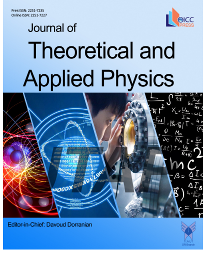

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Optimal fractional-order PID controllers design for plasma current and horizontal position control in IR-T1 tokamak based on particle-swarm optimization

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Original Research

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Abstract:

Tokamak reactors' performance is inherently tied to the precise control of plasma shape, position, and current while staying within the operational constraints, specifically managing the control signals and power supply voltages. Furthermore, many tokamak models exhibit strong coupling between control variables, necessitating the use of Multiple-Input Multiple-Output (MIMO) decoupling controllers. The primary control objectives include achieving high tracking and decoupling performance within these operational constraints, along with a focus on robustness. Fractional Order Proportional-Integral-Derivative (FOPID) controllers offer an advantage due to their additional degrees of freedom, which contribute to improved performance, robustness, and flexibility compared to conventional control methods. In light of these advantages, we have designed Optimal FOPID, and also two Integer Order optimal PID (IOPID), controllers for plasma current and horizontal position control in the IR-T1 tokamak, which were optimized using Particle Swarm Optimization to minimize objective functions. Our results have shown that the Integral of Time-weighted Absolute Error (ITAE) criterion exhibits the best tracking and robustness behavior in this context. Examining an actual experimental discharge in this tokamak as a test case, validate that the OFOPID control scheme is effective at maintaining stability when faced with disturbances and fast variations in the plasma parameters.

Keywords: IR-T1 tokamak; ITAE criterion; Fractional order PID controller; Optimal fractional order PID controller; Particle swarm optimization

1. Introduction

The escalating demand for fusion power as a sustainable energy source has garnered significant attention in recent years. To address this challenge, various approaches have been explored. Among these, the tokamak, a magnetic confinement device designed for plasma confinement, has emerged as a particularly promising technology for realizing the goal of controlled fusion power. Nonetheless, regulating crucial plasma parameters, including temperature, density, and pressure, proves to be an intricate undertaking due to the intricate and nonlinear dynamics inherent in plasma behavior. In industrial settings, Proportional-Integral-Derivative (PID) controllers have been widely employed for process control, largely due to their simplicity and efficacy [1–3]. However, traditional PID controllers exhibit limitations when applied to systems characterized by nonlinearity and time-varying behavior, such as tokamaks. In response to this challenge, fractional order PID (FOPID) controllers have emerged as a compelling alternative [4].

FOPID controllers offer enhanced tunability owing to the inclusion of additional parameters, enabling better alignment with the specific dynamics of the controlled system. Notably, FOPID controllers have demonstrated superior performance in various applications, including the regulation of plasma parameters within tokamaks. Parameters such as plasma current, position, and shape have been the focus of extensive investigation by researchers, to refine the performance and robustness of these controllers. The overarching goal of these control systems is to accurately track predefined trajectories for controlled variables, thereby maintaining the plasma at a desired equilibrium point during the flat-top phase of operation. It is imperative to acknowledge, however, that the practical implementation of these controllers can be fraught with challenges. Consequently, ongoing research endeavors are vital to comprehensively explore the full potential of FOPID controllers and to address the aforementioned obstacles effectively.

Recent years have witnessed a burgeoning interest in the development and deployment of Optimal OFOPID controllers for the precise regulation of plasma parameters within tokamak systems. These controllers are meticulously crafted by leveraging optimization techniques, with the primary aim of outperforming conventional FOPID controllers [5–8]. It is important to note that the choice of optimization criteria can vary depending on the specific application, system complexity, and available resources, leading to the utilization of diverse methodologies to address distinct control problems. Typically, these approaches involve the minimization of a cost function tailored to encapsulate the control objectives. Numerous optimization techniques have been advanced for the creation of OFOPID controllers, including genetic algorithms (GA), particle swarm optimization (PSO), fuzzy logic, and others. These methods have found success in addressing a spectrum of plasma control challenges, spanning the regulation of plasma current, position, shape, safety factor, and pressure [9–19]. This versatility underscores the efficacy of optimization techniques in the design of FOPID controllers for plasma control in tokamaks. Indeed, several notable tokamaks, including HL-2A, HT-7, TCV, and KSTAR, have witnessed the successful implementation of OFOPID controllers [20–23], substantiating their potential to enhance the performance and stability of these advanced fusion devices.

Simultaneously, a range of MATLAB-based tools have been developed to cater to the needs of fractional-order control systems. These tools, including FOMCON [24], CRONE [25, 26], and Ninteger [27, 28], are dedicated to addressing various aspects of fractional-order control systems. They encompass functions for stability analysis, time domain analysis, frequency domain analysis, state-space utilization, and specialized applications. However, it is worth noting that most of these tools have been primarily tailored for Single-Input, Single-Output (SISO) systems, while in practical scenarios, Multi-Input, Multi-Output (MIMO) systems predominate [29]. Consequently, there exists a pressing need for a comprehensive and efficient fractional-order MIMO toolbox to accommodate the evolving demands of practical applications. In this context, the latest iteration of the MATLAB toolbox, FOTF, has emerged as a pivotal resource. This toolbox is equipped to address fractional-order MIMO stability issues, conduct analyses in both the time and frequency domains, and facilitate design processes. Moreover, it seamlessly integrates with Simulink modelling, further bolstering its utility [4, 30]. With these capabilities, FOTF stands as a significant advancement in the field of fractional-order control, empowering engineers and researchers to tackle the intricacies of MIMO systems effectively.

In this paper, we aim to elucidate the design and implementation of OFOPID controllers for the precise regulation of plasma current and horizontal position in the IR-T1 tokamak. Our approach leverages the source codes available within the FOTF toolbox. Additionally, we will offer an in-depth analysis of the particle swarm optimization technique employed in our design, comparing its performance to that of conventional integer order Optimal PID controllers. Ultimately, an experimental discharge has been employed to evaluate the performance of designed controllers for stabilizing tokamak plasma against disruptions and sudden changes under real operating conditions. To culminate, we will provide a comprehensive discussion of our findings and draw relevant conclusions.

2. MIMO control system of plasma current and horizontal position in IR-T1 tokamak

This section delves into the design of a MIMO control system dedicated to the regulation of plasma horizontal position and plasma current, with a specific focus on decoupling. In MIMO control systems, one of the pivotal considerations lies in mitigating the effects of cross-couplings, emphasizing the need to minimize their influence. Our exposition commences with an introduction to the IR-T1 tokamak, followed by the presentation of the MIMO transfer function about this tokamak. We also furnish the transfer functions associated with the power supply for the coils. Subsequently, we outline the unique control requirements and employ MATLAB software to derive a set of finely tuned parameters for two PID controllers. These parameters will serve as the initial values for the subsequent design of Optimal OFOPID controllers for the IR-T1 tokamak, as elucidated in Section 3.

2.1 IR-T1 tokamak

IR-T1 is a compact air-core tokamak characterized by its small scale, absence of a copper shell, and plasma featuring a circular cross-section. Notably, it possesses a major radius $R = 0.45$ m and a minor radius $a = 0.125$ m. The plasma current (I_p) within IR-T1 is maintained at levels below 40 kA, while the toroidal magnetic field (B_t) varies between 0.7 and 0.8 Tesla. The average electron density exhibits a range from approximately $n = 0.30-1.50\times 10^{19}$ particles per cubic meter. The plasma discharge duration (τ_d) lasts for a period of 30 to 35 milliseconds, and the electron temperature (T_e) is elevated to around 200 eV. Detailed characteristics of the IR-T1 tokamak are presented in Table 1, offering a comprehensive overview of its specifications. For visual reference, Figure 1 provides a depiction of the diagnostic equipment and capacitors utilized within this tokamak [31].

2.2 Plasma response MIMO transfer function

The transfer function for plasma response, represented in a classical state-space formulation for both plasma current and horizontal position, is derived through the utilization of a linearized plasma-circuits model [32]. This model is expressed as:

$$\frac{d\mathbf{x}}{dt} = \mathbf{Ax} + \mathbf{Bu} \tag{1}$$

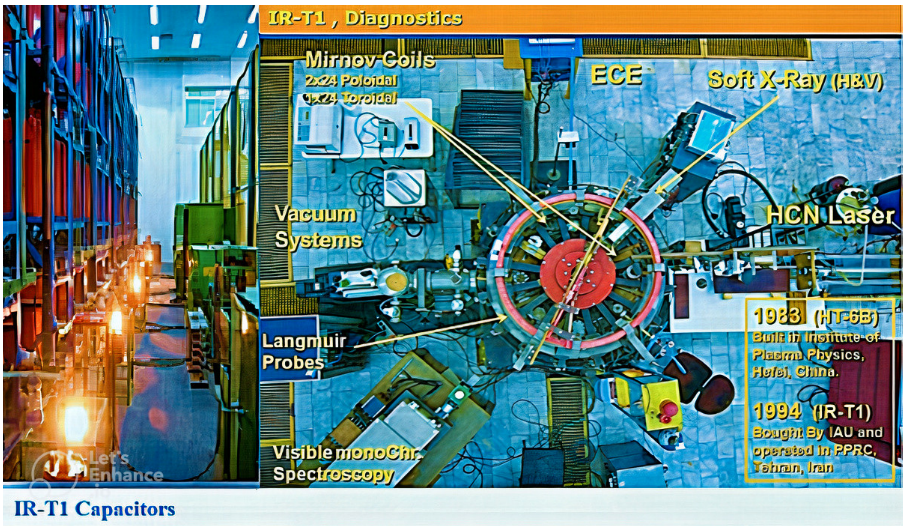

Figure 1. Top view of IR-T1 tokamak diagnostics, right including; Mirnov coils, Soft X-Ray detector, HCN laser, Langmuir probes, Vacuum systems, Visible monochromatic spectroscopy and Electron Cyclotron Emission (ECE) diagnostic; and left: array of capacitors as power supplies.

with $\mathbf{A} = -\mathbf{L}^{*-1}\mathbf{R}$ and $B = \mathbf{L}^{*-1}$. Also, the internal state vector $\mathbf{x} = [\delta\mathbf{I}, \delta\mathbf{I}_p]^T$, and the input vector $\mathbf{u} = [\delta\mathbf{V}, 0]^T$, $\mathbf{I}$ the set of currents flowing in the external (active and passive) conductors, $\mathbf{R}$ the resistance matrix of the circuits, $\mathbf{V}$ the complete set of applied voltages, and the entries of $\mathbf{V}$ for the passive circuits are zero. Furthermore, the quantities $\delta\mathbf{I}$, $\delta\mathbf{I}_p$, and $\delta\mathbf{V}$ represent deviations from nominal (equilibria) values. The matrix $\mathbf{L}^* = \partial(\mathbf{\Psi}, \mathbf{\Psi}_p)^T / \partial(\mathbf{I}, \mathbf{I}_p)^T$ is the modified inductance matrix. A linearized model can also predict linearized output parameter changes $\mathbf{y}$, using the standard output equation:

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \tag{2}$$

where $\mathbf{C}$ and $\mathbf{D}$ are the state-to-output and input-to-output matrices, respectively. Then, the voltage-driven model coil current changes δx_a, is extracted from the above equations as:

$$\delta\dot{x}_a = -\left(R_a + \frac{R_p L^*_{pa}}{L^{*2}_p}\right)\left(L^*_a - \frac{L^*_{ap}L^*_{pa}}{L^*_p}\right)^{-1}\delta x_a + \left(L^*_a - \frac{L^*_{ap}L^*_{pa}}{L^*_p}\right)^{-1}\delta u,$$

$$\begin{pmatrix}\delta h\\ \delta I_p\end{pmatrix} = \begin{pmatrix} C \\ -\frac{L^*_{pa}}{L^*_p}\end{pmatrix}\delta x_a \tag{3}$$

where h is the horizontal displacement of the plasma centroid from the equilibrium. The subscripts a and p indicate active and plasma components, respectively. Comparison of Eq. (3) with Equations (1) and (2), the matrices A, B, C, and D are calculated by considering the characteristic parameters for IR-T1 tokamak (Sec. 2.1) and the tokamak-circuits method presented in Ref. [33].

The transfer functions for the power supply systems of the vertical coil and central transformer coil in the IR-T1 tokamak are approximated as first-order linear dynamical filters. These filters are characterized by specified time delays and bandwidths, and their representation is as follows:

$$\begin{aligned} G_v(s) &\cong K_v \frac{e^{-T_v s}}{s + a_v}, \quad K_v \simeq 1, \quad T_v = 10\mu s \\ G_0(s) &\cong K_0 \frac{e^{-T_0 s}}{s + a_0}, \quad K_0 \simeq 1, T_0 = 100\mu s \end{aligned} \tag{4}$$

where $K_v(K_0)$, $T_v(T_0)$, and $a_v(a_0)$ are respectively the gain, time delay, and bandwidth-related quantity for the vertical coil (central transformer coil) power supply whose values are determined by the system requirements [34].

In light of the challenging cross-coupling of plasma parameters in MIMO system designs, various decoupling methods have been developed to address this issue. Among these methods, we have chosen to implement the inverted decoupling method [35, 36], also known as feed-forward decoupling control, in our design. As a result of this approach, we obtain the ultimate transfer function, denoted as the plasma

Table 1. Characteristic parameters and corresponding values of IR-T1 tokamak.

Parameters	Value	Parameters	Value
β_p, Poloidal beta	1	Vertical field coil current (kA)	5
κ, Elongation	1	Plasma resistance (mΩ)	1
δ, Triangularity	0	Vertical field coil-related resistance (Ω)	5
l_i, Internal inductance	1	Vacuum vessel resistance (mΩ)	0.40
Major radius of vacuum vessel (m)	0.45	Number of vertical field coil turns	2
Minor radius of vacuum vessel (m)	0.16		

response MIMO transfer function, as well as the transfer functions for the power supplies, represented as $G_p(s)$:

$$G_p(s) = \begin{pmatrix} U_1 & U_2 \\ U_3 & U_4 \end{pmatrix}$$

where

$$\begin{cases} U_1 = \frac{1.001s+6.203\times10^{11}}{s^2+(1.239\times10^{12})s+3.84\times10^{23}}, \\ U_2 = \frac{-0.000511s-3.167\times10^{8}}{s^2+(1.239\times10^{12})s+3.84\times10^{23}} \\ U_3 = \frac{(9.15\times10^{-8})s+5.67\times10^{4}}{s^2+(1.239\times10^{12})s+3.84\times10^{23}} \\ U_4 = \frac{0.9992s+6.192\times10^{11}}{s^2+(1.239\times10^{12})s+3.84\times10^{23}} \end{cases}.$$

With the corresponding matrices:

$$A = \begin{pmatrix} -6.197\times10^{11} & 0 \\ 0 & -6.197\times10^{11} \end{pmatrix}$$

$$B = \begin{pmatrix} -1.584 & -6.08\times10^{-5} \\ -0.4981 & 0.6685 \end{pmatrix}$$

$$C = \begin{pmatrix} -0.6319 & -5.733\times10^{-5} \\ -0.4697 & 1.495 \end{pmatrix}$$

$$D = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

It's important to emphasize that due to the minimal delay times outlined in Equation (4), the final transfer function is devoid of any delay components. As a consequence, we can design a MIMO PID-tuned controller for the precise regulation of plasma current and plasma horizontal position within the tokamak. The typical block diagram for controlling MIMO processes, featuring a decoupling matrix transfer function denoted as $D(s)$, the plant transfer function ($G(s)$) representing the controlled system (comprising the actuator, plasma within the tokamak, and sensors), independent PID controllers p_1 and p_2, distinct inputs v_1 and v_2 into the system, and plant outputs $y_1 = \delta_h$ and $y_2 = \delta_{I_p}$, with inputs u_1 and u_2 to the decoupling matrix, is illustrated in Figure 2.

3. Optimal fractional order PID controller design

3.1 Fractional order calculus

FOPID controller has its roots in fractional calculus, a field as old as its integer-order counterpart. However, the utilization of fractional calculus was historically hindered by the complexity of mathematical expressions associated with fractional-order differentiation and integration. Nevertheless, in recent years, several methodologies have been introduced to facilitate the handling of these mathematical constructs. Some of the widely recognized expressions for describing fractional calculus include Riemann-Liouville, Grünwald-Letnikov, and Caputo, among others [37]. The Caputo fractional-order differentiation is formally defined as follows:

$${}_aD_t^{\alpha} = \frac{1}{\Gamma(n-\alpha)} \int_a^t \frac{f^n(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \qquad (5)$$

where ${}_aD_t^{\alpha}$ is for Caputo notation with $n-1 < \alpha < n$, $\alpha > 0$, α is a real number, n is an integer number, Γ is the Gamma function, a and t are the limit of integration, and $f^n(\tau)$ is the nth-order derivative of the function $f(\tau)$.

3.2 FOPID controller design

FOPID was proposed by Oustaloup [38]. The typical transfer function of FOPID can be shown as follows [39]:

$$C(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \qquad (6)$$

where K_p, K_i, and K_d are the proportional, integrative, and derivative tuning parameters for proper controller operation, respectively, also involving an integrator of order λ and a differentiator of order μ, where λ and μ can be any real numbers (λ, $\mu > 0$). The FOPID controller not only retains the benefits of the conventional PID control method but also extends its capabilities by two additional degrees of freedom. This expansion provides the controller with the capacity to manage the controlled system with enhanced flexibility and precision, making it a valuable tool for a

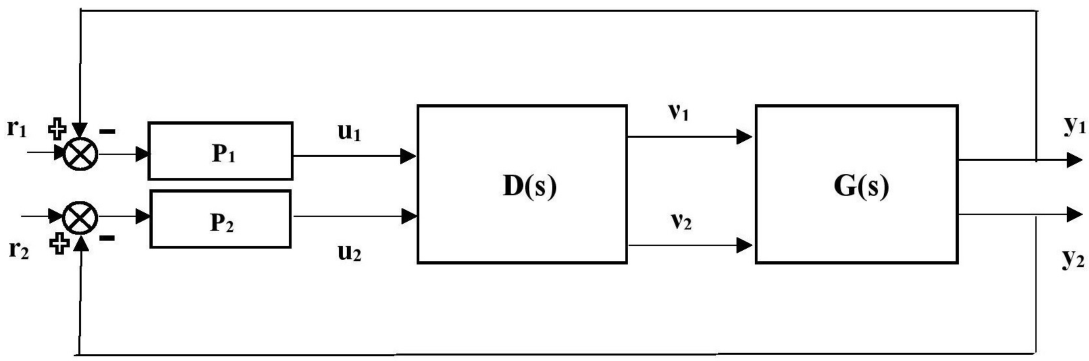

Figure 2. Block diagram for controlling the structure of TITO processes with the decoupling matrix D(s) by the designed a PID controller including p_1 and p_2.

wider range of applications and improved control performance.
Controller parameter tuning is a fundamental aspect of optimizing closed-loop control systems, and it must align with the critical criterion of loop stability. The overarching objective in these control systems encompasses several essential performance criteria. First and foremost, it is imperative to ensure the stability of closed-loop responses, avoiding undesirable oscillations or instability under varying operating conditions. Additionally, a well-designed control system must exhibit proficiency in rejecting disturbances, thereby preserving the controlled process's integrity in the face of external perturbations. Moreover, the system should excel in set-point tracking, accurately aligning the controlled variable with the reference signal, while minimizing any offset errors to ensure that the controlled variable converges to the set point with minimal deviation. Furthermore, robustness is of paramount importance, as the control system's performance must withstand variations in system parameters, external disturbances, and uncertainties. To address these challenges effectively, robust control strategies are indispensable. In the realm of FOPID controllers, real-time applications often favor tuning methods grounded in the minimization of specific time domain objective functions. These methods allow for precise adjustments of FOPID controller parameters, thus enabling the attainment of the desired closed-loop system performance. It is worth noting that these strategies consider the fractional order dynamics, which can offer superior control capabilities compared to traditional PID controllers. They are especially relevant in applications where intricate and dynamic process requirements demand a high degree of control system customization and adaptability. In the servo control systems, we often expect the error signal $e(t)$ as small as possible. Since the error signal $e(t)$ is a dynamic signal, integral-type criteria such as Integral of Square Error (ISE):

$$\mathrm{ISE} = \int_0^\infty e^2(t)dt \tag{7}$$

Integral of Time Absolute Error (ITAE):

$$\mathrm{ITAE} = \int_0^\infty t|e(t)|dt \tag{8}$$

Integral of Absolute Error (IAE):

$$\mathrm{IAE} = \int_0^\infty |e(t)|dt \tag{9}$$

Integral of Time Square Error (ITSE):

$$\mathrm{ITSE} = \int_0^\infty te^2(t)dt \tag{10}$$

are usually adopted, since they correspond to the weighted area of the error signal [40].

3.3 Optimization of FOPID controllers

In control system design, the selection of the most suitable integral-type criteria, such as ISE (Integral of Squared Error), ITAE (Integral of Time-weighted Absolute Error), IAE (Integral of Absolute Error), and ITSE (Integral of Time-weighted Squared Error), is pivotal. This selection is made through a comprehensive comparison of the step response and disturbance rejection behavior of the plant under these criteria. Numerical optimization techniques play a key role in fine-tuning fractional-order PID-type controllers, and various methods have been proposed for this purpose. Among these techniques, one can find the particle swarm optimization (PSO) algorithm [41], genetic algorithm [42], pattern search [43], and others.

3.3.1 Particle swarm optimization

The PSO method is a parallel evolutionary computation technique, as elucidated in reference [44], which draws its inspiration from the social behavior metaphor. It stands out as one of the more sophisticated yet straightforward approaches for guiding optimization processes toward optimal values, often outperforming other methods. The PSO algorithm commences with the initialization of a population comprised of randomly generated candidate solutions, akin to particles. Each particle is endowed with a randomized velocity and is systematically propelled through the problem space. Throughout this iterative process, particles are drawn towards two distinct focal points. Firstly, they are attracted to the location in the problem space that represents the best fitness value they have achieved thus far (individual best), and secondly, they are influenced by the location of the best fitness value attained across the entire population

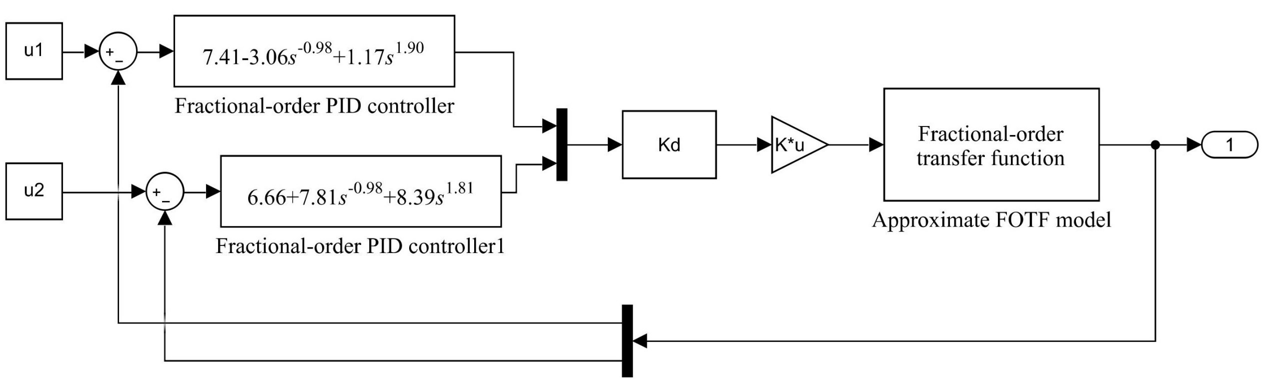

Figure 3. Simulink blocks for the designed OFOPIDs under the ITAE criterion (as an example).

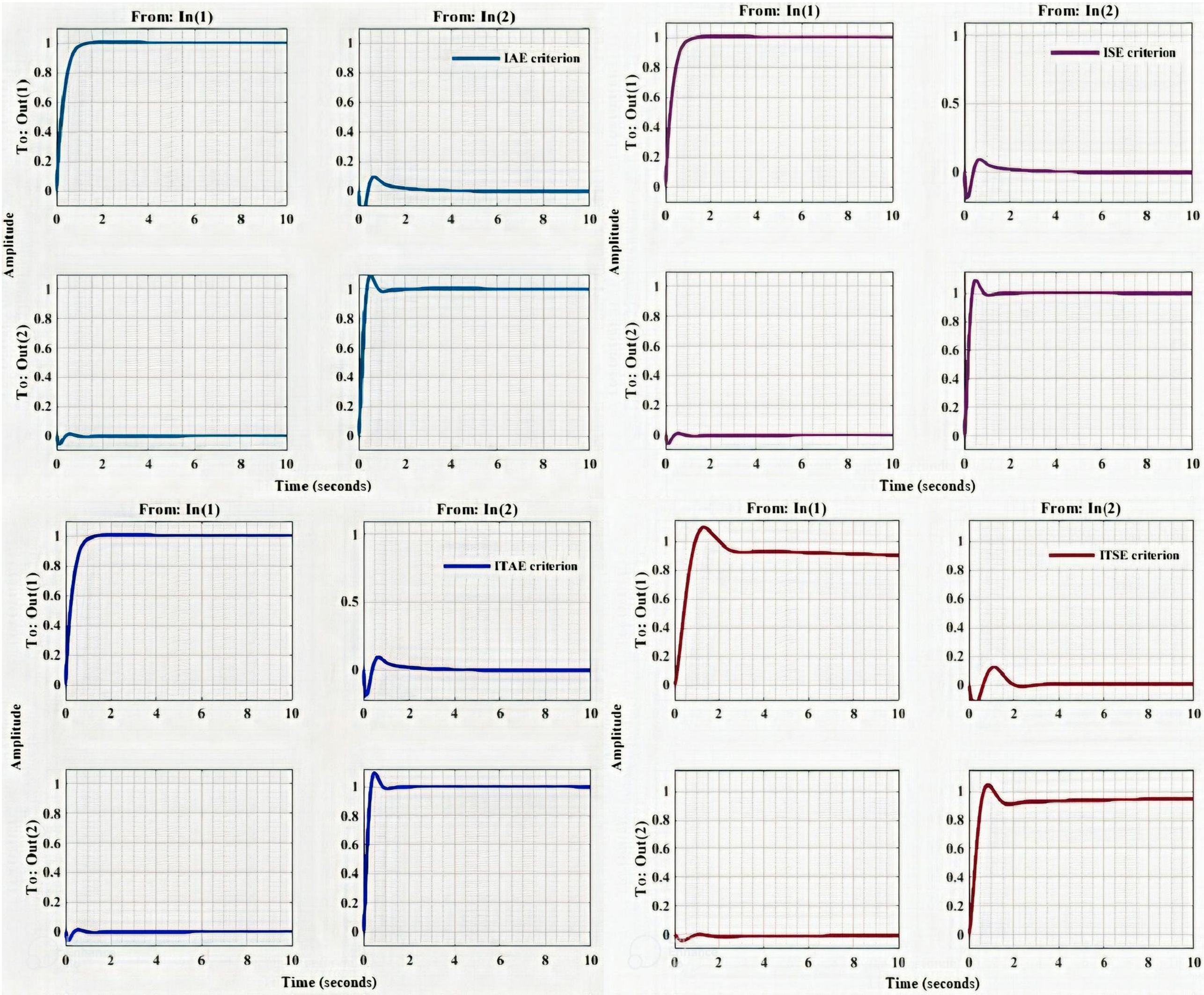

Figure 4. Step responses of the MIMO controlled system with the designed OFOPIDs under IAE, ITAE, ISE and ITSE criteria.

(global version of the algorithm). The efficacy of PSO as an optimization method is well-documented, particularly in the context of designing FOPID controllers for plasma control within tokamaks. PSO has been successfully employed in this domain, as demonstrated by the references [45, 46].

3.3.2 FOTF toolbox

The design of controllers for fractional-order MIMO plants presents a significant advantage when approached from both the frequency and time domains. A valuable resource in this regard is the recently extended FOTF Toolbox, as referenced in [47], which now provides the capability to address MIMO systems directly. When it comes to designing integer-order multivariable controllers for MIMO fractional-order plants, a systematic parameter optimization algorithm, which includes methods like Particle PSO, Genetic Algorithm, Pattern Search, and fminsearchbnd, proves to be highly effective. The process begins with the selection of the desired integer-order closed-loop transfer function. Subsequently, the parameter optimization algorithm is utilized to determine both the numerator and denominator of the controller. To evaluate the performance and robustness of this approach, simulations are conducted, as outlined in [48]. These simulations help ascertain the effectiveness of the method in achieving the desired control objectives. It's worth noting that this methodology is not only applicable to MIMO systems but can also be effectively employed in the design of controllers for systems with time delays. The convenience and versatility of this approach make it a valuable tool for engineers and researchers engaged in control system design for complex and dynamic processes.

4. Results and discussion

In our research, we have introduced fractional-order calculus into the control of plasma parameters within the IR-T1 tokamak. Our objective is to optimize FOPID controllers and to achieve this, we have utilized a performance index that incorporates the integral-type criteria discussed previously. To determine suitable parameters for the Optimal OFOPID controllers, we have employed the PSO method in conjunction with the FOTF Toolbox. The utilization of PSO is particularly advantageous when the search space is extensive and the problem exhibits irregular characteristics, as is often the case with FOPID controllers that

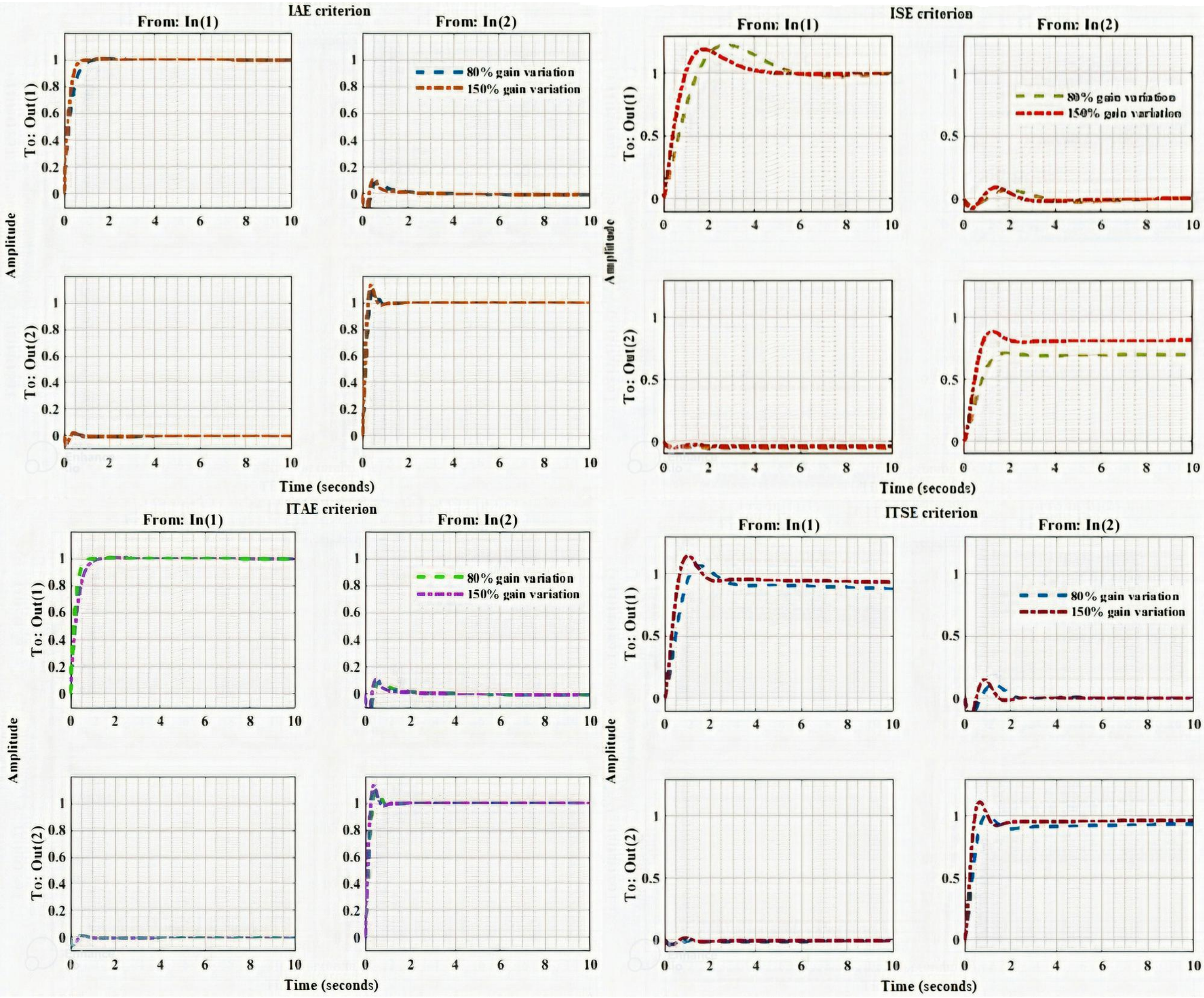

Figure 5. Robustness analysis of the MIMO controlled system under 80% and 150% gain variations with the designed OFOPIDs under IAE, ITAE, ISE and ITSE criteria.

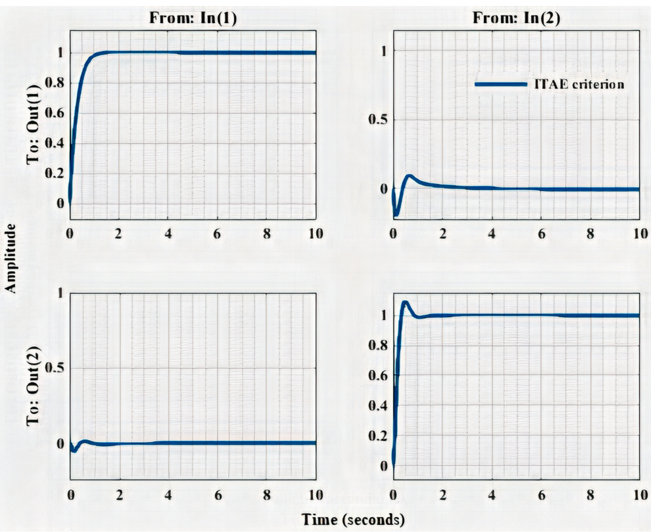

Figure 6. Step responses of the MIMO controlled system with the designed IOPIDs under ITAE criterion.

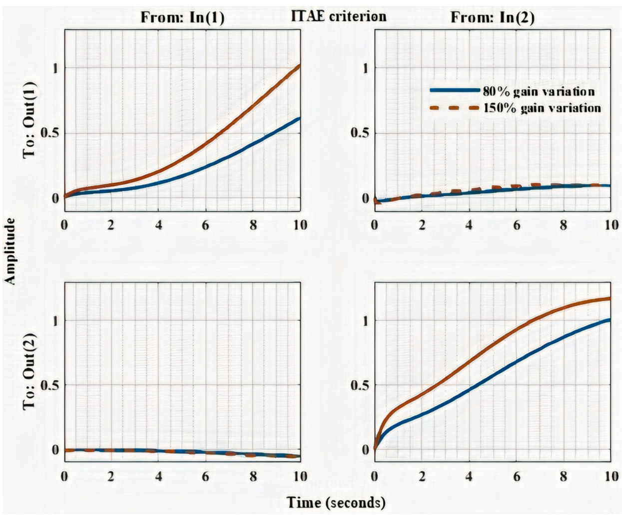

Figure 7. Robustness analysis of the MIMO controlled system under 80% and 150% gain variations with the designed IOPIDs under ITAE criterion.

involve five parameters $\{K_p,\ K_i,\ K_d,\ \lambda,\ \mu\}$. The initial values of the controller parameters for starting the PSO algorithm are $\{0,\ -3.93\times10^{-10},\ 0,\ 0.95,\ 1.25\}$ for plasma horizontal position and $\{3.04\times10^{-6},\ 4.96\times10^{-8},\ 2.29\times10^{-6},\ 0.95,\ 1.5\}$ for the plasma current. Therefore, the proposed OFOPID control design is developed and two separate FOPID controllers for decoupled into 1-DOF plasma horizontal position and 1-DOF plasma current are obtained. The range of FOPID parameters are selected, $K_p \in \{-1,10\}$, $K_i \in \{-1,10\}$, $K_d \in \{-1,10\}$, $\lambda \in \{0,1\}$ and $\mu \in \{0,2\}$. A Simulink block of the OFOPIDs under the ITAE criterion is provided (as an example) in Fig. 3.
The step responses of the MIMO system, taking into account the parameters of the obtained OFOPID controllers, were analyzed and presented in Figure 4. Furthermore, the robustness of the designed control system was assessed by examining the step response of the closed-loop system when subjected to variations in gain ranging from 80% to 150%. The results of this analysis are illustrated in Figure 5.
Figure 4 reveals that there isn't a significant disparity in performance when considering the IAE, ISE, and ITAE criteria. However, the results from the robustness analysis presented in Figure 5 indicate that the ITAE criterion, and to a lesser extent, the IAE criterion, exhibit superiority compared to the other criteria. This suggests that, when it comes to the robustness of the control system, these integral-type criteria outperform the alternatives. The same procedure, parameter range, and initial values were employed in the design of IOPID controllers for both plasma horizontal position and plasma current, with $\lambda = \mu = 1$. The selection of the ITAE criterion was made due to its superior performance in the assessment of FOPID controllers. The results of this evaluation for the IOPID controllers are presented in Figures 6 and 7, offering insights into the comparative performance of FOPID and IOPID controllers in the control of plasma parameters.
In order to examine the comparative performance of OFOPID and IOPID controllers more comprehensively, the obtained parameters related to the OFOPID and IOPID controllers are given, considering the criteria mentioned above, in Table 2 for horizontal position control and Table 3 for plasma current control.
While the step responses for both controllers appear to be quite similar, it is evident that the OFOPID controllers demonstrate greater robustness to variations. The OFOPID controllers exhibit a smaller response to variations in the system and display a quicker recovery from such disturbances. This underscores the advantages of employing fractional-order control techniques, particularly in scenarios where robustness and adaptability to system changes are of paramount importance.
The evaluation of controllers through an actual experimental discharge on the IR-T1 tokamak offers a practical scenario to assess their effectiveness in sustaining plasma stability amidst disturbances and rapid changes, mirroring real-world tokamak operations. Following our prior research [34], we chose a common discharge with a 3 kV vertical field coil voltage. The horizontal displacement was monitored using magnetic probes and Rogowski coils installed on the tokamak. We then analyzed the feedback responses of the designed controllers, specifically for horizontal displacement, and presented these findings in Fig. 8(a). A more detailed examination of the feedback response of the designed controllers is provided in Fig. 8(b) (for the IOPID controller) and 8(c) (for the OFOPID controller). The comparison between the OFOPID and the IOPID controllers revealed minimal performance differences. However, in terms of counteracting disturbances and rapid shifts in horizontal plasma position, the OFOPID controller demonstrated superior efficacy. These results align with the step response observations depicted in Figures 5 and 7, further validating the OFOPID controller's enhanced stability control.
In summary, our study has focused on the analysis of control performance, particularly in terms of time response and robustness to variations, comparing the OFOPID controllers with their IOPID counterparts. Our findings indicate that the OFOPID controllers outperformed the IOPID controllers when it comes to controlling disturbances and rapid changes in plasma horizontal position in the IR-T1 tokamak.
However, it's worth noting that the implementation of fractional-order controllers in real-time control systems can present challenges, primarily due to the computational complexity involved. Successful application in such systems necessitates the development of efficient algorithms and hardware implementations. Furthermore, real-time estimation of fractional derivatives and integrals is essential.

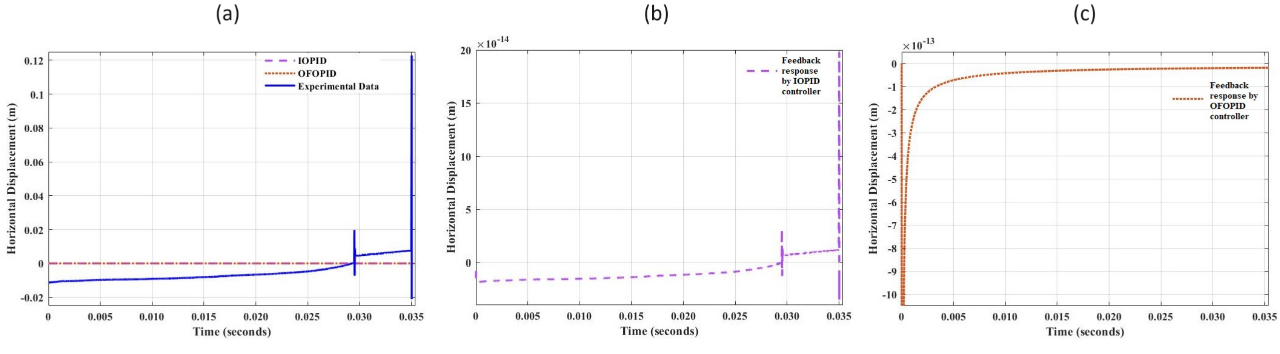

Figure 8. (a) Experimental data together with feedback responses by IOPID and OFOPID controllers of plasma horizontal displacement for 3 kV vertical field coil voltage in IR-T1 tokamak, (b) and (c) separate responses of the IOPID and OFOPID controllers, respectively.

Table 2. Obtained parameters for the OFOPID controller designed, under the mentioned criteria, together with the IOPID designed controller parameters (under ITAE criterion), to control plasma horizontal position in the IR-T1 tokamak.

Parameters	K_p	K_i	K_d	λ	μ
IAE	5.5135	1.3738	5.2060	0.9795	0.5126
ITAE	7.4065	3.0613	1.1731	0.9802	1.99
ISE	5.0094	3.8056	4.9735	0.9811	0.5857
ITSE	8.7450	-0.7429	9.3749	0.9825	0.3797
ITAE (the IOPID designed controller)	-0.1056	0.1331	0.3699	1	1

Table 3. Obtained parameters for the OFOPID controller designed, under the mentioned criteria, together with the IOPID designed controller parameters (under ITAE criterion), to control plasma current in the IR-T1 tokamak.

Parameters	K_p	K_i	K_d	λ	μ
IAE	5.5427	0.9462	6.6222	0.9721	1.99
ITAE	6.6568	7.8110	8.3923	0.9772	1.8055
ISE	0.5698	0.0449	4.0503	0.9832	0.3475
ITSE	9.2048	0.3082	6.0937	0.9875	0.6224
ITAE (the IOPID designed controller)	0.2980	0.2980	0.8062	1	1

Addressing these challenges is pivotal to the effective utilization of fractional-order control techniques for tokamak plasma control.

5. Conclusion

The control of plasma parameters plays a pivotal role in achieving and sustaining fusion reactions. In this context, FOPID controllers have emerged as a promising and effective control technique for tokamaks. Their capability to accurately manage complex and nonlinear systems is a key advantage. In this study, we have introduced OFOPID controllers based on the PSO algorithm to minimize an objective function. We have employed these controllers in a MIMO system designed for the control of plasma current and plasma horizontal position in the IR-T1 tokamak. Our results, as reflected in the step responses, demonstrate the superiority of the ITAE criterion in assessing control performance. For comparison, we have also presented IOPID controllers designed using the same procedure. An analysis of the results reveals a significant difference in control performance between the OFOPID controllers and the IOPID controllers, particularly in terms of robustness against variations. In this study, we assess the performance of the OFOPID controller by examining a common discharge in the tokamak and measuring the horizontal displacement. Subsequent evaluation of feedback responses highlights the OFOPID controller's robustness in countering disturbances and rapid variations in plasma horizontal position, corroborated by the step response results.
In conclusion, the application of fractional-order PID controllers holds promise for effective plasma control in tokamaks. Nevertheless, further research is warranted to fully explore and harness their potential, as they offer a viable path toward achieving sustained fusion reactions in these complex systems.

Authors Contributions
Both authors have equal role in the intellectual content, conception and preparing the software or analysis and interpretation of the data, as well as the writing of the manuscript.

Availability of data and materials
The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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