2. FOPID controller

$$G_{FOPID} = K_P + K_I s^{-\lambda} + K_D s^{\mu} \tag{5}$$

The symbols $K_P$, $K_I$, and $K_D$ stand for the proportional, integral, and derivative gains, whereas λ and μ respectively signify the order of the integrator and differentiator.

## 4. OPTIMIZATION ALGORITHMS

Figure 3 shows the feedback control loop of the CSTR. The tuning methods like GA, differential evolution (DE), grey wolf optimizer (GWO), and SCA are used for self-tuning the system to control the reactor's output temperature, via an FOPID controller [3], [10]. The objective of these techniques is to minimize the ITAE.

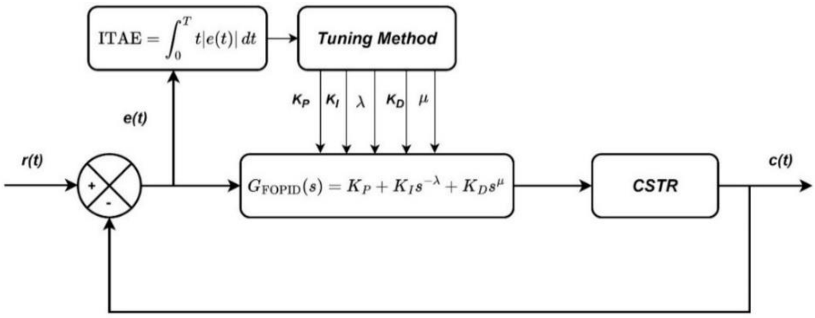


Figure 3. The feedback control loop of the CSTR system

### 4.1. Sine-cosine algorithm

SCA [11], [20]–[25] a novel population-based heuristic algorithm, begins by generating multiple random solutions and subsequently directs them to converge or diverge with respect to the optimal solution. Furthermore, to prioritize the exploration and exploitation of the search space, the algorithm incorporates a mix of random and adaptive variables. Stochastic population-based optimization typically comprises two key phases, exploration and exploitation, and in the case of SCA, both of these phases are incorporated into the subsequent position updating equations. Where $X_j^t$ and $P_j^t$ are the position of current solution and destination point in $^{th}$ dimension at t$^{th}$ iteration respectively. $r_1$, $r_2$ and $r_3$ are the random no, and |.| indicate absolute value as in (6) [24], [26].

$$X_j^{t+1} = \begin{cases} X_j^t + r_1 * \sin(r_2) * \left|r_3 P_j^t - X_j^t\right|, r_4 < 0.5 \\ X_j^t + r_1 * \cos(r_2) * \left|r_3 P_j^t - X_j^t\right|, r_4 \geq 0.5 \end{cases} \quad (6)$$

The range for the following position, denoted by $r_1$, is specified inside the interval [-2, 2] in the (6) above. The degree of movement towards or away from the destination is determined in this work by $r_2$, which is between 0 and $2\pi$. Furthermore, $r_3$ adds a stochastic random weight to the destination, which might increase ($r_3$>1) or decrease ($r_3$<1) the distance. Finally, $r_4$ is limited to the interval [0, 1] and determines an equal transition between the sine and cosine functions, or vice versa. More research has to be done on the effects of the sine and cosine functions in (6).

In (6), a distinct space is established between two potential solutions within the search space. These solutions possess the capability to explore beyond the boundaries of their designated destinations by adjusting the amplitudes of sine-cosine functions. This dynamic adaptation makes sure that the larger search space is effectively explored. In addition, because sine-cosine functions are periodic, it is possible to consistently shift one solution closer to another, which facilitates exploitation.

To achieve a balanced exploration and exploitation phase inside an algorithm, the following formula is used to dynamically modify the sine and cosine function magnitudes in (7).

$$r_1 = a - t\frac{a}{T} \quad (7)$$

In this case, $a$ stands for a fixed constant, t for the current iteration count, and T for the maximum number of iterations.

## 5. RESULTS AND DISCUSSION

MATLAB/Simulink is used for both the implementation of the suggested controller for the CSTR system and their analyses. Among the analyses performed for this study are: i) analysis performed in the time domain, ii) analysis using the frequency domain (bode plot), and iii) performance index comparison. The superiority of the proposed method is explained based on the these analysis.

### 5.1. Time-domain analysis

In this section, a CSTR system controlled by different optimization algorithms is analyzed, considering both transient and steady-state responses. The controller parameters are presented in Table 2. The CSTR system's transient response characteristics, such as rise time (tr), peak time (tp), and peak overshoot (Mp), are shown in Table 3 and Figure 4, respectively. A short setting time, rise time, and peak time are obtained by the proposed SCA-FOPID which is shown in Table 3. A short setting time means that the system reaches its final steady-state value relatively quickly. On the other hand, A short rise time suggests that the system reacts quickly to input changes and quickly reaches a sizable fraction of its final value. This is often desirable in control systems when we want the system to track changes in the reference signal or disturbances as quickly as possible, without significant delay or sluggishness. However, a short peak time is generally desirable in control systems when we aim to minimize overshoot and ensure that the system quickly settles to its final steady-state value without significant oscillations or excessive overshoot. The rise time, settling time, overshoot, and peak time are found to be 0.4115, 0.5870, 0.0877, and 0.8614 respectively, using the proposed method. The results obtained using the proposed method show the fastest rise time and settling time among all the listed algorithms. It also exhibits a relatively small overshoot, indicating good transient behavior with a fast response. The concentration-response of the CSTR system without a controller is shown in Figure 5. It has been found that the SCA-tuned FOPID controller settled down earlier compared to other controllers.

Table 2. Optimized controller parameter

| | FOPID Controller Parameters | | | | |
|---|---|---|---|---|---|
| | $K_p$ | $K_i$ | $K_d$ | λ | μ |
| SCA | 17.6473 | 100 | 7.5468 | 1.0008 | 0.0009 |
| DE | 28.56206 | 100 | 0 | 1.000033 | 0.943613 |
| GWO | 38.4525 | 95.4276 | 4.7123 | 1.0003 | 0.8594 |
| GA | 50.84428 | 79.80106 | 30.43453 | 0.999878 | 0.038782 |
| SMS [1] | 12.1 | 32.5 | 1 | 1.006 | 0.1000 |
| CS [1] | 21.7 | 50 | 0.2 | 1.002 | 0.7850 |
| CSMSEOBL [1] | 15.8 | 43.3 | 1.9 | 0.9999 | 0.1386 |
| PSO [8] | 0.2510 | 0.0243 | 0.499 | 0.5968 | 0.0706 |

Table 3. Obtained transient characteristics

| Controller | Rise time (s) | Setting time (s) | Overshoot (%) | Peak time (s) |
|---|---|---|---|---|
| SCA | 0.4115 | 0.5870 | 0.0877 | 0.8614 |
| DE | 0.4377 | 0.6798 | 0.0133 | 1.0814 |
| GWO | 0.7196 | 1.0957 | 0.0257 | 1.7519 |
| GA | 0.8804 | 2.5296 | 4.56E-07 | 9.842 |
| SMS [1] | 1.22 | 2.27 | .38 | 1.53 |
| CS [1] | 1.13 | 1.86 | .12 | 1.36 |
| CSMSEOBL [1] | 2.04 | 1.43 | 0 | 1.68 |
| PSO [8] | 3.65 | 14 | 7 | 4.76 |

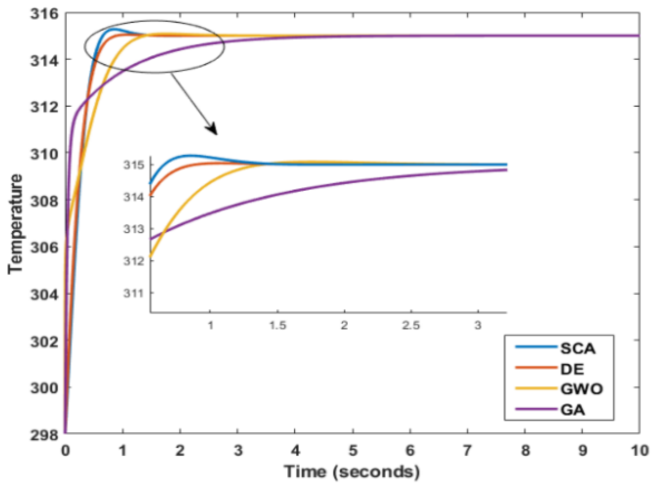


Figure 4. Controlling the CSTR system's temperature using an alternative optimization algorithm

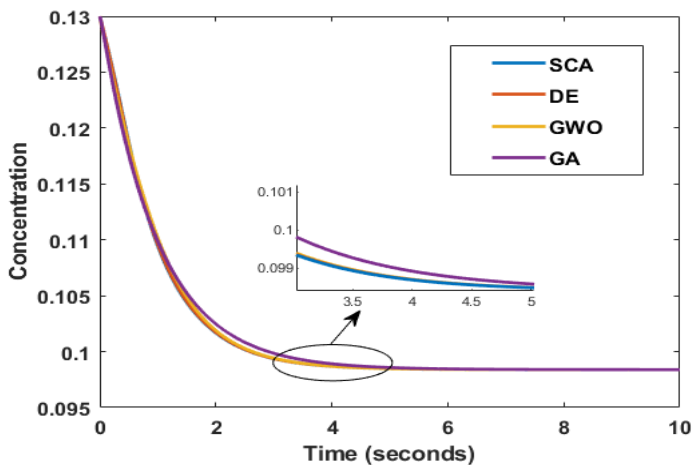


Figure 5. CSTR system's concentration using an alternative optimization algorithm

### 5.2. Frequency domain analysis

The suggested controller's frequency response properties are shown in this subsection. A comparison of the bode plots for different controllers for the CSTR system is shown in Table 4 and Figure 6, where phase margin, delay margin, and gain crossover frequency are tabulated. Additionally, the delay margin refers to the maximum time delay that the system can overcome without becoming unstable. The phase margin is the extent of phase shift that can be introduced into a system without inducing instability. The proposed method provides a reasonable phase margin and the highest delay margin, indicating good robustness to delays, but has the lowest gain crossover frequency, suggesting a slower response time.

Table 4. Obtained frequency response

| Controller | PM (deg) | Delay Margin(sec) | Gain Crossover Freq. (rad/s) |
|---|---|---|---|
| SCA-FOPID | 73.3 | 0.155 | 8.28 |
| DE-FOPID | 77 | 0.148 | 9.09 |
| GWO-FOPID | 147 | 0.0851 | 30.2 |
| GA-FOPID | 92.2 | 0.0629 | 25.6 |

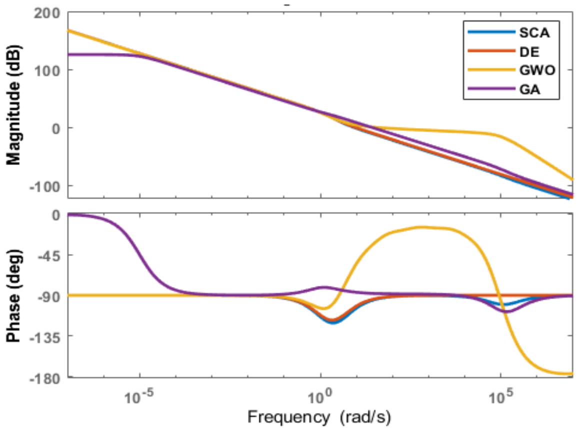


Figure 6. Bode diagram of the CSTR system utilizing various optimization algorithms

### 5.3. Performance index comparison

Performance index values of the CSTR system for different controllers are given in Figure 7 and Table 5. As seen in Figure 7, the controller based on the SCA algorithm exhibits the lowest ITAE values when compared to other controllers. The proposed method outperfoems other methods as shown in Table 5.

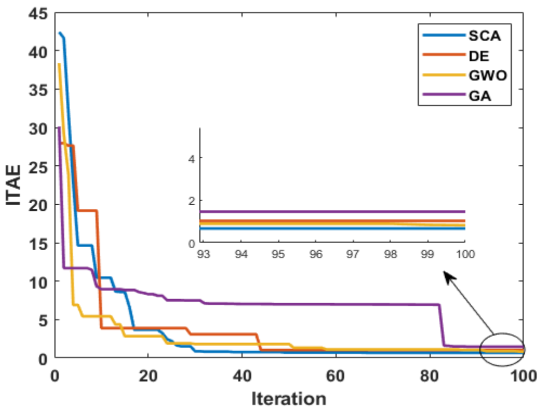


Figure 7. Convergence curve of different optimization algorithms

Table 5. Statistical analysis of performance index for different optimization techniques

| | SCA-FOPID | DE-FOPID | GWO-FOPID | GA-FOPID |
|---|---|---|---|---|
| Avg. | 0.674731 | 1.140444 | 1.312878 | 3.381959 |
| Std. | 0.002137 | 0.125918 | 0.545574 | 1.327857 |
| Best | 0.672488 | 1.031395 | 0.826646 | 1.464424 |
| Worst | 0.677101 | 1.249492 | 2.011023 | 4.364437 |

## 6. CONCLUSION

In this research, an SCA-FOPID controller was introduced to improve the performance of the CSTR system. Leveraging the SCA, a straightforward yet powerful optimization algorithm, the controller parameters were meticulously adjusted. The FOPID controller's performance was carefully evaluated in comparison to previously published literature-optimized settings for the identical CSTR system. Simulation results demonstrate that the proposed method outperforms other algorithms in terms of rise time and settling time, with minimal overshoot, indicating its superior transient response. These results highlight the superior efficiency of the SCA-FOPID controller in handling the complex, nonlinear dynamics of CSTR systems. By demonstrating a substantial reduction in the ITAE, our findings indicate that the SCA-based approach offers a more robust and accurate solution for temperature control in such systems. This advancement contributes to the ongoing efforts to optimize control strategies for industrial processes, particularly in environments where precision and stability are critical. Time-domain analysis was conducted to demonstrate the advantages of the proposed controller. Additionally, frequency-domain analysis such as bode diagrams with different controllers was used to assess the stability of the CSTR system. The results unambiguously showed that the suggested SCA-FOPID controller significantly improves the CSTR system's performance in terms of convergence rate. The limitations of the proposed method are the impact on efficiency, accuracy, and scalability, particularly when applied to large, noisy, or heterogeneous datasets. For future studies, the result may be validated with experimental analysis.

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