

Robust Fractional-Order Multimodel Control of Electromechanical Systems with Parametric Uncertainty

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Submitted 08/04/2026

Accepted 25/05/2026

Published 11/09/2026

DOI: [10.64518/uohjs.2026.04](https://doi.org/10.64518/uohjs.2026.04)

Abstract:

In this paper, fractional-order control concepts are applied within a multimodel framework to develop a robust control strategy for uncertain and complex systems. Two control architectures are implemented in this work. The first employs a multimodel fusion approach to apply a global fractional-order controller to a DC motor, ensuring the desired performance. The second is a decentralized fractional-order control scheme, which offers improved response against disturbances. Simulations are conducted for both architectures. The results obtained demonstrate the effectiveness of the proposed approaches for uncertain and complex systems.

Key words: Fractional-order control; Multimodel systems; Robust control; Uncertain electromechanical systems; DC motor; Disturbance rejection.

1. INTRODUCTION

Modern industrial applications are very sensitive systems, where high precision, reliability, and robustness are required despite the presence of disturbances and uncertain operating conditions (Ma et al., 2021; Zhang et al., 2025). Conventional integer-order control strategies fail to ensure stability and robustness, especially when the system operates across multiple regimes. Fractional-order control has emerged as an efficient method to ensure robustness in uncertain systems (Abdelkrim, 2025). However, when the system has strong nonlinearities, the single global model becomes insufficient. Multimodel approaches address this limitation by representing the plant through a set of local submodels, each valid within a specific operating region. This structure enhances robustness against uncertainties. Integrating fractional-order control within a multimodel approach provides a powerful approach for robust control of uncertain systems (Dong, H., et al . 2026, Yu, D., et al . 2026). Robust fractional-order control is considered as a powerful approach for DC motor systems operating under significant disturbances and uncertainties (Alqarni, Z. 2026, Bouyahia et al ., 2023). In practice, uncertainties and disturbances increase errors that can destabilize the closed-loop response when using conventional controller such as PID, PI, and PD. Fractional-order control addresses these limitations by incorporating non-integer differentiation and integration orders, which provide additional degrees of freedom. Simulation and experimental results consistently demonstrate that fractional-order controllers provide improved responses such as reduced overshoot and faster disturbance rejection (Syam, S. M., Siri, Z., Altoum, S. H., & Md Kasmani, R. 2026). These features of fractional-order control give an effective stabilization method for DC motor applications in robotics, industrial drives and they give robustness under uncertainty. Multimodel approaches have become increasingly used in the design of robust control approaches for complex systems, especially when

disturbances and uncertainties exist (Tavazoei and Haeri, 2021; Chen et al ., 2022). In practice, the system behavior cannot be controlled by a main model due to nonlinearities, disturbances and uncertainties.

To overcome this limit, the multimodel concept decomposes the global dynamics into a set of locally valid fractional-order submodels, each representing the system in a specific operating point (González et al ., 2024). These submodels are then fused through an interpolation method to construct a global representation that preserves both modeling accuracy and structural flexibility (Hernández and Duarte-Mermoud, 2021). This architecture enables the formulation of robust controllers. The idea of combining the multimodel structures with fractional-order robust control principles represents a powerful control method, capable of providing high performance and strong robustness systems.

The structure of this paper is organized as follows: Section 2 provides a detailed description of the uncertain DC motor dynamics considered in this study. Then, Section 3 develops a fractional-order control strategy for the DC motor. In Section 4, the design of robust fractional-order controller is presented to stabilize and ensure desired performances under disturbances and uncertainties. The paper concludes with a conclusion and future perspectives.

2. STUDIED PROCESS: UNCERTAIN DC MOTOR DYNAMICS UNDER NO-LOAD, HALF-LOAD, AND FULL-LOAD CONDITIONS

Electromechanical processes exhibit strong nonlinearities and load-dependent variations, caused by external factors. A typical example is the DC motor shown in Figure. 1, whose electromechanical coupling makes it highly sensitive to variations (Tahar and Abdelkrim, 2011). These characteristics make it difficult for classical single-model controllers to maintain consistent performance across the full operating envelope. To overcome these limitations, the present work adopts a multimodel fractional-order control framework in which the global dynamics of the DC system are approximated by a set of locally valid linear fractional-order models, each capturing the behavior around a specific operating region and several architectures are adopted based on this representation.

2.1. Dynamic Representation of the DC Motor for Variable Load Scenarios

To ensure stability of DC motor (1) under varying operating conditions, three transfer-function models are identified corresponding to the no-load Eq. (1), half-load Eq. (2), and full-load Eq. (3) regimes. These transfer functions are used in multimodel representation to design and validate the proposed fractional-order multimodel control method.

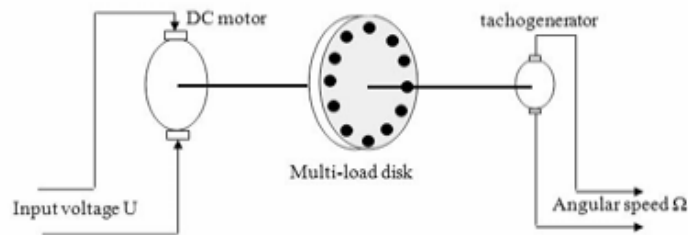


Figure 1. Experimental Platform for DC Motor Evaluation Under No-Load, Half-Load, and Full-Load Conditions

The studied process, represented in the figure (1), is a DC motor rated at 100 W output power. It drives a multi-load disc with 12 holes of 1 cm diameter, equidistant from the axis of the disc. A 120g load can be attached at each hole to vary the process inertia. A tachogenerator provides a voltage proportional to the angular speed of the motor. The objective is to control, by a new approach, the angular speed Ω of the electromechanical process. The models identified (Tahar and Abdelkrim, 2011); no-load (no mass on the disc) $G_u(p)$, half load (6 masses on the disc) $G_h(p)$ and full-load (12 masses on the disc), **based on practical results**, transfer functions are given of the form:

$$G_u(p) = \frac{5.123(1 + 0.079p)}{(1 + 2.749p)(1 + 0.078p)} \quad (1)$$

$$G_h(p) = \frac{4.734(1 + 0.663p)}{(1 + 7.954p)(1 + 0.530p)} \quad (2)$$

$$G_f(p) = \frac{5.098(1 + 0.781p)}{(1 + 13.902p)(1 + 0.589p)} \quad (3)$$

2.2. Multimodel Representation of the DC Motor Under Variable Load Conditions

The global process is obtained as a multimodel representation that combines the three previously identified transfer-function models no-load, half-load, and full-load providing a description of the DC motor dynamics for all operating conditions Eq. (4) and Eq. (5).

$$G_{global}(p) = 0.1 G_u(p) + 0.35 G_h(p) + 0.55 G_f(p) \quad (4)$$

$$G_{global}(p) = \frac{5.33p^5 + 87.74p^4 + 272.1p^3 + 276.8p^2 + 75.72p + 4.982}{7.402p^6 + 125.6p^5 + 432.6p^4 + 518.1p^3 + 200.5p^2 + 25.8p + 1} \quad (5)$$

3. FRACTIONAL-ORDER CONTROL FOR UNCERTAIN DC MOTOR DYNAMICS

3.1. Design of Fractional-Order Local Controllers

The first step consists of identifying the desired robustness specifications by selecting the phase margin φ and the desired crossover frequency ω_c , with the robustness bandwidth $[\omega_A, \omega_B]$ selected around $\omega_c \in [\omega_A, \omega_B]$, with $\omega_B = 10\omega_A$.

The second step consists in analyzing the frequency response of the nominal plant $G(s)$ by computing its Bode plot and examining its behavior around the desired crossover frequency ω_c . The next step is to find the fractional-order ν , which is selected to guarantee the desired first overshoot D_1 . This order is obtained from the following relation Eq. (6):

$$D_1 = a v^2 + b v + c \quad (6)$$

With

$$\begin{cases} a = 79.195 \\ b = -138.507 \\ c = 59.528 \end{cases}$$

The controller is then obtained in Eq. (7):

$$C(s) = C_0 \left(\frac{1 + \frac{s}{\omega_h}}{1 + \frac{s}{\omega_l}} \right)^v \quad (7)$$

With $\omega_l = \frac{\omega_A}{10}$ and $\omega_h = 10\omega_B$

where ω_l and ω_h denote the low- and high-frequency corner values, respectively, C_0 is the controller gain at crossover frequency ω_c and v is the fractional-order satisfying $0 < v < 1$.

Then, the operator s^v is approximated

using the Oustaloup method, which replaces the non-integer power by a rational transfer function composed of a finite number of real poles and zeros. The method defines an approximation band $[\omega_l, \omega_h]$ and distributes N poles and zeros logarithmically. The approximation has the form presented in Eq. (8):

$$s^v \approx C_0 \prod_{i=-N}^N \frac{s + \omega_{z,i}}{s + \omega_{p,i}} \quad (8)$$

where $\omega_{z,i}$ and $\omega_{p,i}$ are respectively the Oustaloup zero and pole frequencies, (Abdelkrim, 2026) .

3.1.1 Design of a Fractional-Order Controller for the No-load Process

To enhance the performance of the DC motor operating under no-load conditions (Eq. 1), a fractional-order controller Eq. (9) is designed. The approximate controller is obtained using the Oustaloup approximation Eq. (10). In fact, the desired gain-crossover frequency is set to $\omega_u=200$ rad/s, and the overshoot is 7%.

$$K_{frac}(p) = 202.8 \left(\frac{1}{p} \right)^{0.19} \quad (9)$$

The transfer function of no-load process is in Eq. (10).

$$K_{frac_approx}(p) = \frac{6.509e^{-8}p^4 + 0.0002492p^3 + 0.1433p^2 + 13.91p + 202.8}{1.217e^{-9}p^4 + 3.339e^{-6}p^3 + 0.001376p^2 + 0.0957p + 1} \quad (10)$$

The step response obtained with the fractional-order controller, shown in Figure 2, shows an improvement in the system behavior and ensures stability.

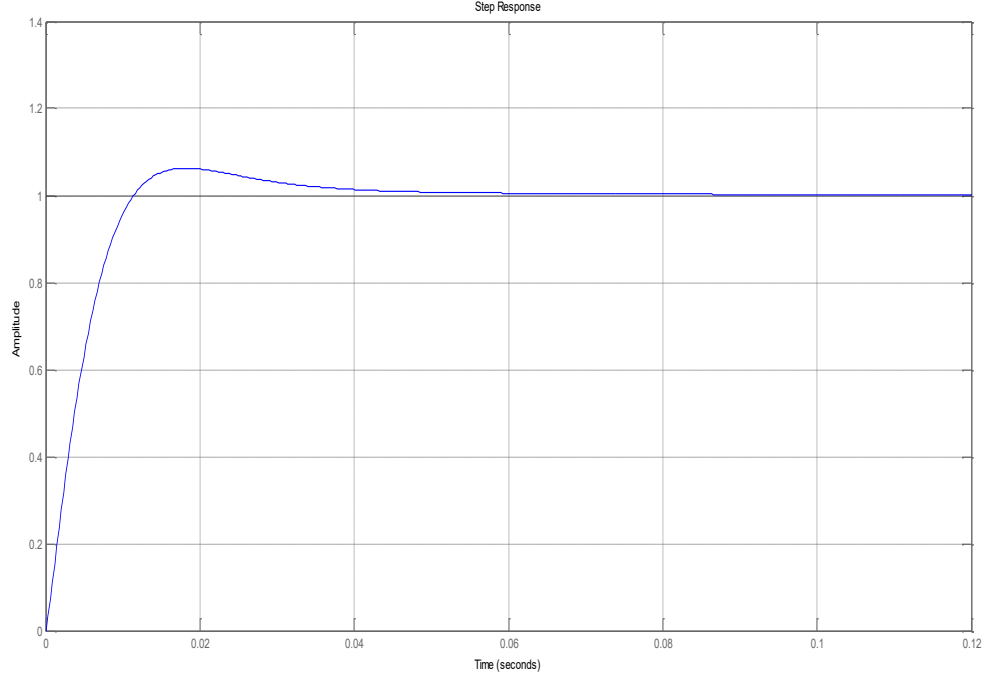


Figure 2. Step response of the no-load DC motor using the fractional-order controller

3.1.2 Design of a Fractional-Order Controller for the Half-Loaded Process

For the half-load operating regime of the DC motor Eq. (2), a fractional-order controller Eq. (11) and its approximation in Eq.(12) is adopted to improve the system response and ensure system regulation.

$$K_{frac_h}(p) = 261.5 \left(\frac{1}{p} \right)^{0.19} \quad (11)$$

$$K_{frac_h_approx}(p) = \frac{1.343e^{-6}p^4 + 0.002571p^3 + 0.7395p^2 + 35.88p + 261.5}{1.947e^{-8}p^4 + 2.671e^{-5}p^3 + 0.005506p^2 + 0.1914p + 1} \quad (12)$$

The fractional-order controller satisfies the prescribed performance and the system stability shown in Figure 3.

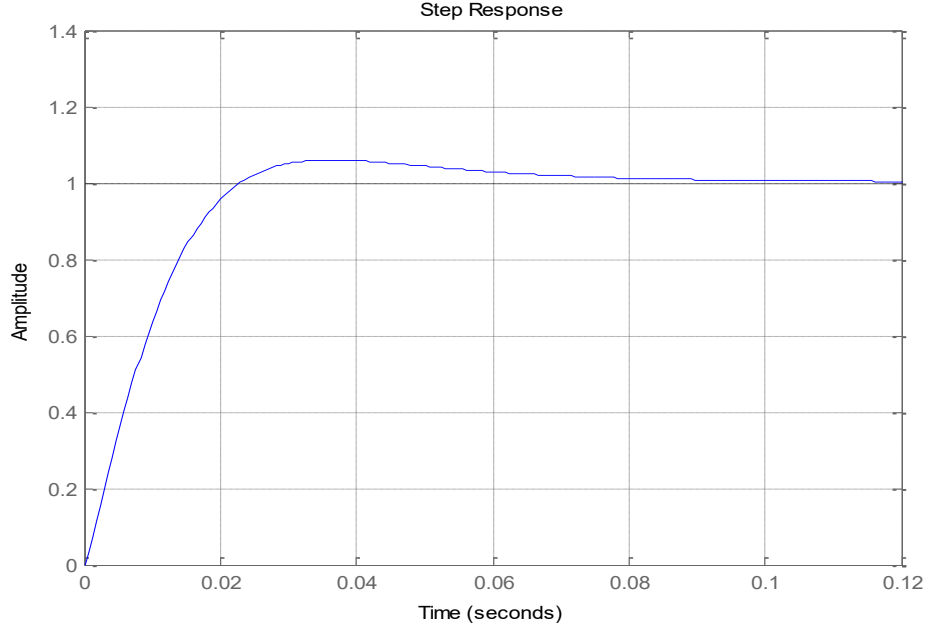


Figure 3. Step response of the half-load DC motor using the fractional-order controller

3.1.3 Design of a Fractional-Order Controller for the Full-Loaded Process

Under full-load operating conditions, a fractional-order controller in Eq. (13) and (14) is employed to improve the dynamic of the DC motor in Eq. (3) and ensure stability, as shown in Figure 4.

$$K_{frac_f}(p) = 200.2720 \left(\frac{1}{p} \right)^{0.19} \quad (13)$$

$$K_{frac_f_approx}(p) = \frac{1.646e^{-5}p^4 + 0.01575p^3 + 2.265p^2 + 54.94p + 200.3}{3.115e^{-7}p^4 + 0.0002137p^3 + 0.02202p^2 + 0.3828p + 1} \quad (14)$$

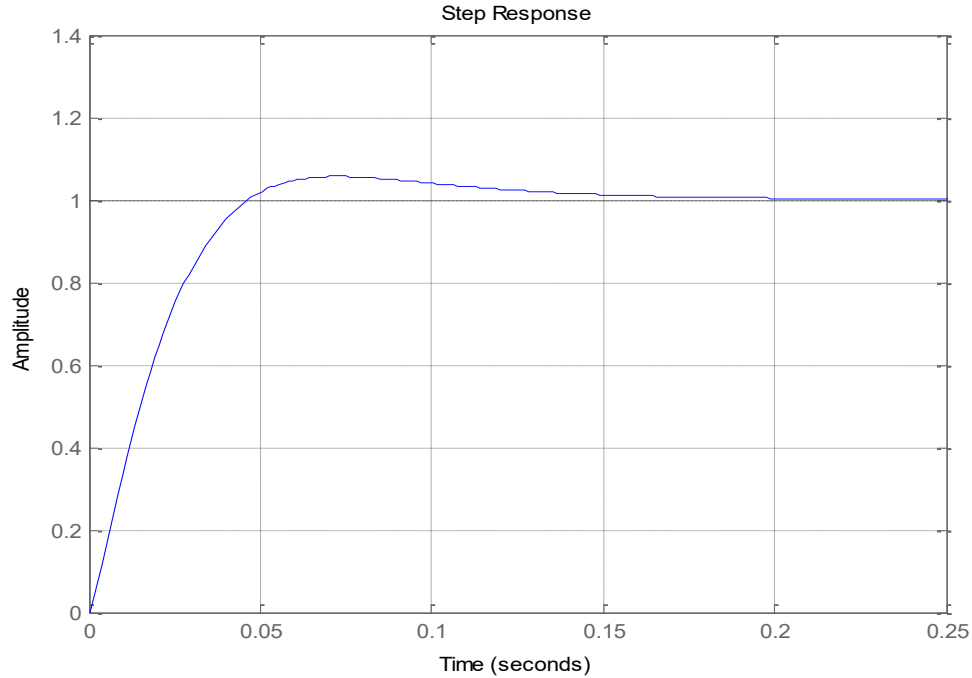


Figure 4. Step response of the full-load DC motor using the fractional-order controller

The evaluation of the closed-loop responses in Figures 2-4 demonstrates that the static error converges to zero, indicating that the proposed control architecture ensures high precision and accurate reference tracking, for each model.

3.2. Synthesis of a Fractional-Order Global Controller Based on the Multimodel System

The multimodel representation of the DC motor is constructed from three local linear models the no-load, half-load, and full-load operating conditions, in Figure 5.

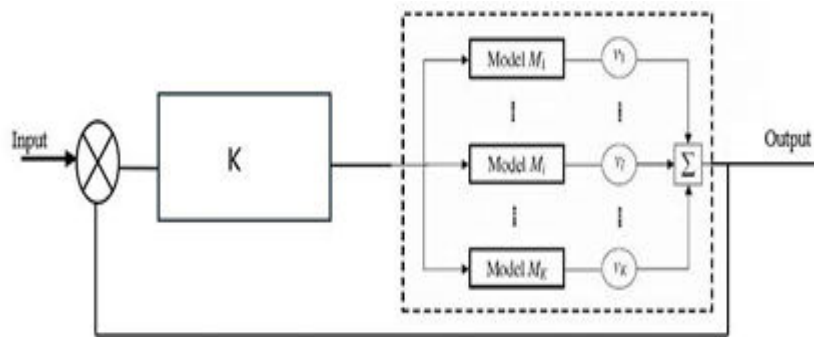


Figure 5. Architecture 1- Global Fractional Controller from Multimodel Representation

The fractional-order controller in Eq. (15) is designed to guarantee global closed-loop stability, as shown in Figure 6. An approximation of controller in Eq. (15) using Oustaloup approximation, is done and expressed in Eq. (16).

$$K_{frac_global}(p) = 189.3237 \left(\frac{1}{p}\right)^{0.19} \quad (15)$$

$$K_{frac_global_approx}(p) = \frac{4.05e^{-6}p^4 + 0.005426p^3 + 1.092p^2 + 37.1p + 189.3}{8.11e^{-8}p^4 + 7.787e^{-5}p^3 + 0.01124p^2 + 0.2734p + 1} \quad (16)$$

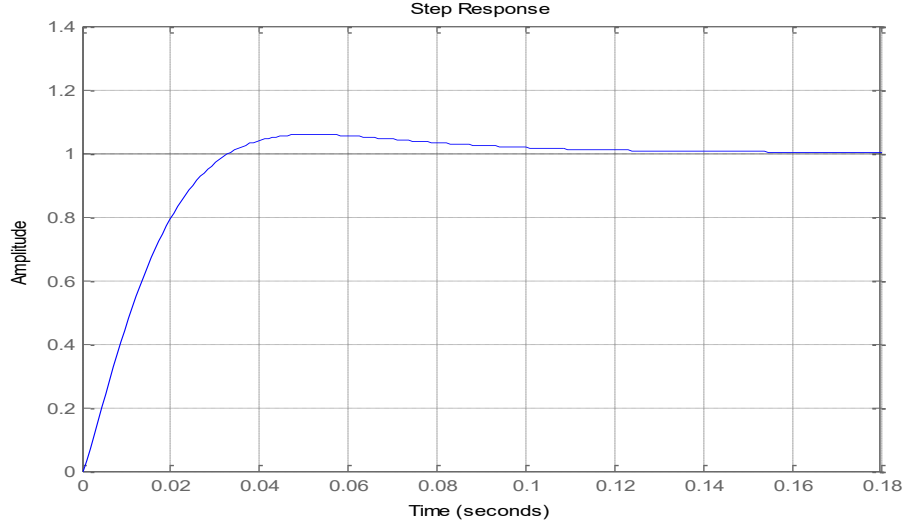


Figure 6. Step response of the multimodel DC motor controlled by the global fractional-order controller

As shown (6), the global controller achieves precise and reliable reference tracking across all models of the multimodel structure.

3.3. Design of a Fractional-Order Decentralized Local Controller for Multimodel Systems

In the architecture shown in Figure 7, a fractional-order decentralized local controller is adopted.

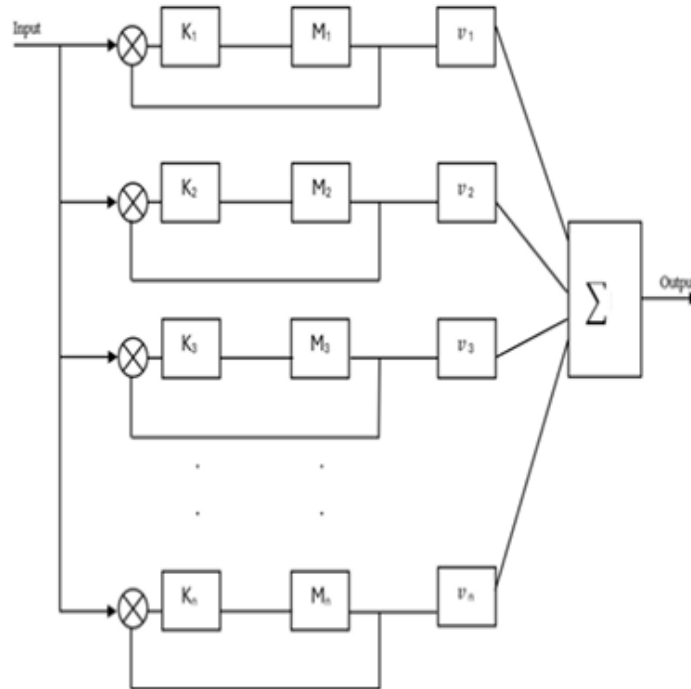


Figure 7. Architecture 2 - Fractional-Order Decentralized Local Controller for Multimodel Systems

As shown in Figures 8 and 9, the step response is stable and the corresponding control signal obtained using this architecture provide good performance.

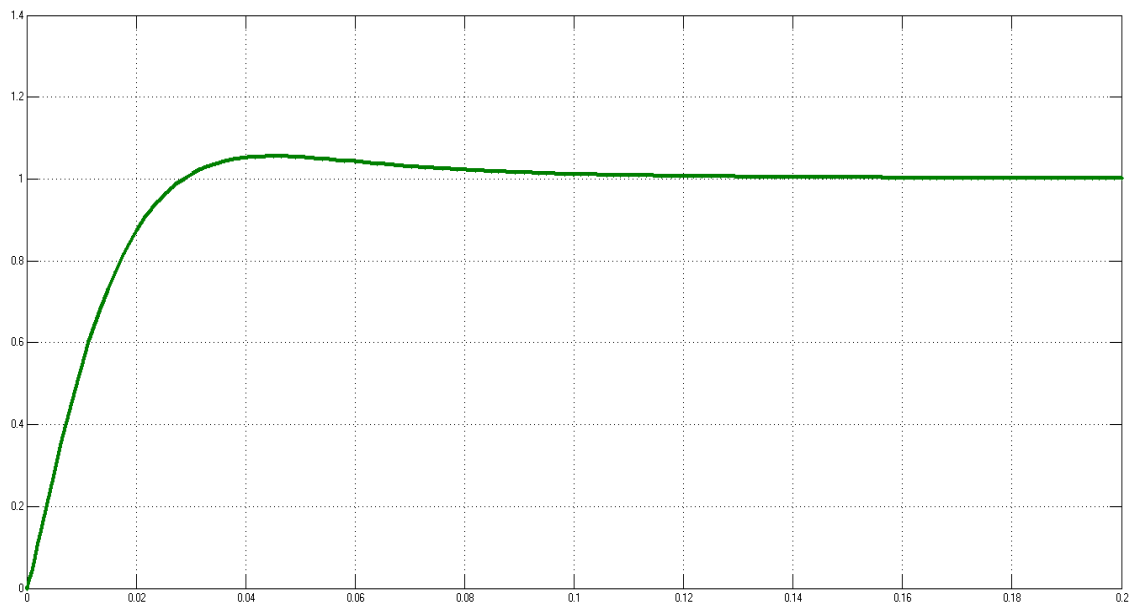


Figure 8. Step Response of the Fractional-Order Decentralized Controller

In addition, as shown in Figure 8 the **static error converges to zero**, confirming that the decentralized controller ensures **high-accuracy reference tracking** and eliminates any permanent deviation between the desired and actual outputs.

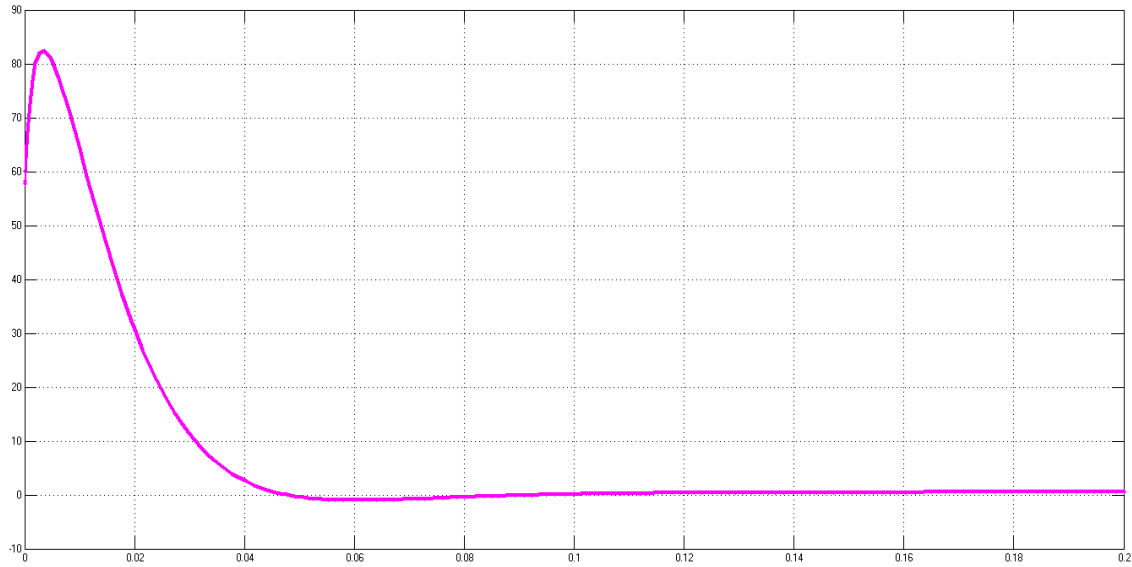


Figure 9. Fractional-Order Decentralized Control Signal

4. ROBUST FRACTIONAL-ORDER CONTROL FOR UNCERTAIN DC MOTOR DYNAMICS

In this section, several classes of perturbations are introduced as shown in Figure 10, including loss of control effectiveness, output friction, and uncertainty on the static gain. The global controllers synthesized within Architectures 1 and 2 are applied to the perturbed multimodel system. For each disturbance type, the resulting closed-loop output and the corresponding control signal are plotted and examined to assess the robustness of the proposed control strategies.

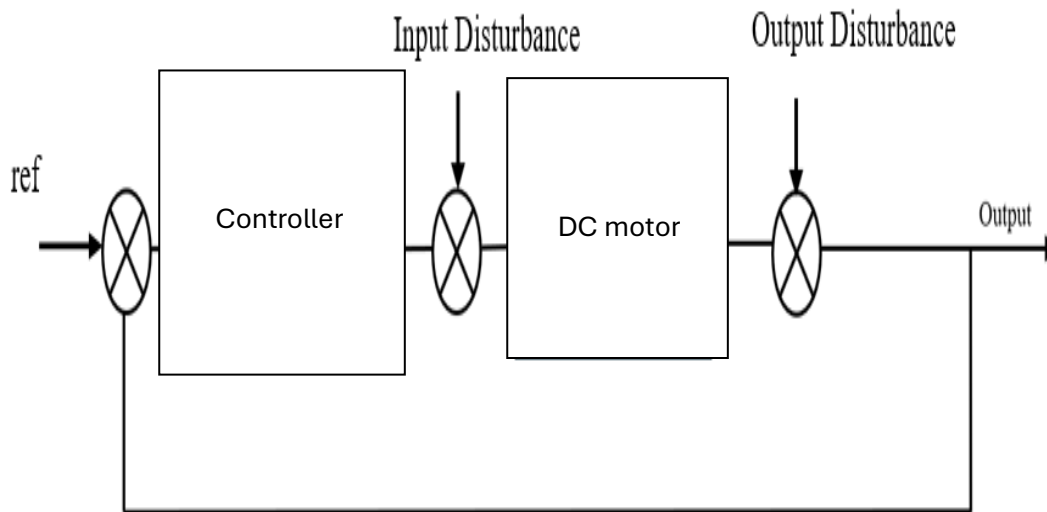


Figure 10. Control System Architecture in the Presence of Disturbances

4.1. ROBUST FRACTIONAL-ORDER CONTROL DESIGNED FROM THE MULTIMODEL

4.1.1 Analysis of Global Controller Performance under Control-Effectiveness Loss

This section presents the performance of the global controller in presence of disturbances.

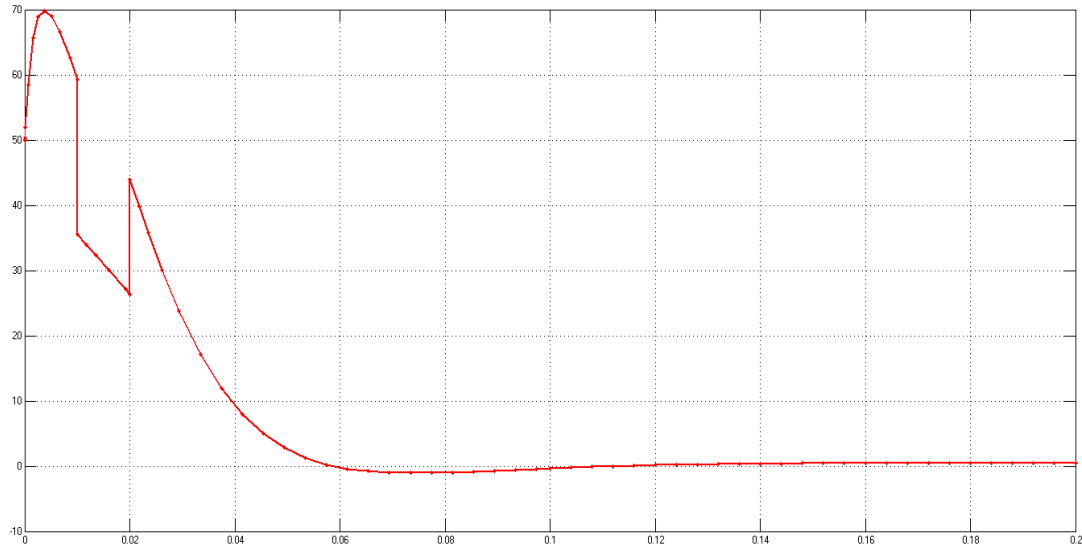


Figure 11. Control Signal Under a -20% Loss of Effectiveness (0.01–0.02s)

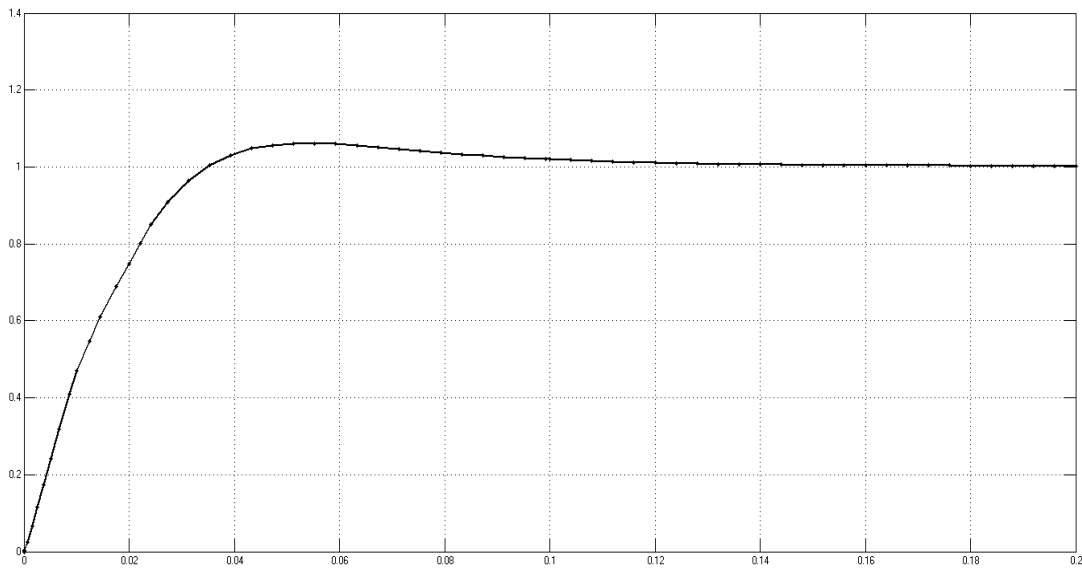


Figure 12. Step response Under a -20% Loss of Effectiveness

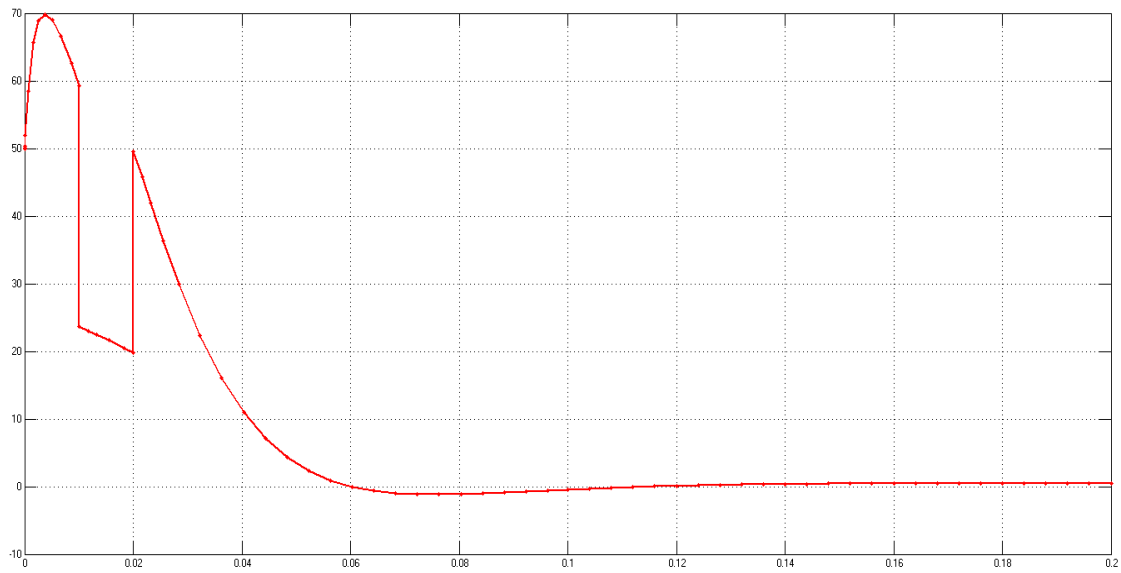


Figure 13. Control Signal Under a -60% Loss of Effectiveness (0.01–0.02s)

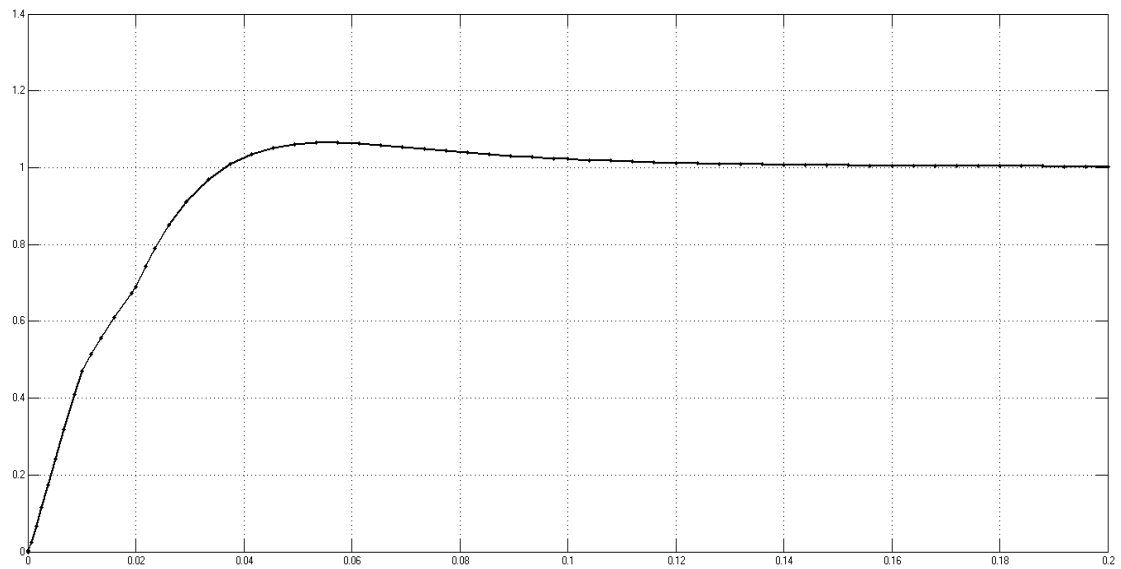
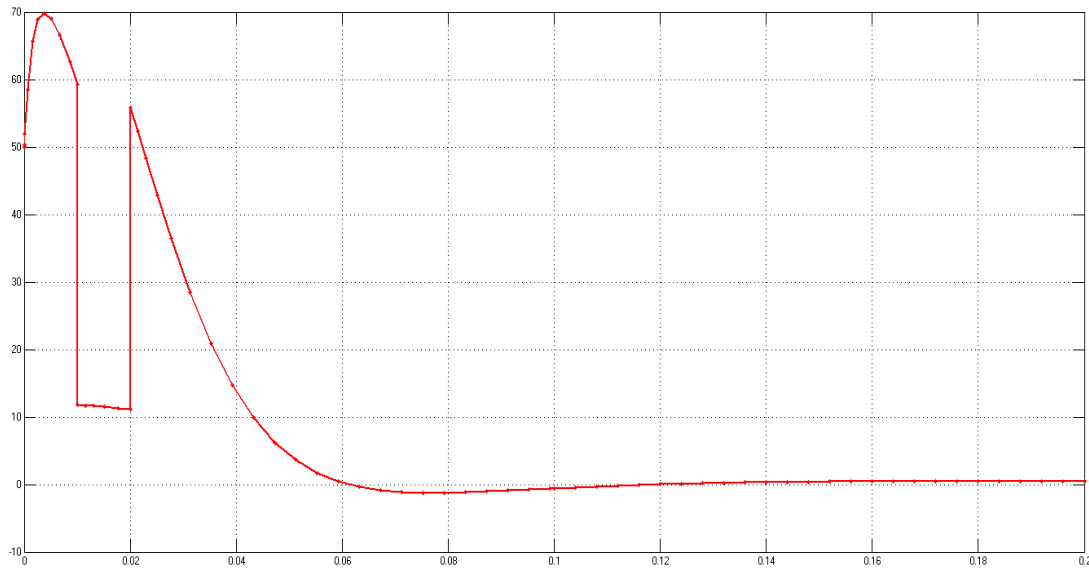
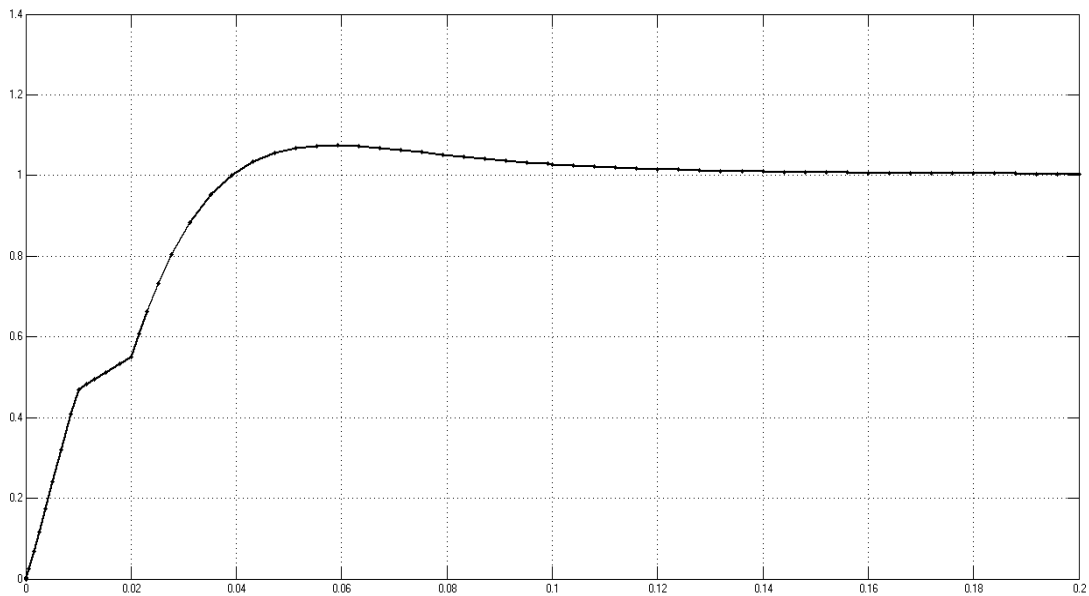


Figure 14. Step response Under a -60% Loss of Effectiveness

Figure 15. Control Signal Under a -80% Loss of Effectiveness (0.01–0.02s)Figure 16. Step response Under a -80% Loss of Effectiveness

As shown in Figures 11-16, even when the loss of control effectiveness is varied from -20% to -80% , the closed-loop system maintains a stable response with an overshoot of 6%. As shown in Figures 12, 14 and 16, even when the loss of control effectiveness is varied from -20% to -80% , the **dynamic tracking error remains negligible**, as the system rapidly compensates for the variations in actuator effectiveness and returns to the reference trajectory within a short time. This behavior confirms that the proposed control architecture ensures **high precision and robust reference tracking** despite severe degradation in control authority.

4.1.2 Analysis of Global Controller Performance under Output-Friction Disturbances

An output-friction perturbation is introduced to show the robustness of the global controller. The friction level is varied from -5% to -20% . As illustrated in the corresponding figures 17-19, the closed-loop response remains stable. Furthermore, the **dynamic tracking error rapidly converges to zero**, indicating that the controller effectively compensates for friction variations and preserves **high-precision reference tracking** throughout the transient phase.

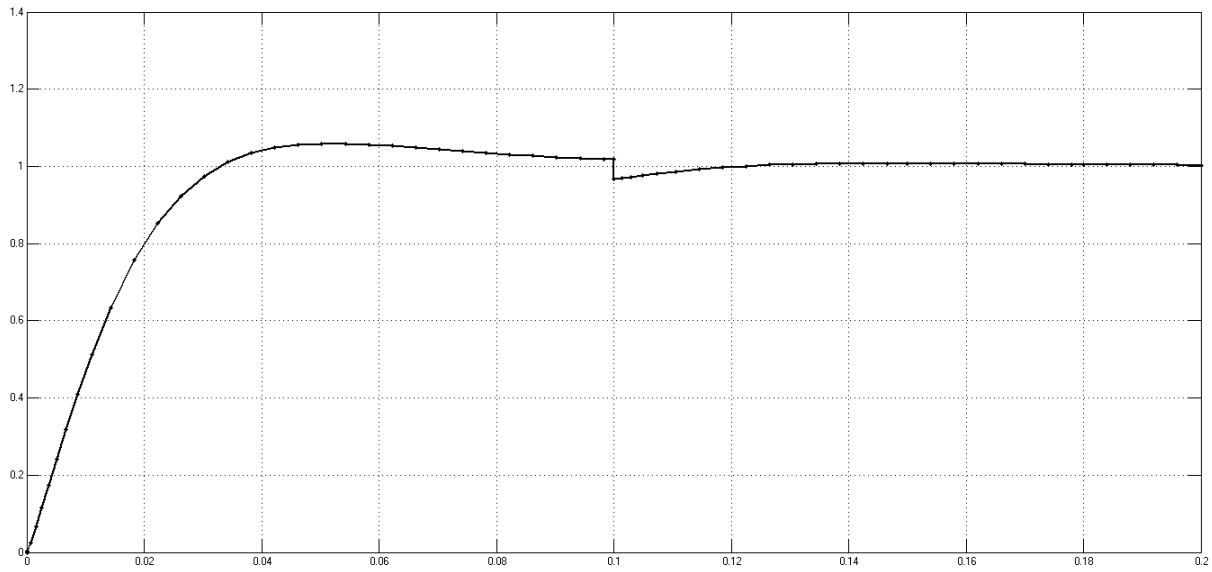


Figure 17. Step response of the system with friction level varied to -5% at $t=0.1$ s

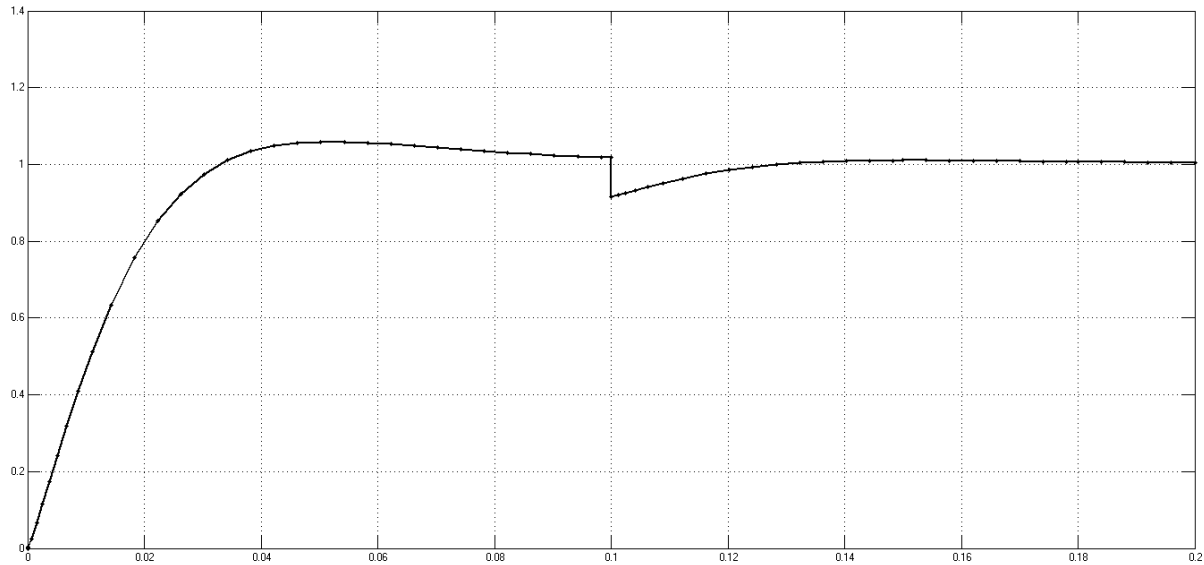


Figure 18. Step response of the system with friction level varied to -10% at $t=0.1$ s

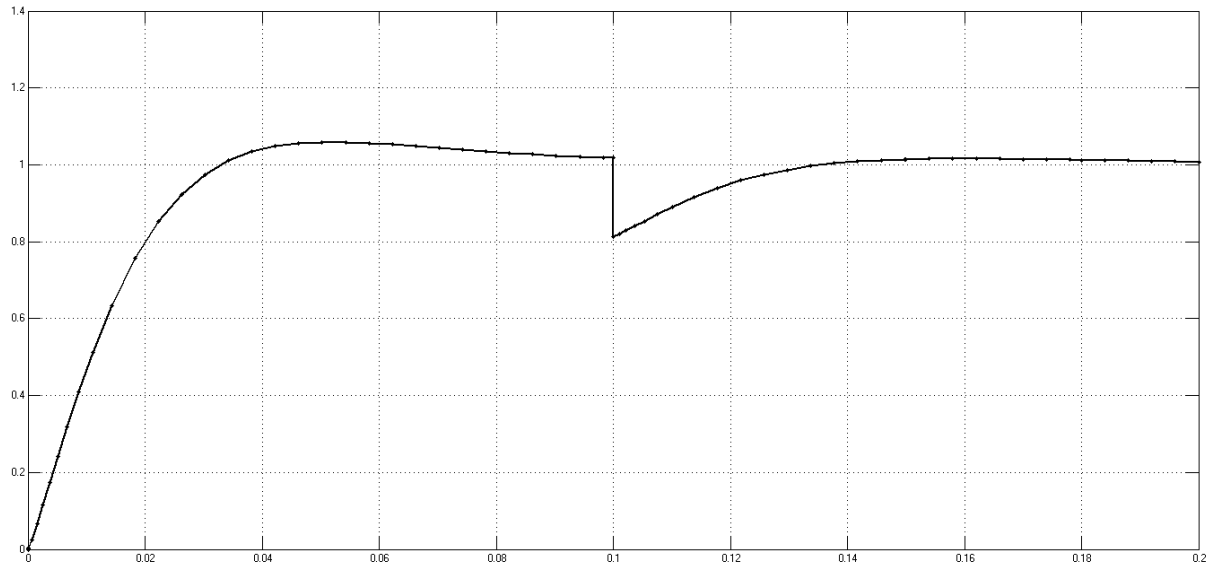


Figure 19. Step response of the system with friction level varied to -20% at $t=0.1$ s

4.1.3 Evaluation of Global Controller Performance under Static-Gain Variations

In this section, the gain is varied, from one-quarter to four times its nominal value. The resulting outputs and control signals demonstrate that the global controller provides stability.

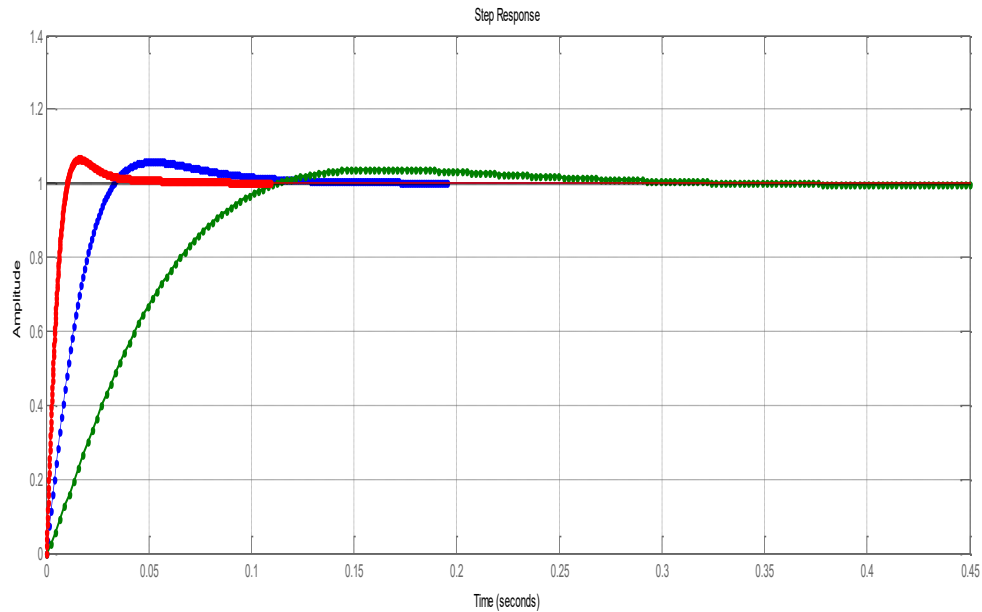


Figure 20. Step response illustrating the effect of static-gain uncertainty in the multimodel system

The blue response represents the fused model operating with its nominal static gain ($K = K$), while the red and green responses correspond to significant gain uncertainties, with $K = 4K$ and $K = K/4$, respectively. **All responses converge to the desired reference and the static error is effectively zero, demonstrating** that the global controller preserves stable dynamics and ensures accurate tracking performance across the entire range of gain perturbations.

4.2 ROBUST FRACTIONAL-ORDER CONTROL DESIGNED WITH THE LOCAL CONTROLLERS

The same analysis done in the previous section, is now performed for the **decentralized architecture** in order to evaluate the effectiveness of the fractional-order controllers.

4.2.1 Robustness Evaluation of the Decentralized Architecture under Control-Effectiveness Loss

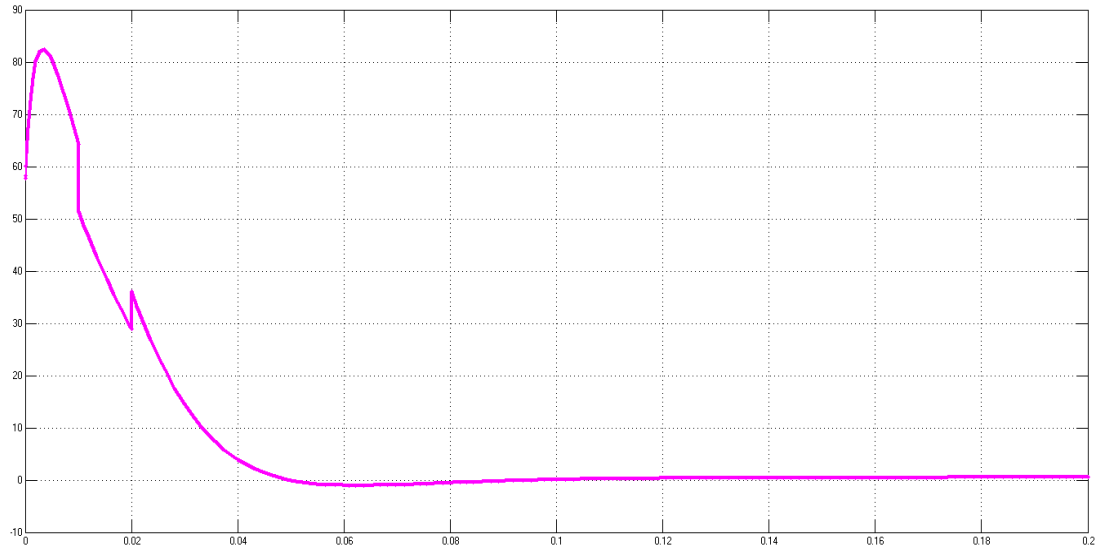


Figure 21. Control Signal Under a -20% Loss of Effectiveness (0.01–0.02s)

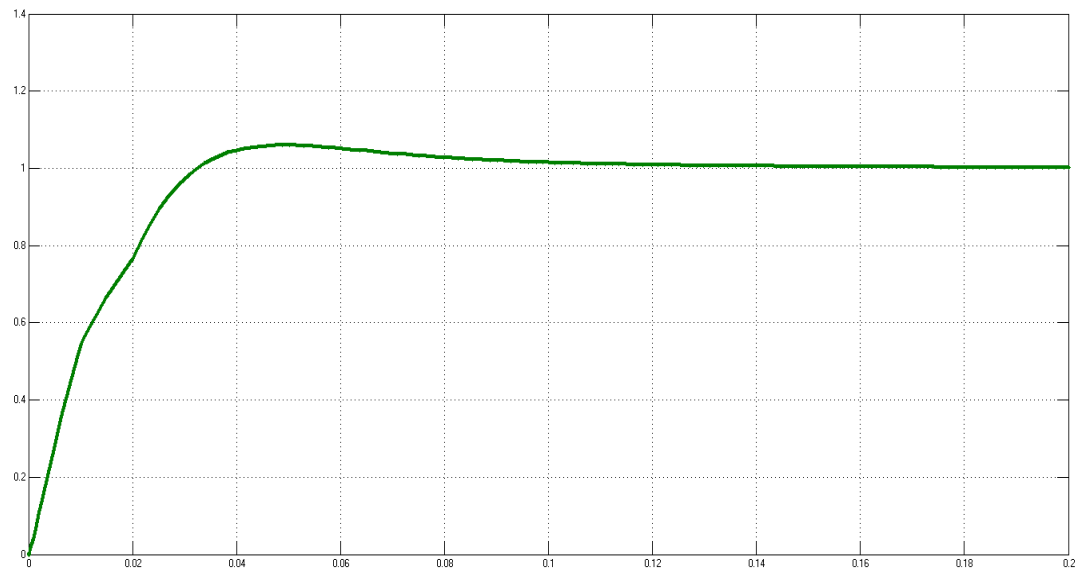


Figure 22. Step response Under a -10% Loss of Effectiveness

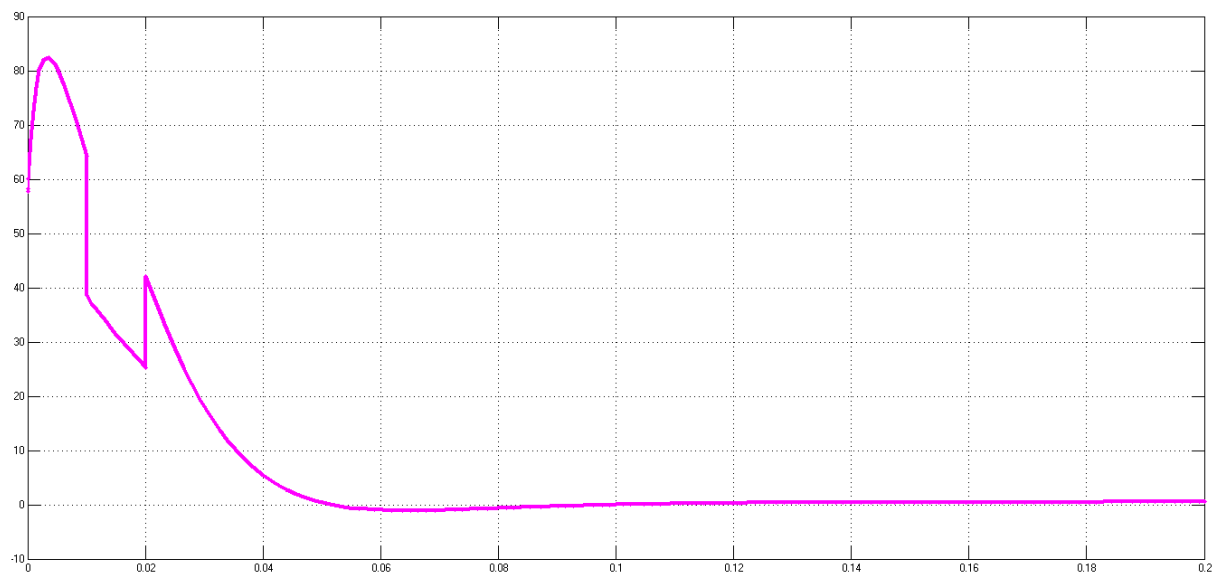


Figure 23. Control Signal Under a -40% Loss of Effectiveness (0.01–0.02s)

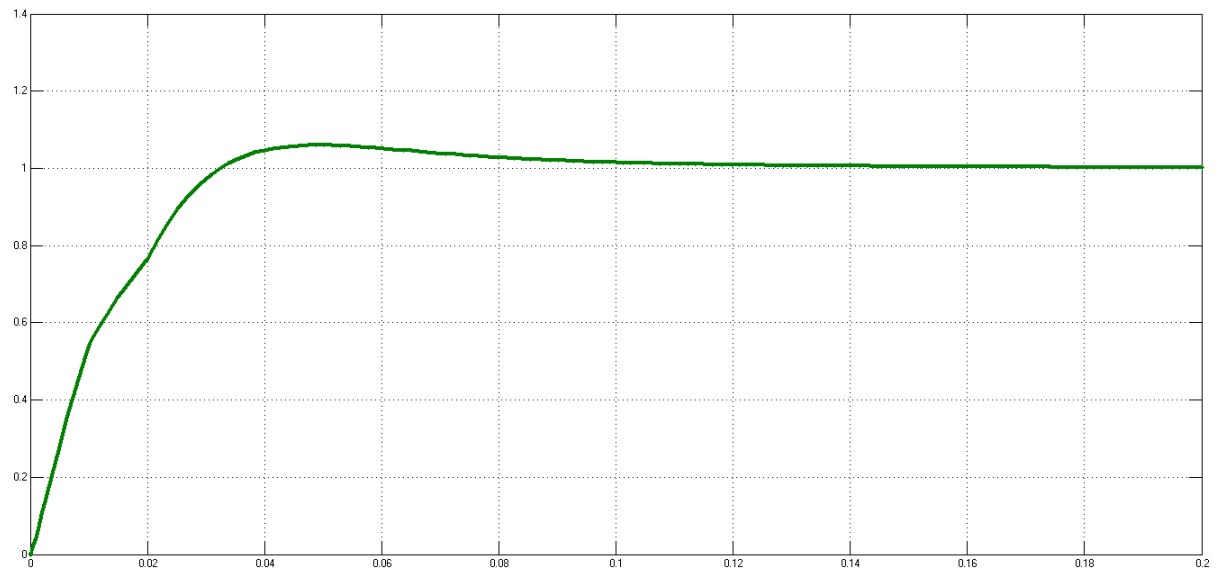


Figure 24. Step response Under a -40% Loss of Effectiveness

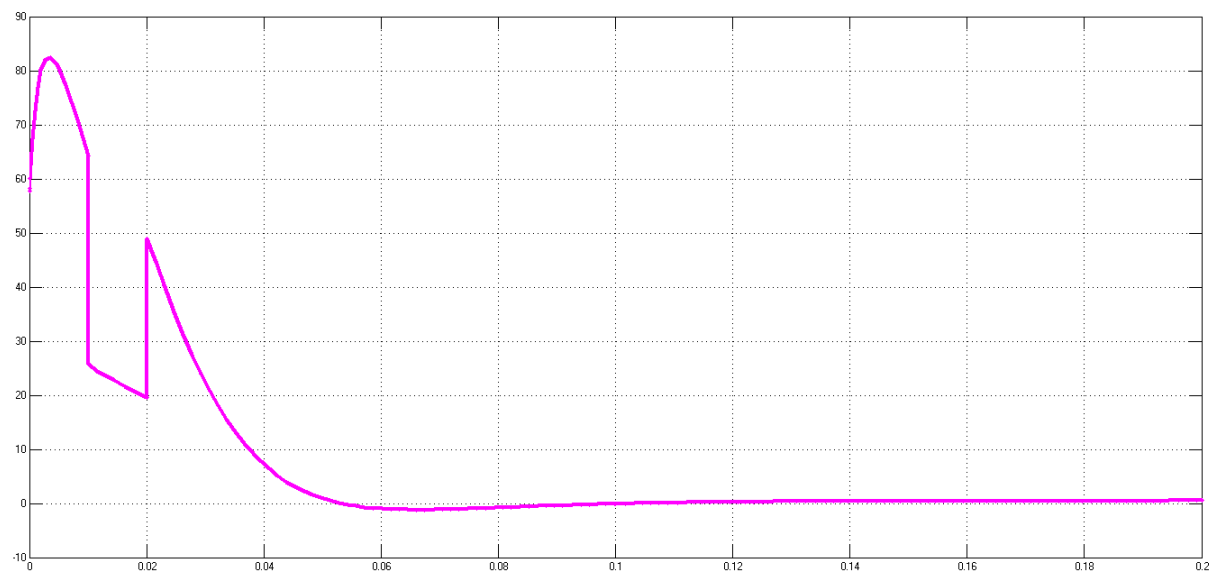


Figure 25. Control Signal Under a -60% Loss of Effectiveness (0.01–0.02s)

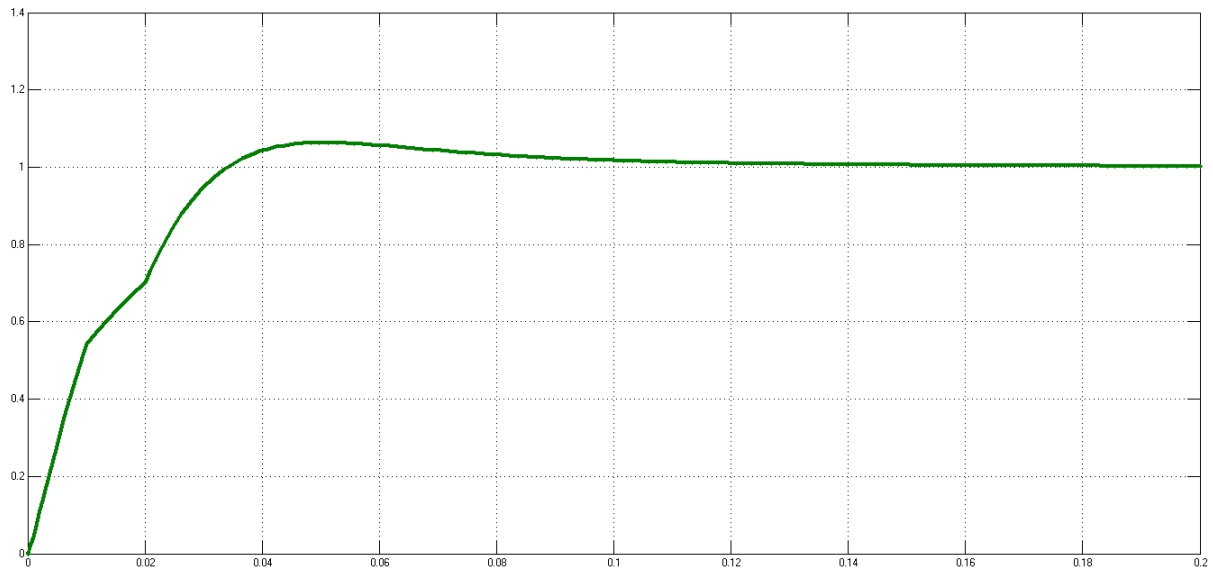


Figure 26. Step response Under a -60% Loss of Effectiveness

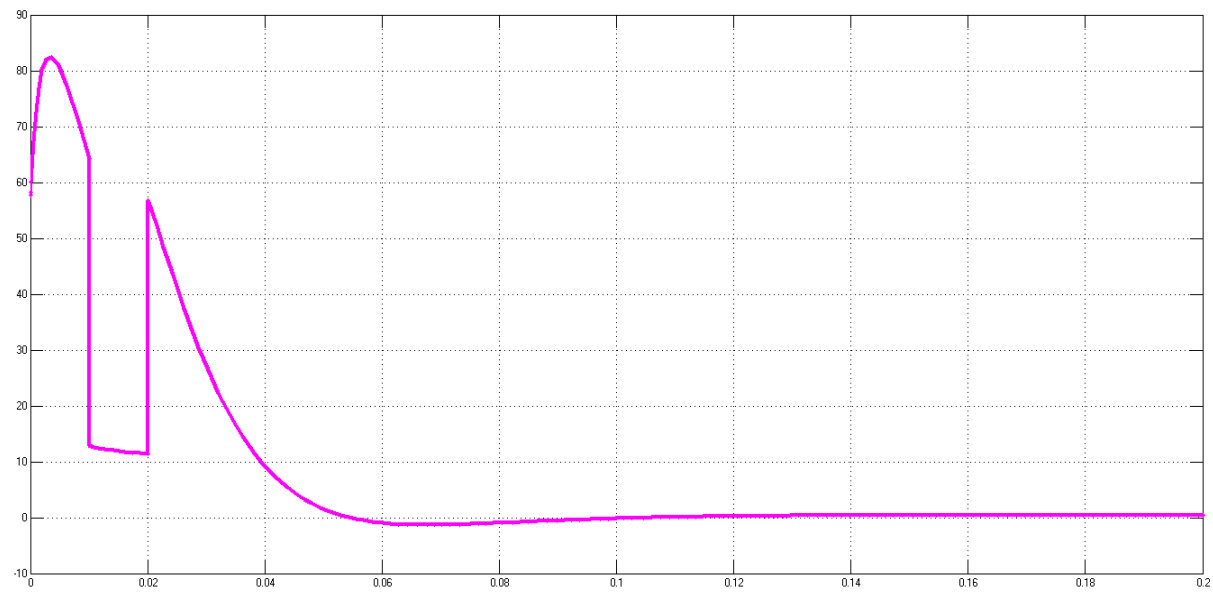


Figure 27. Control Signal Under a -80% Loss of Effectiveness (0.01–0.02s)

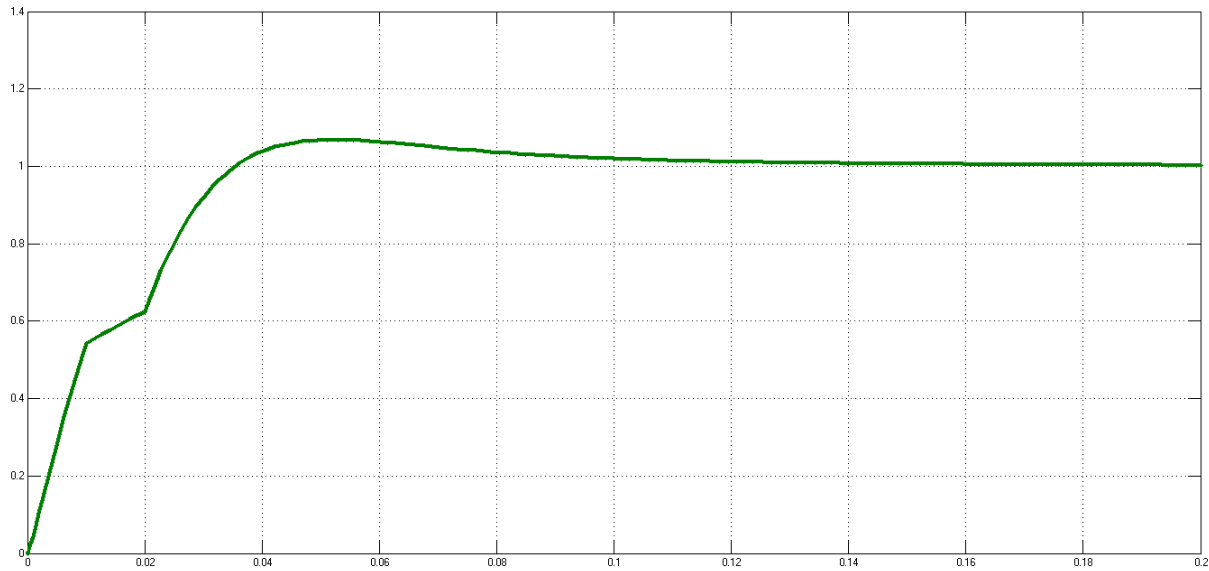


Figure 28. Step response Under a -80% Loss of Effectiveness

The results presented in Figures 21 - 28 show that the decentralized architecture gives a good step response across all levels of effectiveness loss. in fact **the decentralized fractional-order controllers** compensate for the applied perturbations and ensure robust closed-loop performance.

For the decentralized architecture, the responses in Figures 22, 24, 26 and 28 show that **the dynamic error is fully absorbed**, indicating that each local controller successfully compensates for transient deviations and preserves accurate tracking performance.

4.2.2 Robustness Assessment of the Decentralized Architecture under Output-Friction Perturbation

For the decentralized architecture, an output-friction perturbation is applied to evaluate the robustness of the fractional-order local controllers. The disturbance is introduced at $t=0.1$ s, where the friction level is successively increased to -5% , -10% , and -20% . The resulting closed-loop responses in Figures 29-31 show that the decentralized fractional-order controllers remain stable, **induced error is absorbed within approximately 0.02 s, demonstrating the controllers' ability to rapidly restore accurate tracking**, despite the friction variations.

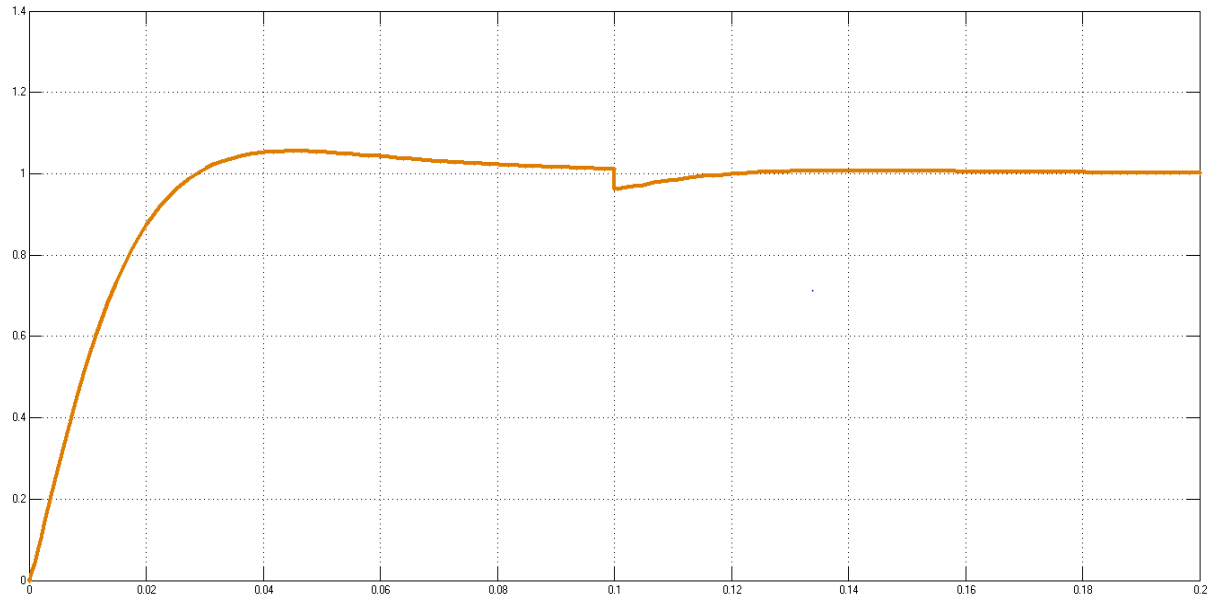


Figure 29. Step response of the system with friction level varied to -5% at $t=0.1$ s

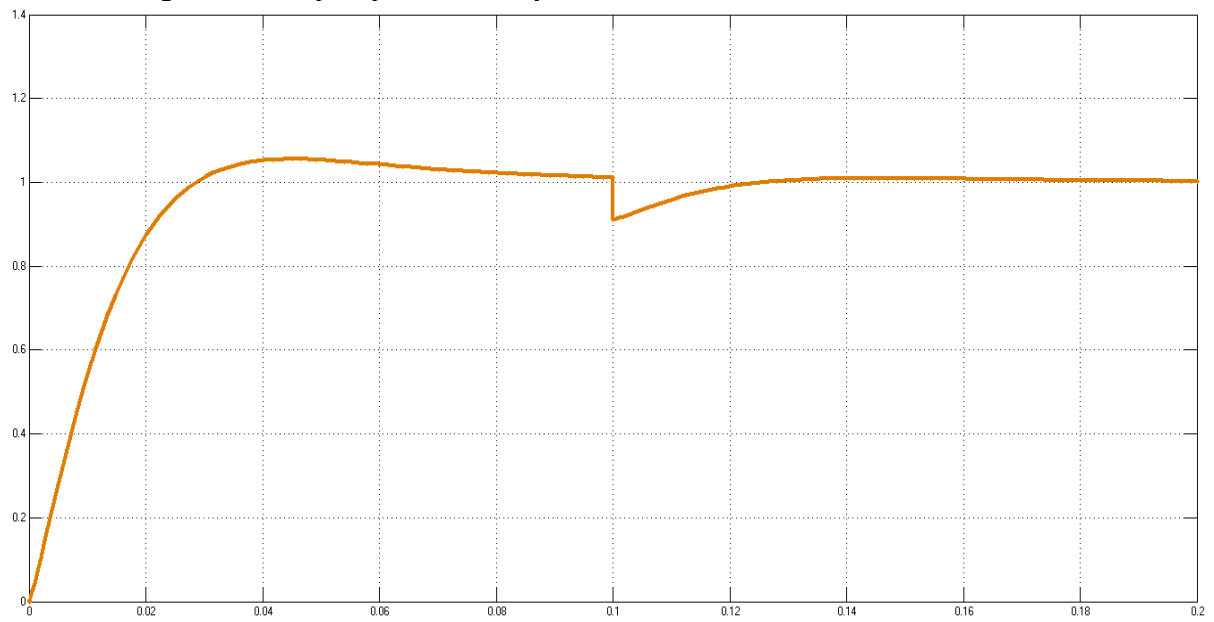


Figure 30. Step response of the system with friction level varied to -10% at $t=0.1$ s

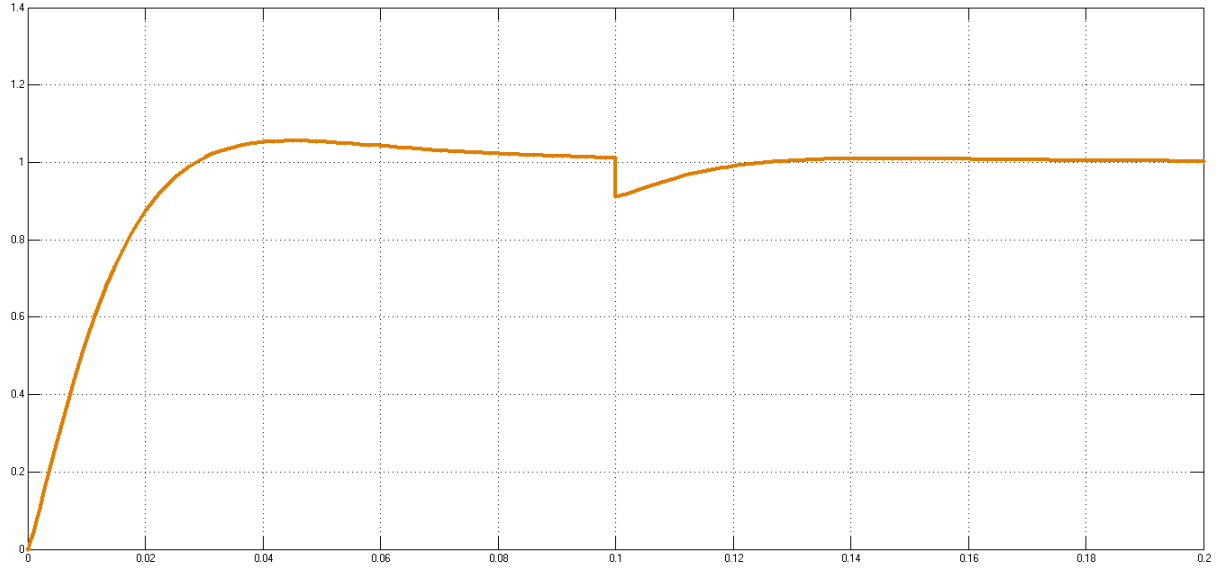


Figure 31. Step response of the system with friction level varied to -20% at $t=0.1$ s

4.2.3 Robustness Evaluation of the Decentralized Architecture under Static-Gain Uncertainty

For the decentralized architecture, an uncertainty on the static gain of the fused model is introduced to assess the robustness of the fractional-order local controllers. The resulting closed-loop responses show, in Figures 32-34, that **the decentralized fractional-order controllers** preserve stability and provide the desired performance.

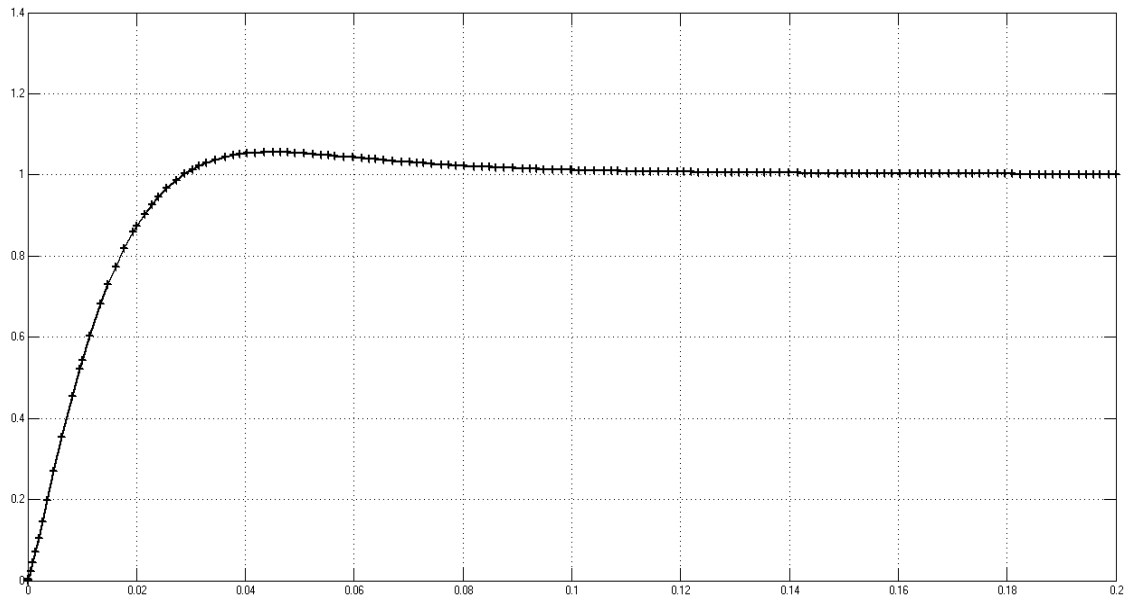


Figure 32. Multimodel Step Response with No Static Gain Variation ($k=k$)

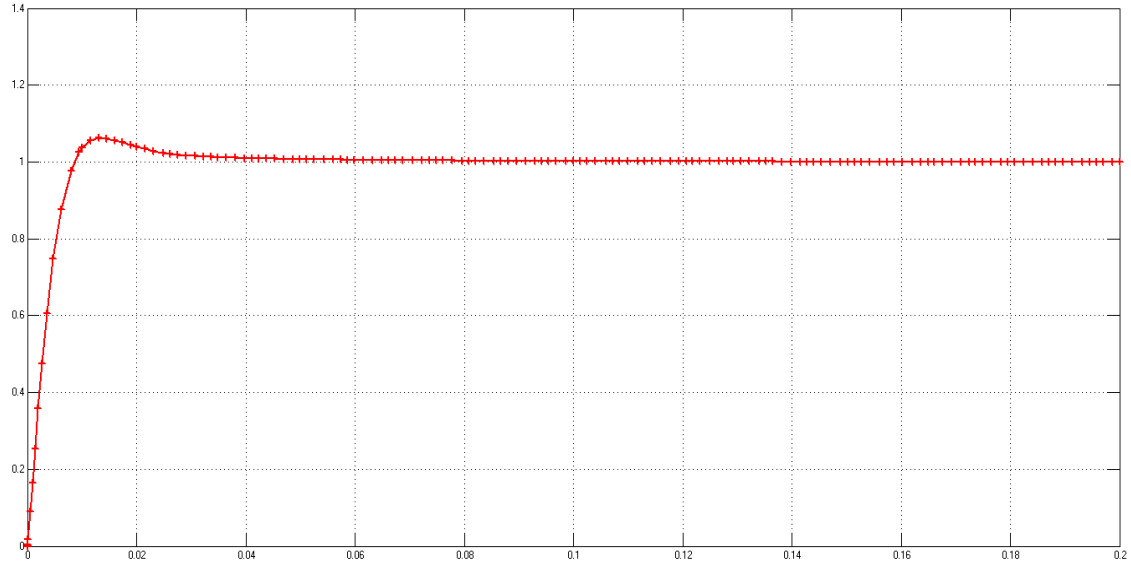


Figure 33. Dynamic Response of the Multimodel Framework with Quadrupled Static Gain ($k=4k$)

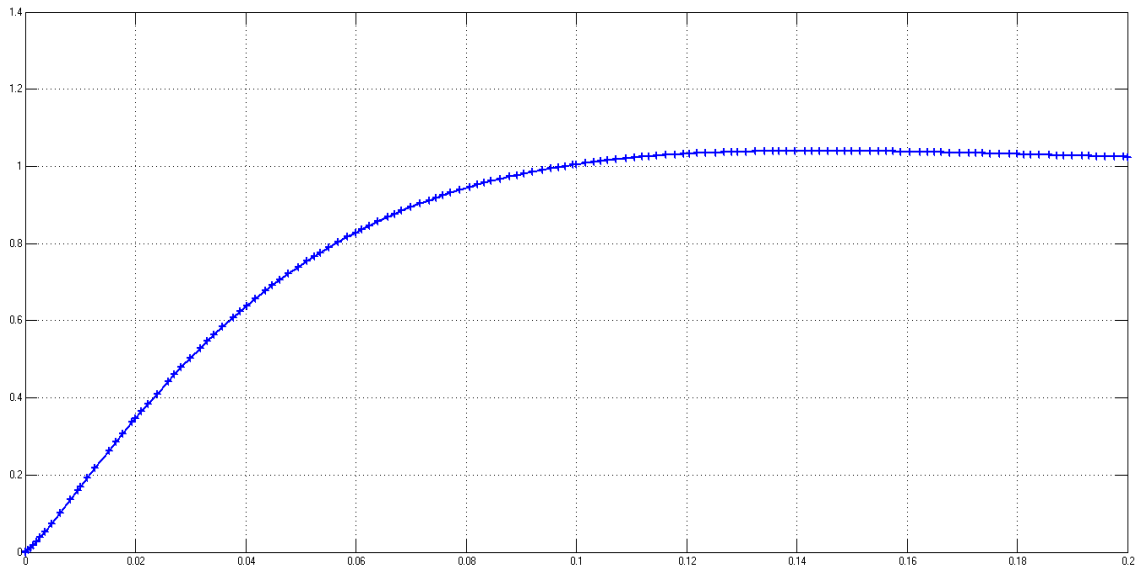


Figure 34. Step Response Characteristics with Static Gain Attenuated to One-Quarter of Its Nominal Value ($k=k/4$)

In all cases, the static error is fully absorbed, as the outputs converge precisely to the reference value despite the gain variations. This confirms that the decentralized controllers maintain accurate tracking even under significant static-gain uncertainty.

4.2.4 Global Robustness Assessment of the Decentralized Architecture under Combined Disturbance Scenarios

For the decentralized architecture, a robustness evaluation is done by introducing several fault types. First, an actuator loss-of-effectiveness fault is applied between $t=0.01$ s and $t=0.02$ s, with a degradation level of -40% . Next, an output-friction perturbation of -10% is introduced at $t=0.1$ s. The resulting closed-loop response in Figure 35 demonstrates that the decentralized fractional-order controllers maintain stability.

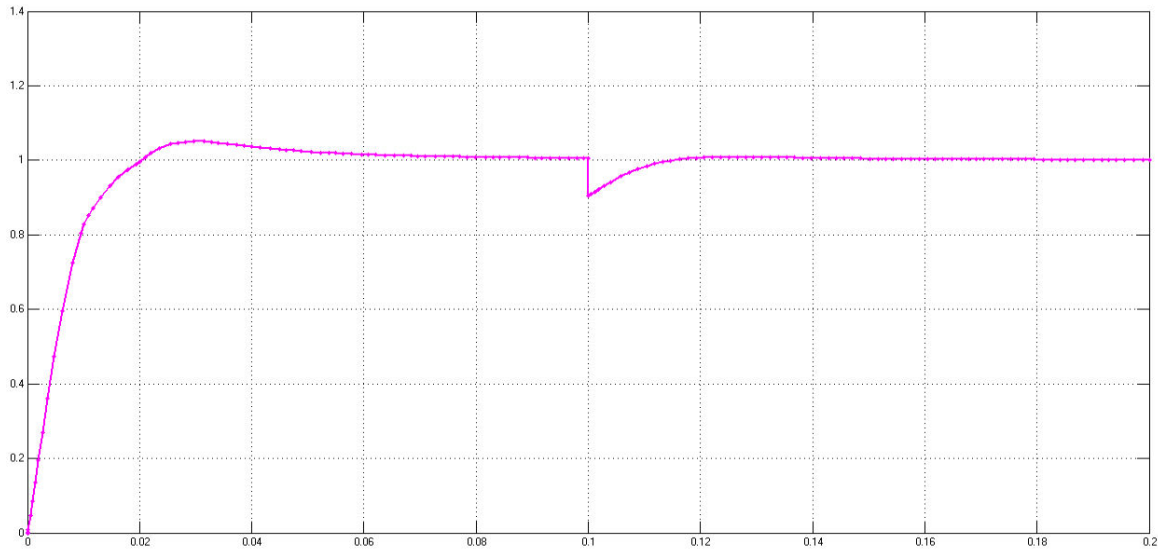


Figure 35. Dynamic Response of the Multimodel under Combined Disturbance Scenarios

In all scenarios, Figure 35 shows that the dynamic error is perfectly absorbed, with the system rapidly compensating for each disturbance. This confirms the strong transient robustness and precise tracking capability of the decentralized fractional-order controllers.

4.2.5 Robustness Analysis of the Decentralized Architecture under Model-Dependent Static-Gain Uncertainty

In the decentralized architecture, an additional robustness evaluation is performed by adding static-gain uncertainties across the different operating conditions. **In the first case**, the static gain is increased to 1.10 for the no-load model, 1.35 for the half-load model, and 1.55 for the full-load model. **In the second case**, the gain is significantly amplified, being doubled for the no-load model, tripled for the half-load model, and quadrupled for the full-load model.

The system remains stable showing the strong resilience of the decentralized control structure to load-dependent static-gain uncertainties in Figures (37) and (38). The static error is fully absorbed, and the outputs converge to the reference, confirming the robustness of the decentralized fractional-order controllers.

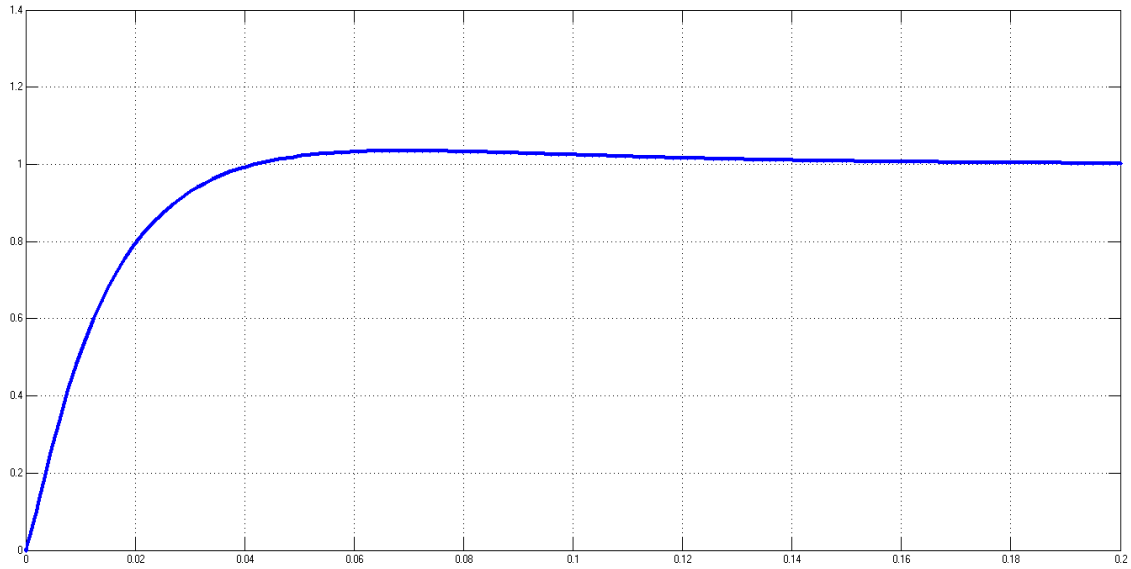


Figure 36. Reference Step Response of the System Under Nominal Gain Conditions

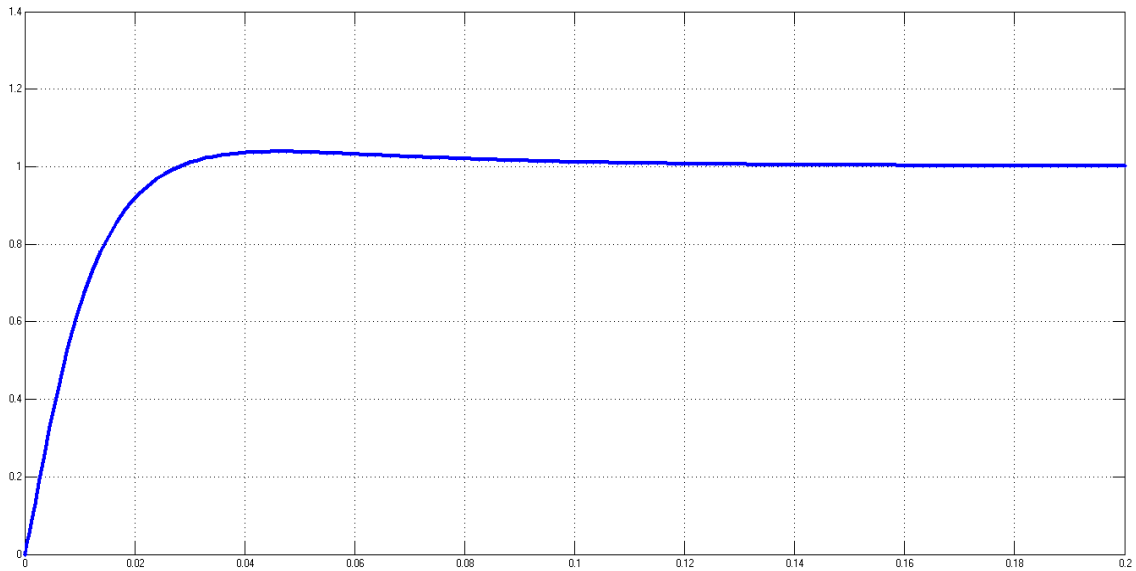


Figure 37. Step Response of the System Under the Gain Conditions of the First Case

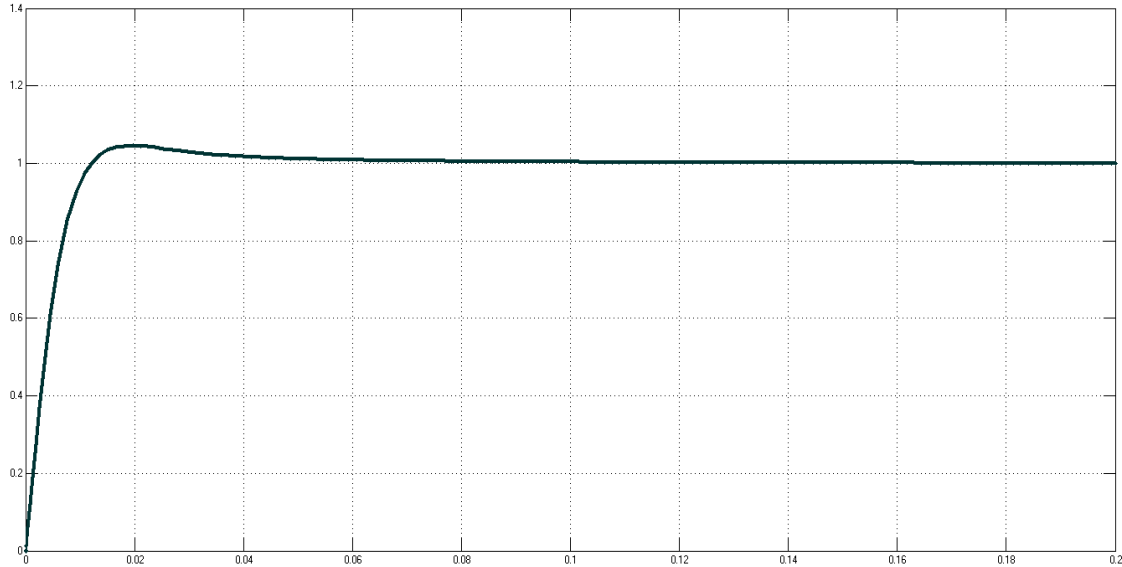


Figure 38. Step Response of the System Under the Gain Conditions of the Second Case

Conclusions

This work presented a robust control strategy for uncertain electromechanical systems by integrating fractional-order control principles within a multimodel framework. The study showed that combining fractional-order controllers with a multimodel representation can offer a stable and efficient solution for systems affected by parameter variations, nonlinear behaviors, and load-dependent disturbances. The obtained results confirm that this structure improves both robustness and tracking performance, even when the system operates under significant uncertainty. Looking forward, several research directions can be explored to enhance the proposed approach. First, machine learning techniques could be used to automatically identify sub models when the system conditions change, instead of relying only on predefined models. Also, reinforcement learning can be introduced in tuning the fractional-order parameters online, which might improve adaptability in real-time applications. Finally, deep learning-based estimators could be integrated to provide more accurate state and disturbance estimation, making the overall control strategy more robust.

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