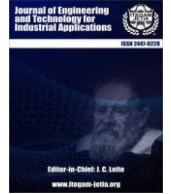




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A NOVEL AND ROBUST FRACTIONAL ORDER PROPORTIONAL INTEGRAL DERIVATIVE ACCELERATION CONTROLLER FOR ELECTRIC FURNACE TEMPERATURE REGULATION

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ABSTRACT

Electric furnaces are widely used in industrial thermal treatments because they combine high energy efficiency with precise temperature regulation. However, the nonlinear system dynamics, inherent time delays, and large thermal inertia often limit the achievable level of control performance in practice. A novel fractional-order Proportional–Integral–Derivative–Acceleration ($PI^{\alpha}DA$) controller is presented in this work, with its parameters tuned via a Modified Flower Pollination Algorithm (MFPA) to address the aforementioned limitations. The tuning procedure is formulated to explicitly improve transient response characteristics while enhancing robustness, thereby supporting reliable operation under varying operating conditions. Controller performance is assessed through comprehensive simulation studies that include reference tracking, step changes in the temperature setpoint, external disturbance rejection, and tracking under noisy reference signals. Compared with MFPA-tuned benchmark controllers (i.e., the MFPA-optimized PIDA and the conventional PID), the proposed MFPA-optimized $PI^{\alpha}DA$ controller achieves higher tracking accuracy, shorter rise and settling times, reduced overshoot, and improved robustness against disturbances and measurement noise. Overall, these findings indicate that combining fractional-order control structures with advanced metaheuristic optimization can substantially enhance temperature regulation performance in industrial electric furnace applications.



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I. INTRODUCTION

Maintaining stable temperature regulation in electric furnaces is critical to ensure energy efficiency, reliable operation, and consistent product quality [1]. However, nonlinear behavior, variations in thermal loading, and external disturbances often impair the effectiveness of traditional control approaches [2].

Although Proportional–Integral–Derivative (PID) controllers remain popular because they are simple to implement and generally robust, they frequently deliver unsatisfactory performance when the process becomes highly nonlinear or operating conditions change over time [3]. Therefore, more advanced control strategies are needed to achieve improved temperature regulation in electric furnace applications [4]. A range of enhanced control strategies is used to improve electric furnace temperature regulation, including cascaded Proportional–Integral–Derivative (PID) controllers to strengthen setpoint tracking [5] and Proportional–Integral (PI) / PID controllers obtained via system identification approaches [6]. Fractional-order Proportional–Integral–Derivative (FOPID) controllers tuned with metaheuristic optimizers—such as Harris Hawks Optimization (HHO) [7], and Artificial Rabbits Optimization (ARO) are also reported to improve dynamic performance [8].

In parallel, fuzzy PID controllers optimized with bio-inspired methods (e.g., dung beetle optimization) show improved disturbance rejection and robustness [9], while Proportional–Integral–Derivative–alpha (PID^α) and Proportional–Integral–Derivative–Double-Derivative (PIDD²) structures are introduced to better address nonlinearities and enhance transient behavior [10],[11]. By adding an acceleration term, Proportional–Integral–Derivative–Acceleration (PIDA) controllers improve transient response, reduce overshoot, and enhance disturbance rejection in high-inertia, time-delay processes such as electric furnaces [12],[13]. More recently, a two-degree-of-freedom (2-DOF) PIDA design with parameter optimization based on the Greater Cane Rat Algorithm (GCRA) has been shown to outperform conventional PID and single-degree-of-freedom PIDA controllers in both setpoint tracking and robustness [13].

Realizing the full potential of advanced control schemes depends on precise controller parameter tuning, especially when the controller includes several adjustable gains and weighting factors. Conventional trial-and-error or manual tuning is time-consuming and often impractical for complex controller structures, so robust optimization is used as a core element of modern controller design. Accordingly, bio-inspired and metaheuristic methods—such as Particle Swarm Optimization (PSO) [14], Harris Hawks Optimization (HHO) [7],[10],[15], Quadratic Interpolation Optimization (QIO) [16], and the Flower Pollination Algorithm (FPA) [17], [18]—are widely applied to efficiently search for high-quality tuning solutions. These optimizers typically minimize time-domain performance measures such as the Integral of Time-weighted Absolute Error (ITAE), along with transient metrics (e.g., rise time) and actuation-related measures (e.g., control effort), to balance tracking quality and practical implementability.

Despite these improvements, integer-order PIDA controllers often lack the flexibility required for complex, time-varying thermal systems. To address these challenges, this paper proposes a novel Fractional-Order PIDA (PI^αDA) controller. This architecture expands the control design's degrees of freedom by integrating non-integer order into the integral action. Such adaptability allows for superior management of the high inertia, time lags, and complex dynamics inherent in industrial heating furnaces. Compared to standard integer-order PID or PIDA schemes, our proposed PI^αDA significantly improves tracking accuracy and disturbance rejection without compromising robustness. The main contributions of this paper can be summarized as follows:

1. A new Fractional-Order PIDA (PI^αDA) controller is proposed for electric furnace temperature regulation, extending the conventional PIDA framework by incorporating non-integer integral order to enhance control flexibility and dynamic performance.
2. The parameters of the proposed PI^αDA controller are optimally tuned using a Modified Flower Pollination Algorithm (MFPA), enabling efficient exploration–exploitation balance and improved convergence toward optimal control solutions.
3. A detailed comparative analysis is conducted between the proposed PI^αDA controller and conventional PID and PIDA controllers, demonstrating superior tracking accuracy, reduced overshoot, faster settling time, and minimal steady-state error.
4. The robustness of the proposed control scheme is thoroughly investigated under four realistic operating conditions, including reference tracking, step changes in target temperature, external disturbances, and noisy reference signals, confirming its effectiveness in handling uncertainties and disturbances typical of industrial electric furnaces.

The remainder of this paper is organized as follows: Section 2 details the implementation of the Modified Flower Pollination Algorithm (MFPA) used for controller optimization. Section 3 outlines the mathematical modeling of the temperature control system and describes the design of the proposed PI^αDA controller. Section 4 discusses extensive simulation results, including a comprehensive analysis of performance and robustness. Finally, Section 5 summarizes key insights and concludes the study.

II. MODIFIED FLOWER POLLINATION ALGORITHM (MFPA)

The Flower Pollination Algorithm (FPA), proposed by [19], is a metaheuristic inspired by the reproductive behaviors of flowering plants. Engineering esteems this method for its computational efficiency and reduced parameter needs compared to other optimization techniques. The algorithm emulates the interaction between flowers and pollinators, such as insects and birds, to traverse the search space. The FPA functions according to four guiding principles: biotic cross-pollination, abiotic self-pollination, floral constancy, and a switching probability that equilibrates local and global search efforts. Global pollination specifically enables long-distance transfers via Lévy flights, a mechanism essential for avoiding local optima and promoting diversity within the solution space. The global search method is mathematically expressed in Equation (1), as elaborated in [20]:

Global Pollination Step

$$x_i^{t+1} = x_i^t + L(x_i^t - g^*) \quad (1)$$

In this instance, x_i^t signifies the position of pollen i at iteration t , whereas g^* indicates the current global optimum identified within the population. The parameter L serves as the pollination strength, thereby influencing the step size via a Lévy flight distribution. This distribution is essential for facilitating the extensive leaps necessary for global search, as delineated by Equation (2):

Lévy-flight step size

$$L \approx \frac{\lambda \Gamma(\lambda) \sin\left(\frac{\pi\lambda}{2}\right)}{\pi} \frac{1}{s^{1+\lambda}}, (s \gg s_0 > 0) \quad (2)$$

Here, the symbol $\Gamma(\lambda)$ denotes the standard gamma function, while s represents the step size. Conversely, the algorithm shifts to the local pollination phase whenever a randomly generated value falls below the switching probability, p . This local search mechanism is defined by Equation (3):

$$\begin{aligned} &\text{Local pollination} \\ x_i^{t+1} &= x_i^t + \epsilon(x_j^t - x_k^t) \end{aligned} \quad (3)$$

Where:

$$\begin{aligned} &\text{Uniform distribution} \\ \epsilon(\rho) &= \begin{cases} \frac{1}{b-a}, & a \leq \rho \leq b \\ 0, & \rho < a \text{ or } \rho > b \end{cases} \end{aligned} \quad (4)$$

In this expression, x_j^t and x_k^t represent pollen collected from distinct flowers of the identical species. The parameter ϵ is drawn from a uniform distribution within $[0,1]$, thereby effectively modeling a local random walk. This mechanism encapsulates the dynamics of localized fertilization and exploitation within the proximate search vicinity. The Modified Flower Pollination Algorithm (MFPA) signifies a substantial advancement of the conventional Flower Pollination Algorithm (FPA) framework. The fundamental innovation lies in using a stochastic switching probability to control transitions between local and global pollination stages. MFPA achieves higher convergence rates and more resilient global exploration by replacing the traditional fixed threshold with a dynamic stochastic parameter.

This method more accurately reflects the intrinsic randomness of biological pollination, therefore reducing premature convergence and aiding in the identification of the global optimum. The decision-making process is governed by a random variable $rand$ distributed uniformly on $[0,1]$. Nevertheless, the proposed method deviates from the conventional FPA in terms of the specification of the switching threshold. In contrast to the original method, which often employs a fixed probability (e.g., $p = 0.2$), the proposed alternative incorporates a dynamic, randomized switching probability (p) selected from the range $[0, p_{max}]$. By establishing $p_{max} \leq 0.5$, this alteration incorporates a stochastic element that more precisely reflects the variety evident in natural pollination activities.

In the canonical FPA paradigm, the shift between global and local pollination modes relies on the threshold condition $rand > p$, where $rand$ is a random number. The proposed Modified FPA (MFPA) alters this condition to $rand > randp$. Here, $rand$ and $randp$ are independent random variables drawn from uniform distributions over the intervals $[0,1]$ and $[0, p_{max}]$, respectively. In this revised strategy, the global pollination phase commences if $rand > randp$; otherwise, the algorithm proceeds with the local pollination mode. This update significantly enhances stochastic flexibility in the search process while maintaining the foundational mathematical structure of the original algorithm as delineated in Equations (1)–(4).

III. PROPOSED PI^αDA CONTROLLER BASED ON MFPA ALGORITHM

III.1 MODELING OF ELECTRIC FURNACE TEMPERATURE CONTROL SYSTEM

The architectural framework of the electric furnace (EF) temperature management system—comprising the furnace unit, controller, thermocouple feedback sensor, and heating element—is depicted in Figure 1 [4], [21]. In this configuration, the variables r , U , and y denote the reference input voltage, the controller output voltage, and the thermocouple feedback voltage, respectively, while R represents the heating element resistance.

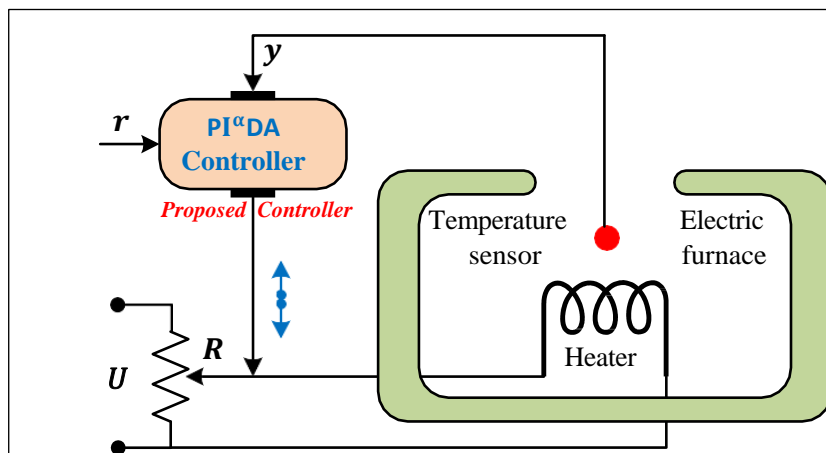


Figure 1: Schematic representation of the electric furnace.

Source: [4], [21].

Mathematically, the dynamic behavior of the EF temperature system is modeled by a second-order transfer function characterized by an inherent time delay, formulated as follows:

The general transfer function of the electric furnace

$$G_p(s) = \frac{b_0}{a_2 s^2 + a_1 s + a_0} e^{-Ds} \quad (5)$$

To ensure validation and comparability with the established literature, this study adopts benchmark parameters: $a_0=0.2$, $a_1=1.1$, and $a_2=1$, along with a transport delay of $D = 1.5$. These specific values are widely cited in the assessment of control strategies for electric furnace temperature management [22], [23]. Adhering to these standardized coefficients facilitates a rigorous performance comparison between the proposed controller and the existing state-of-the-art method

The transfer function of our electric furnace.

$$G_p(s) = \frac{0.15}{s^2 + 1.1 s + 0.2} e^{-1.5s} \quad (6)$$

Equation (7) illustrates how the time delay is estimated using the first-order Padé approximation.

Padé First-Order Time Delay Approximation

$$e^{-1.5s} = \frac{1 - 0.75s}{1 + 0.75s} \quad (7)$$

The EF temperature system's transfer function will then be:

The approximated transfer function of our electric furnace

$$G_p(s) = \frac{-0.1125s + 0.15}{0.75s^3 + 1.825s^2 + 1.25s + 0.2} \quad (8)$$

III.2 PROPOSED PI^αDA CONTROLLER

The proposed control approach is derived from the conventional Proportional–Integral–Derivative–Acceleration (PIDA) controller. In this study, a modified structure is introduced in which only the integral action is formulated with a fractional order, whereas the proportional, derivative, and acceleration actions remain of integer order. This modification yields a Modified Fractional-Order PIDA controller, denoted (PI^αDA), that increases tuning flexibility by better capturing the memory characteristics commonly observed in thermal processes. Consequently, the (PI^αDA) structure aims to improve temperature regulation performance in electric furnace systems affected by nonlinear dynamics and pronounced thermal inertia. The standard PIDA controller configuration is expressed as follows:

$$G_{PIDA}(s) = K_p + \frac{K_i}{s} + K_d s + K_a s^2 \quad (9)$$

The incorporation of fractional-order calculus into the control framework generalizes the classical PIDA law. Specifically, it substitutes the standard integer-order integral operator ($1/s$) with its fractional counterpart, $1/s^\alpha$ [24]. This modification permits the decomposition of the fundamental integral action as follows [25-29]:

Decomposition of the integrator into two fractional integrators

$$s^{-1} = s^{-\alpha} \cdot s^{-(1-\alpha)}, \quad 0 < \alpha < 1 \quad (10)$$

It is important to emphasize that the numerical and rational approximations of the fractional operators $s^{-\alpha}$ and $s^{-(1-\alpha)}$ are completely different from the approximation of the integer-order integral operator s^{-1} . The proposed PI^αDA controller introduces an extra tuning parameter, α , via the fractional operator $1/s^\alpha$. This addition grants superior flexibility in shaping the system's low-frequency response. Such an expanded design space proves particularly effective in addressing the substantial thermal inertia and nonlinearities inherent to electric furnace operations.

Resulting,

$$PI^\alpha DA$$

$$G_{PI^{\alpha}DA}(s) = \frac{\text{Transfer function}}{s^{\alpha}s^{1-\alpha}} = \frac{K_a s^3 + K_d s^2 + K_p s + K_i}{s^{\alpha}s^{1-\alpha}} \quad (11)$$

Figure. 2 shows the block diagram of PI^αDA controller.

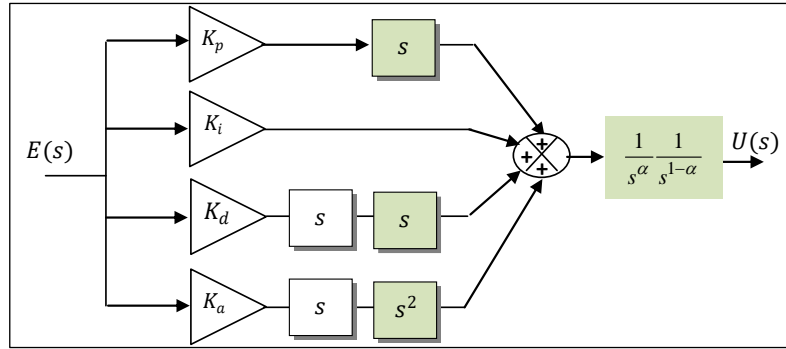


Figure 2: Shows the block diagram of PI^αDA controller. Source: Authors, (2026).

The suggested control methodology combines a fractional-order PI^αDA controller with the Modified Flower Pollination Algorithm (MFPA) to enhance thermal management and transient response in electric furnace systems. This framework uses the MFPA for accurate, adaptable parameter optimization, thereby improving performance in the complex dynamics of industrial furnaces. Figure 3 presents the block diagram of the closed-loop temperature control system. In this arrangement, the proposed controller, referred to as $G_{PI^{\alpha}DA}(s)$, processes the error signal $E(s)$ to produce an optimal control signal $U(s)$. This control action aims to guarantee that the system output $Y(s)$ precisely follows the reference input $R(s)$ while efficiently mitigating external disturbances $D(s)$.

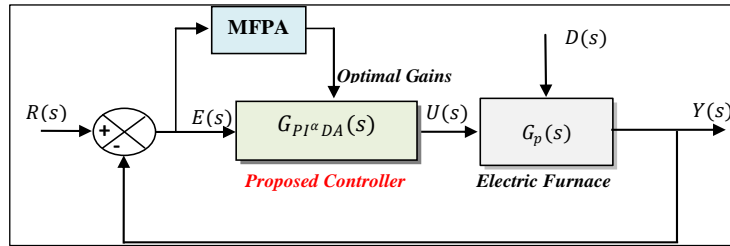


Figure 3: Proposed MFPA based PI^αDA Controller. Source: Authors, (2026).

This study employs the Integral Absolute Error (IAE) as the primary performance metric to guide the optimization. The tracking error $e(t)$ is defined as the instantaneous discrepancy between the reference signal and the measured output. Minimizing the IAE directs the adjustment of controller parameters to enhance tracking precision while maintaining stable closed-loop performance.

Objective function: Integral Absolute Error.

$$J = \int_0^{t_{sim}} |r(t) - y(t)| dt \quad (12)$$

The optimization challenge is formulated as minimizing the IAE to diminish the discrepancy between the reference input and the system output. This function (J) quantifies the cumulative absolute difference between the reference temperature and the actual temperature, as specified in Equation (12) within the system design context. The function J is subsequently submitted to the MFPA block for minimization to determine the ideal parameter vector $\{K_p, K_i, K_d, K_a, \alpha\}$ for the PI^αDA controller.

The MFPA search parameters are set to $n = 40$ and $p_{max} = 0.5$ (50%). Furthermore, the controller gains are constrained within the following ranges: $0 \leq K_p \leq 5.00$, $0 \leq K_i \leq 1.00$, $0 \leq K_d \leq 10.00$, $0 \leq K_a \leq 10.00$ and $0.01 \leq \alpha \leq 0.5$. The termination criterion (TC) is set to $Max Gen = 500$ generations. Fifty test runs were conducted to determine the optimal PI^αDA controller ($G_c(s)|_{PI^{\alpha}DA}$) for the electric furnace temperature control system. The MFPA technique was successfully used to make the controller for the system model $G_p(s)$, yielding the following optimized parameters: $K_p = 3.98$, $K_i = 0.66$, $K_d = 4.99$, $K_a = 0.99$, and $\alpha = 0.5$.

Optimal PI^αDA Controller

$$G_c(s)|_{PI^{\alpha}DA} = \frac{0.99s^3 + 4.99s^2 + 3.98s + 0.66}{s^{0.5}s^{0.5}} \quad (13)$$

Optimal PID controller

$$G_c(s)|_{\text{PID}} = 3.55 + \frac{0.61}{s} + 3.85 s \quad (14)$$

Optimal PIDA controller

$$G_c(s)|_{\text{PIDA}} = 3.98 + \frac{0.66}{s} + 4.99 s + 0.99 s^2 \quad (15)$$

III.3 FRACTIONAL CALCULUS

The PI^αDA controller was created in MATLAB/Simulink based on the already implemented classic PIDA. Integro-derivatives were approximated initially using a recursive Oustaloup filter [30].

Oustaloup filter

$$G(s) = K \prod_{i=-N}^N \frac{s + \omega'_i}{s + \omega_i} \quad (16)$$

Zero Frequencies

$$\omega'_i = \left(\frac{\omega_h}{\omega_b} \right)^{\frac{i+N+\frac{1}{2}(1+q)}{2N+1}} \quad (17)$$

Pole Frequencies

$$\omega_i = \left(\frac{\omega_h}{\omega_b} \right)^{\frac{i+N+\frac{1}{2}(1-q)}{2N+1}} \quad (18)$$

Where :

- N - order of approximation,
- ω_h - higher bound of frequency fitness,
- ω_b - bottom bound of frequency fitness.

IV. RESULTS AND DISCUSSION

This section delineates the numerical simulation results of the suggested PI^αDA controller, optimized by the MFPA, applied to the electric furnace control system. The analysis focuses on time-domain performance, specifically evaluating transient response and trajectory tracking to validate the controller's effectiveness. Furthermore, stability analysis and disturbance rejection tests are performed to validate the robustness of the suggested control technique.

IV.1 FIRST SCENARIO

The tracking capabilities of the proposed controller were evaluated by subjecting the system to a step change in the temperature setpoint. Figure 4 illustrates the comparative step responses of the PI^αDA, PID, and PIDA control structures. This visualization effectively highlights the distinct differences in their ability to regulate system dynamics during the transient phase. The simulation results demonstrate that while the benchmark control systems are effective, the proposed MFPA-optimized PI^αDA controller exhibits significantly superior dynamic characteristics. Table 1 details the quantitative transient response parameters for the evaluated controllers. Key metrics included are maximum overshoot, rise time, peak time, and settling time (calculated within a standard ±2% tolerance band).

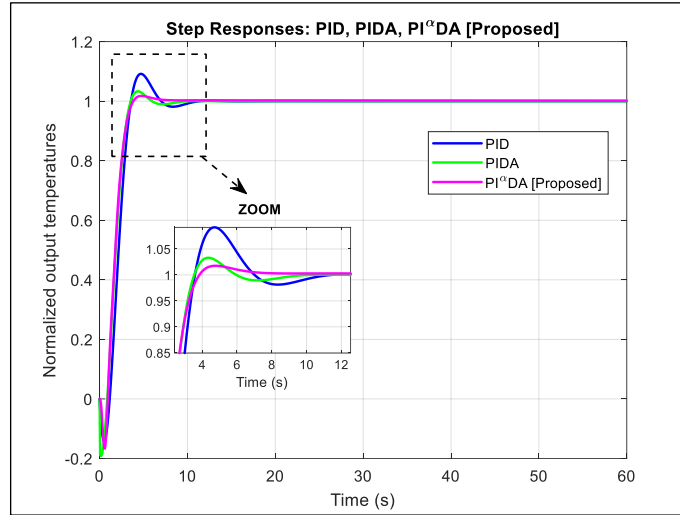


Figure 4: Input Tracking Performance Comparison.
Source: Authors, (2026).

As can be seen from Table 1, the proposed $PI^{\alpha}DA$ controller exhibits a slightly longer rise time (1.8529 s), but this trade-off does not detract from its overall effectiveness. The design instead shows strong stability characteristics, with a very low overshoot (1.5600%) and the fastest settling time (3.5239 s), while completely eliminating steady-state error (0.000). These measures highlight the controller's accuracy, its ability to mitigate thermal variations, and its rapid attainment of equilibrium, thereby affirming its reliability in furnace temperature regulation.

Table 1: Performance comparison of transient responses ($\alpha = 0.5$).

Control methods	T_r [s]	T_s [s]	OS [%]
$PI^{\alpha}DA$ Controller	1.8628	3.5506	1.5600
PID Controller	1.7818	6.4827	9.1687
PIDA Controller	1.8368	5.1277	3.3096

Source: Authors, (2026).

IV.2 SECOND SCENARIO

To evaluate the system's response to a step change in the target temperature, a 0.5-unit perturbation is introduced at $t = 30$ s, as shown in Figure 5. This step variation physically signifies an abrupt alteration in the target operating temperature of the electric furnace, reflecting a shift between distinct process phases or production demands. This variation accurately represents actual industrial operating conditions, in which the furnace must swiftly adjust its thermal energy to attain the new temperature setpoint.

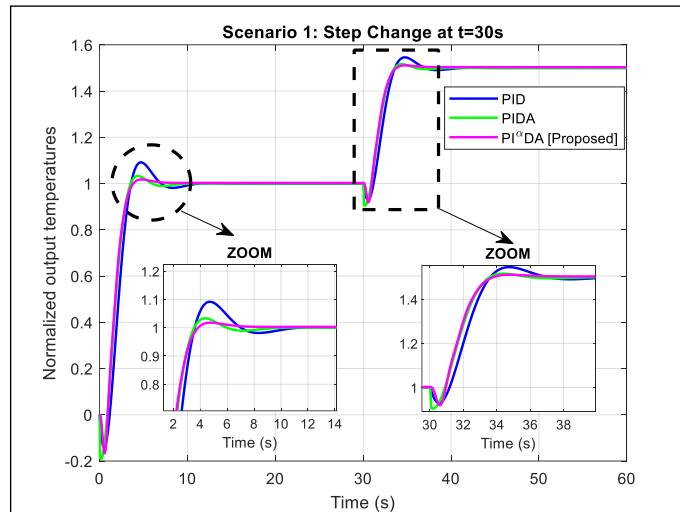


Figure 5: Dynamic Performance Analysis for Scenario 2.
Source: Authors, (2026).

Figure 5, shows that the proposed $PI^{\alpha}DA$ controller achieves a faster response with reduced overshoot and shorter settling time during both the initial setpoint tracking and the step change at $t = 30$ s, compared with the PID and PIDA controllers. The zoomed views further confirm its improved transient behavior and quicker convergence to the reference value.

IV.3 THIRD SCENARIO

To evaluate the robustness of the proposed control framework, Figure 6 illustrates the system's dynamic behavior under Scenario 2. In this scenario, after the initial setpoint tracking phase, a sudden change in the reference signal is applied at $t = 30$ s, representing a perturbation in the operating conditions. Physically, this change reflects a realistic operating situation in an electric furnace, such as a modification in the desired temperature level due to process requirements, production phase transition, or changes in thermal demand.

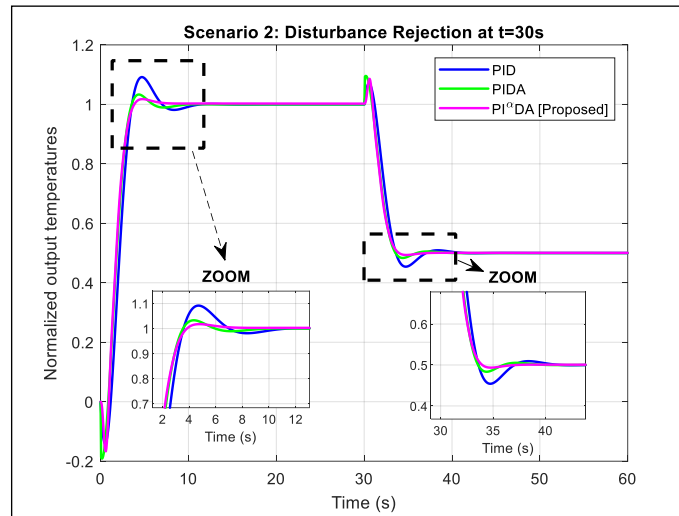


Figure 6: Dynamic Performance Analysis for Scenario 3.
Source: Authors, (2026).

Figure 6 illustrates the enhanced resilience and dynamic adaptability of the proposed $PI^{\alpha}DA$ controller in response to abrupt changes in operating conditions, including unexpected fluctuations in the reference signal. The analysis emphasizes the controller's ability to swiftly adapt to the new reference value while reducing undershoot, oscillations, and settling time, thereby ensuring reliable, consistent performance in real industrial settings. Compared with traditional PID and PIDA controllers, the $PI^{\alpha}DA$ exhibits smoother transient behavior, reduced oscillations, and faster stabilization after reference changes, highlighting its superior stability and robustness across diverse operating conditions.

IV.4 FOURTH SCENARIO

To appraise the system's proficiency in tracking a reference signal contaminated with noise, the results are shown in Figure 7.

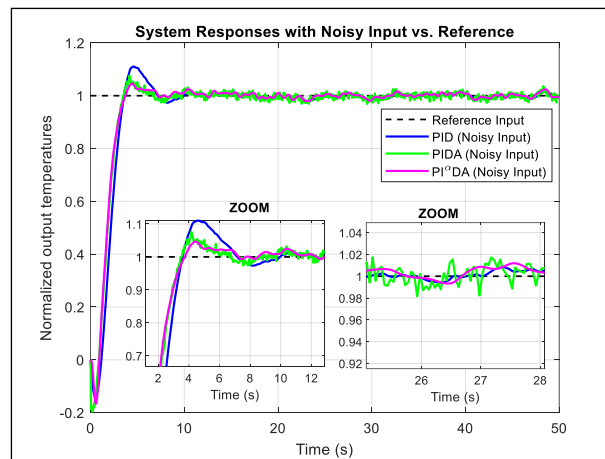


Figure 7: System Response to Noisy Reference Tracking.
Source: Authors, (2026).

As depicted in Figure 7, the comparative performance of the control strategies is evaluated regarding setpoint tracking under measurement noise. The suggested $PI^{\alpha}DA$ controller clearly outperforms typical PID and PIDA controllers in reducing noise disturbances and precisely following the desired trajectory. The $PI^{\alpha}DA$ output exhibits strong alignment with the variable reference signal, marked by reduced fluctuations and more fluid control action, thereby ensuring a more stable operational profile. The sensitivity analysis underscores the significant impact of the fractional-order parameter α on the dynamic performance of the proposed $PI^{\alpha}DA$ controller. Fluctuations in α substantially influence critical performance metrics, such as rise time (T_r), overshoot (OS), settling time (T_s), and steady-state error (SSE), making this parameter vital for achieving an optimal balance between swift response and stability.

Table 2 presents a sensitivity study of the PI^αDA controller with respect to the fractional-order parameter α , clearly demonstrating its influence on closed-loop dynamics and steady-state performance.

Table 2. Sensitivity Analysis of the PI^αDA Controller with Respect to the Fractional Order α .

$[\alpha, 1 - \alpha]$	T_r [s]	T_s [s]	OS [%]	SSE
[0.1, 0.9]	1.8712	5.7215	3.2277	0.00010244
[0.2, 0.8]	1.8455	5.8093	2.7582	0.00021855
[0.3, 0.7]	1.8039	5.4849	2.6613	0.00019844
[0.4, 0.6]	1.6739	8.5287	4.1366	0.00004858
[0.5, 0.5]	1.8628	3.5506	1.5600	0.00199900

Source: Authors, (2026).

As reported in Table 2, as α varies from low to moderate values, noticeable changes in the transient response are observed. Specifically, the interval $\alpha \in [0.4, 0.6]$ yields the minimum rise time (1.6739 s) and an extremely low steady-state error (4.858×10^{-5}), indicating a fast response with high accuracy. While the observed gain in response speed is noticeable, it is accompanied by a larger overshoot (4.1366%) and a longer settling time (8.5287 s), which points to reduced damping. When the fractional order α is set to 0.5, the closed-loop behavior becomes more even: the rise time remains moderate (1.8628 s), the settling time is the smallest (3.5506 s), and the overshoot reaches its minimum (1.56%) across the tested cases. The steady-state error increases slightly, yet it remains acceptable for most practical applications. These observations confirm that α is a key design lever in fractional-order control, influencing both transient and steady-state performance, and therefore requires careful tuning.

V. CONCLUSION

This paper proposed a novel fractional-order PIDA (PI^αDA) controller for electric furnace temperature regulation, extending the classical PIDA structure by introducing a non-integer integral order to enhance control flexibility and dynamic behavior. The controller parameters were optimally tuned using a Modified Flower Pollination Algorithm (MFPA), which ensured an effective balance between exploration and exploitation and enabled fast, reliable convergence to optimal solutions. Comprehensive simulation results demonstrated that the proposed PI^αDA controller significantly outperforms conventional PID and integer-order PIDA controllers in terms of tracking accuracy, overshoot reduction, settling time, and steady-state error minimization. Although a marginal increase in rise time was observed in certain scenarios, this trade-off did not adversely affect overall system stability or precision, which are critical requirements in thermal industrial processes.

Furthermore, the robustness of the proposed control scheme was rigorously validated under multiple realistic operating conditions, including reference tracking, step variations in temperature setpoints, external disturbances, and noisy reference signals. The results confirmed the controller's strong disturbance rejection capability and resilience to uncertainties commonly encountered in industrial electric furnaces. Overall, the findings highlight the effectiveness and practicality of combining fractional-order control with advanced metaheuristic optimization for high-performance thermal regulation. Future research will focus on experimental validation via Hardware-in-the-Loop (HIL) implementation and on investigating hybrid optimization strategies to further improve computational efficiency, robustness, and energy savings in real-time industrial applications.

VI. AUTHOR'S CONTRIBUTION

Methodology: K. Benaouicha, A. Idir.

Investigation: K. Benaouicha, A. Idir.

Discussion of results: K. Benaouicha, A. Idir, H. Akroum.

Writing – Original Draft: K. Benaouicha.

Writing – Review and Editing: K. Benaouicha, A. Idir.

Resources: A. Idir.

Supervision: A. Idir, H. Akroum, Nesri and S. Guedida.

Approval of the final text: K. Benaouicha, A. Idir, H. Akroum, M. Nesri and S. Guedida.

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