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A fractional order PID tuning tool for automatic voltage regulator using marine predators algorithm☆

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ABSTRACT

The fractional-order proportional-integral-derivative (FOPID) controller stands as a widely embraced choice for the task of automatic voltage regulation (AVR) when it comes to maintaining the voltage output of synchronous generators. Nevertheless, fine-tuning the FOPID controller presents a formidable challenge, mainly because it possesses five tuning gains, in contrast to the conventional PID controller, which has three gains. Consequently, this paper introduces a novel tuning tool tailored to the AVR system by utilizing the marine predators algorithm (MPA). To gauge the effectiveness of the proposed approach, two key evaluation criteria are employed: step response analysis and trajectory tracking analysis. The results of this research reveal that the MPA-FOPID controller demonstrates exceptional performance criteria, notably enhancing the AVR transient response in comparison to other FOPID controllers optimized through recent metaheuristic algorithms.

1. Introduction

The primary concern for power system providers lies in maintaining a stable nominal voltage level yielded by synchronous generators, a crucial factor in enhancing electrical energy supply and maximizing profits. Failure to stabilize this voltage level can result in performance deterioration of connected equipment, increased real line losses, and further reduce the quality of electrical energy during distribution. This is where the automatic voltage regulator (AVR) steps in, responsible for maintaining the voltage level of synchronous generators while distributing suitable reactive power among generators that are connected together (Kundur, 1994). However, achieving a rapid and stable response for the AVR system proves challenging due to the inherent characteristics of alternator field windings, characterized by high inductance and load fluctuations. Additionally, disturbances in the power system can lead to insulation breakdowns and damage connected equipment. Hence, a precise control method is imperative to make sure the distribution of the power system is in a stable condition while at the same time improving the security of the system.

Researchers have extensively explored methods to control the AVR system, with the fractional order proportional-integral-derivative (FOPID) controller increasingly becoming a preferred option. The FOPID controller, distinguished by its additional gains in the form of fractional exponential terms of derivative μ and fractional exponential terms of integral λ, has gained popularity due to its potential to offer new control opportunities across diverse engineering domains (Shah and Agashe, 2016). In many instances, the FOPID controller has demonstrated superior results compared to the traditional PID controller concerning stability, robustness, and time domain specifications (Shah and Agashe, 2016). However, determining the optimal gains for a FOPID controller becomes more intricate due to the increased number of controller gains. Consequently, there is a pressing need for appropriate optimization techniques to tune the FOPID gains.

Several studies have delved into the implementation of metaheuristic optimization algorithms to find the optimal FOPID controller gains for AVR systems. These approaches include hybrid simulated annealing-manta ray foraging optimization (SA-MRFO) (Micev et al., 2021), gradient-based optimization (GBO) (Altbawi et al., 2021), chaotic black widow optimization (ChBWO) (Munagala and Jatoth, 2022), non-dominated sorting genetic algorithm II (NSGA II) (Pan and Das, 2012), and particle swarm optimization (PSO) (Ramezanian et al., 2013). These FOPID controller tuning methods utilizing metaheuristic optimization algorithms have indeed enhanced the transient response of numerous AVR systems, yet their precision remains a concern,

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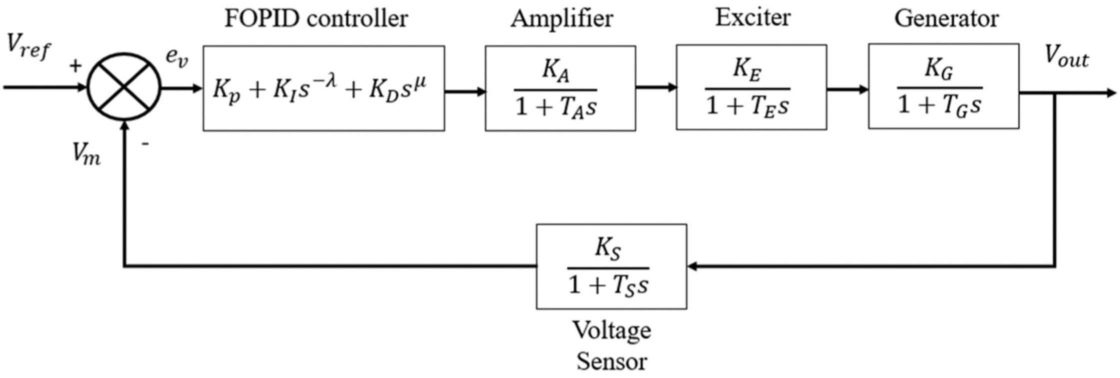


Fig. 1. The AVR system block diagram integrated with the FOPID controller.

necessitating further enhancement. Hence, incorporating cutting-edge metaheuristic optimization algorithms can potentially refine the accuracy of FOPID controller tuning, thereby enhancing the overall performance of the AVR system.

One such advanced metaheuristic optimization algorithm is the marine predators algorithm (MPA), inspired by the foraging behavior of ocean predators through the modeling of predator-prey interactions (Faramarzi et al., 2020). MPA has been employed in solving diverse optimization problems, ranging from 5G networks (Safaa et al., 2022), renewable energy systems (Habib et al., 2022), wind plants (Tumari et al., 2022), tuning the PID-acceleration (PIDA) controller (Yakout et al., 2022), and tuning the PID cascaded controller (Yakout et al., 2021). These studies underscore MPA's versatility in addressing various engineering challenges and its ability to outperform other cutting-edge metaheuristic-based methods. Moreover, pioneering research on MPA has validated its superiority by demonstrating better convergence accuracy than its competitors across most benchmark functions (Faramarzi et al., 2020).

This paper presents an innovative approach to fine-tuning FOPID controllers in AVR systems, employing the marine predators algorithm (MPA). The proposed method is implemented to optimize the FOPID controller gains for the AVR system, and its efficacy is compared with other metaheuristic-based techniques, namely SA-MRFO (Micev et al., 2021), GBO (Altbawi et al., 2021), ChBWO (Munagala and Jatoth, 2022), NSGA II (Pan and Das, 2012), and PSO (Ramezanian et al., 2013). The study encompasses step response analysis and trajectory tracking analysis to comprehensively evaluate the proposed approach's performance. This paper was originally presented at a conference and is part of our research outlined in (Tumari et al., 2023). It should be noted that this paper represents a preliminary outcome of our works discussed in (Tumari et al., 2023), and for more in-depth insights into the theory and experiments, we suggest readers go to that source.

The arrangement of this paper unfolds as follows: Section 2 details the problem formulation related to the FOPID controller in AVR systems. Section 3 offers an outline of the MPA-based approach and the steps involved in applying it to optimize the FOPID controller employed in the AVR system. Section 4 presents the validation process, demonstrating the efficacy of the MPA-based method. Lastly, in Section 5, conclusions are presented.

2. Problem formulation of FOPID controller of AVR system

In this section, the problem formulation for the FOPID controller in the AVR system is elucidated. The study employs the linearized AVR model proposed by (Gaing, 2004). It's crucial to note that the FOPID controller, introduced by (Podlubny, 1999), is the focal point of this research. The transfer functions of each AVR system component are illustrated in Fig. 1, wherein K_D, K_I, K_p, μ, and λ represent the derivative gain, integral gain, proportional gain, exponent of differential term, and exponent of integral term, respectively. Additionally, the gains for the sensor, generator, exciter, and amplifier are denoted as K_S, K_G, K_E, and K_A, while T_S, T_G, T_E, and T_A represent the time constants for these components.

Meantime, according to the literature (Munagala and Jatoth, 2022), specific values for gains and time constants are recommended: $K_S = 1$, $T_S = 0.01$, $K_G = 1$, $T_G = 1$, $K_E = 1$, $T_E = 0.4$, $K_A = 10$, and $T_A = 0.1$. These values are suggested to maintain the AVR system's stability. Additionally, to assess the AVR system performance under the control of the FOPID controller, the objective function, as described in (Gaing, 2004), is adapted by incorporating a weighting coefficient, w. It's important to emphasize that the introduction of this specific weighting coefficient aims to provide users with the flexibility to vary the overshoot independently without impacting other coefficients. This modification is expressed as follows

$$J(K_p, K_I, K_D, \lambda, \mu) = (1 - e^{-\eta}) \times \left(w * M_p + E_{ss}\right) + e^{-\eta}(T_{set} - T_r) \tag{1}$$

In Eq. (1), M_p denotes the overshoot, T_r stands for rise time, T_{set} represents settling time, and E_{ss} signifies steady-state error. The weighting factor denoted as symbol η, adjustable to meet specific system requirements. According to references (Suid and Ahmad, 2022; Tang et al., 2012; Sikander et al., 2018), the value of η has been set to 1.0. Simultaneously, after conducting several preliminary investigations, the weighting coefficient w has been established at 0.3. Conclusively, the problem statement of this study can be succinctly defined as follows: Problem 2.1. Determine the values of the FOPID controller gains (K_p, K_i, K_d, λ, and μ) corresponding to the AVR system block diagram in order to minimize the objective function J.

3. Marine predators algorithm

3.1. Overview of marine predators algorithm

The MPA draws its inspiration from the foraging behavior of ocean predators, employing a strategy that combines both Levy and Brownian walks. The Levy walk, derived from a probability function with power-law tails, involves numerous small steps interspersed with longer relocations. It is typically used for foraging in areas with sparse prey concentrations. On the other hand, the Brownian walk entails step lengths drawn from a probability function based on a normal (Gaussian) distribution, facilitating exploration in prey-rich regions. MPA aims to strike a balance between these walks, creating an optimal strategy that mirrors the survival of the fittest behavior observed in nature (Faramarzi et al., 2020).

To initiate the optimization process, predators and prey are randomly allocated within the search space. This random placement sets the stage for solving the given optimization problem in Eq. (2), marking the beginning of the algorithmic process.

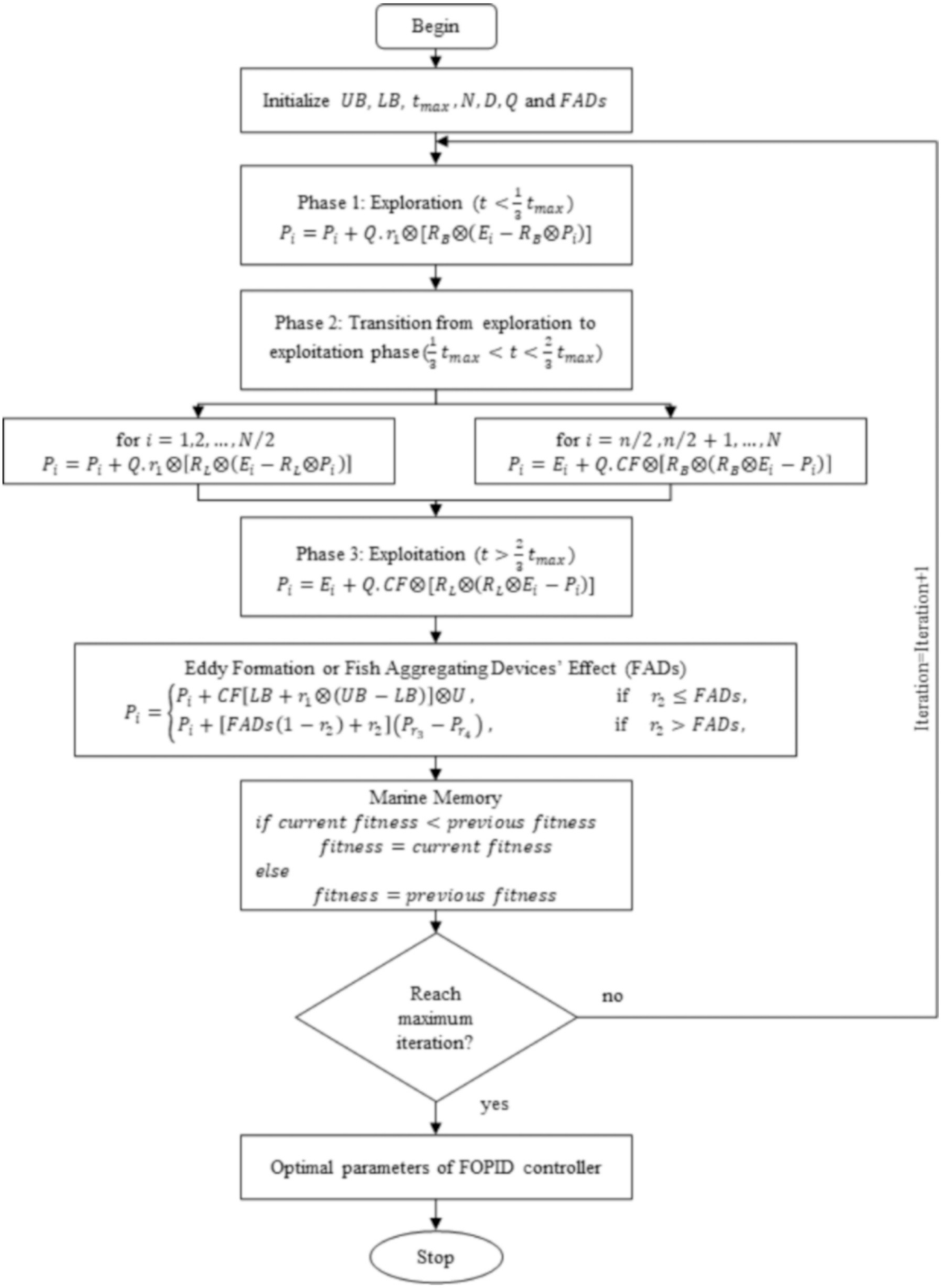


Fig. 2. The flow chart of MPA structure.

$$arg \min_{Y_i(1),Y_i(2)\ldots} J_i(Y_i(\mathrm{t})) \tag{2}$$

for iterations $t = 1,2,\ldots,t_{\max}$. In Eq. (2), Y_i denotes the location vector of agent i, J_i correspond to the objective function of the agent i, and $t_{\max}$ signifies the maximum iterations. The elite matrix E consists of the best predator, while the prey matrix P can be defined as follows

$$E = \begin{bmatrix} Y'_{1,1} & Y'_{1,2} & \cdots & Y'_{1,D} \\ Y'_{2,1} & Y'_{2,2} & \cdots & Y'_{2,D} \\ \vdots & \vdots & \vdots & \vdots \\ Y'_{N,1} & Y'_{N,2} & \cdots & X'_{N,D} \end{bmatrix} \tag{3}$$

$$P = \begin{bmatrix} Y_{1,1} & Y_{1,2} & \cdots & Y_{1,D} \\ Y_{2,1} & Y_{2,2} & \cdots & Y_{2,D} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{N,1} & Y_{N,2} & \cdots & Y_{N,D} \end{bmatrix} \tag{4}$$

In Eq. (3) and Eq. (4), N signifies the total amount of agents, and D denotes the amount of dimensions. In Eq. (4), $Y_{i,j}$ signifies the j-th dimension of the i-th prey or agent Y_i in Eq. (2). In Eq. (3), the matrix E comprises of $Y'_{i,j}$ representing the j-th element of the best predator vector Y'_i. Y'_i is then duplicated N times to create an elite matrix.

Fig. 2 illustrates the application of the MPA-based method to optimize the FOPID controller employed in the AVR system, where $X_{i,5} = (K_p, K_I, K_D, \lambda, \mu)$. The tuning process commences by setting the lower bound LB, the upper bound UB, N, D and two MPA coefficients, namely Q and $FADs$. Subsequently, the prey's location is updated through three main phases and the incorporation of eddy formation or Fish Aggregating Devices' effect (FADs) and marine memory, utilizing corresponding equations outlined in the flow chart (refer to Fig. 2. Upon achieving the $t_{\max}$, the optimal parameters for the FOPID controller are determined and subsequently employed to the AVR system, as depicted Fig. 1. In Fig. 2, R_B denotes a random number based on Brownian distribution. The symbol r_1 represents a random number uniformly distributed within the range of [0, 1]. Additionally, the Levy walk is denoted by R_L, which comprises a random number based on the Levy distribution. Element-wise multiplications are represented by the notation $\otimes$. Meanwhile, CF signifies an adaptive coefficient controlling the step size of predator movement, determined by as follows

$$CF = \left(1 - \frac{k}{k_{\max}}\right)^{\left(2 \times \frac{k}{k_{\max}}\right)}. \tag{5}$$

Moreover, random numbers r_2 are generated uniformly within the range [0, 1]. Simultaneously, a binary vector denoted by the symbol U, comprising values 0 or 1, is employed. Specifically, U sets its array to 1 if $r_2 > 0.2$. Otherwise, U configures its array to zero. Furthermore, r_3 and r_4 denote the random indexes of the columns of the P matrix. For a more comprehensive understanding of the MPA-based method, we suggest readers to look up to the pioneering work on MPA in (Faramarzi et al., 2020).

4. Results and discussion

This section delves into the performance evaluation of the AVR system utilizing an FOPID controller optimized through the MPA. The efficiency of the proposed MPA-FOPID controller is systematically compared with other controllers, namely SA-MRFO-FOPID, GBO-FOPID, ChBWO-FOPID, PSO-FOPID, and NSGA II-FOPID, employing step response analysis and trajectory tracking analysis as the primary performance criteria. For the optimization process, the FOPID gains are constrained within specific ranges: $K_p = (0.1, 3)$, $K_i = (0.1, 1)$, $K_d = (0.1, 1.5)$, $\lambda = (0.5, 1.5)$ and $\mu = (0.5, 1.5)$, as suggested in the study (Munagala and Jatoth, 2022). Then, $k_{\max}$ is set to 100, and n is fixed to 40. Furthermore, the default coefficients for the MPA-based method are defined as $Q = 0.5$ and $FADs = 0.2$. Lastly, the fifth Oustaloup approximation within $\omega \in [10^{-5}, 10^{5}]$ r/s of a frequency range is used for designing the fractional order transfer functions. These parameters collectively form the basis for the comparative performance evaluation of the different FOPID controllers.

Table 1
Optimal FOPID gains achieved through various algorithms.

Algorithm	FOPID gains				
	K_p	K_i	K_d	λ	μ
MPA	2.9409	0.4510	0.4386	1.4027	1.4147
SA-MRFO	1.8931	0.8699	0.3595	1.0408	1.2780
GBO	0.9961	1.4861	0.6124	0.4932	1.1131
ChBWO	2.8204	0.7387	0.4280	1.1294	1.3558
PSO	1.2623	0.5531	0.2382	1.1827	1.2555
NSGA II	0.8399	1.3359	0.3512	0.9147	0.7107

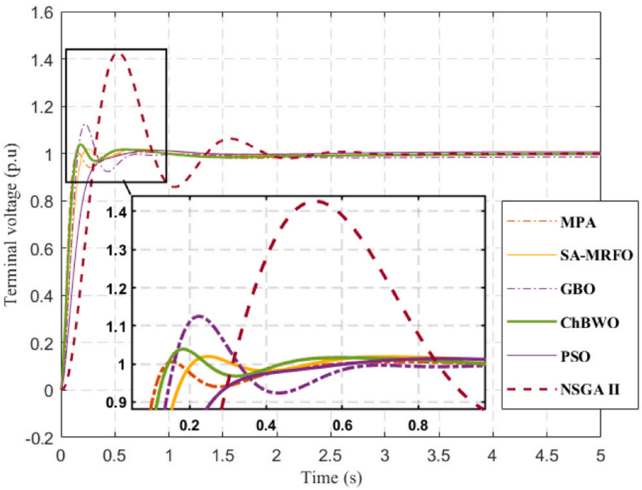
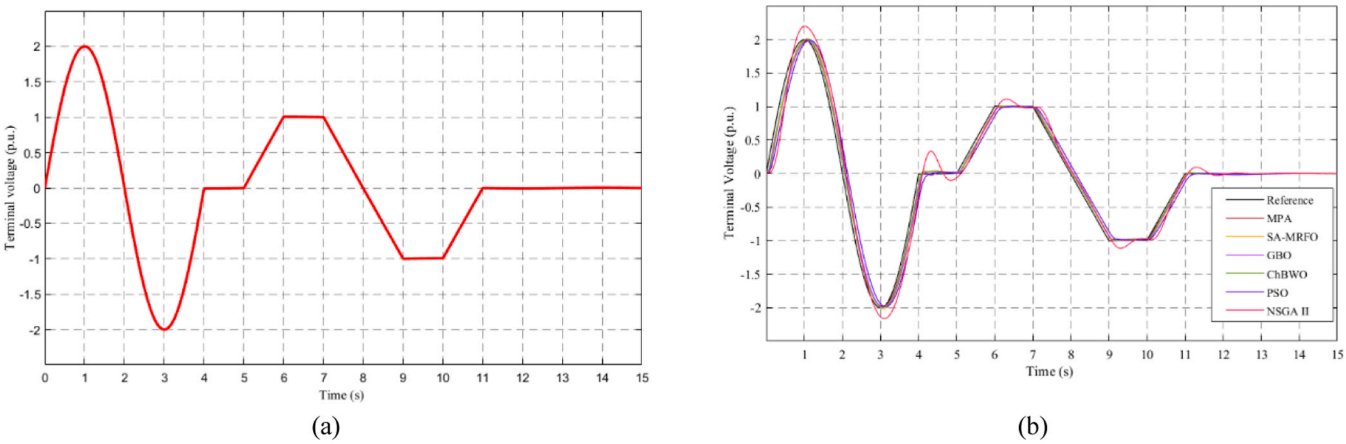


Fig. 3. Step responses by different algorithms.

Table 2
Time response specifications and objective function J achieved through various algorithms.

Type of algorithm	Time response specifications				J
	M_p(%)	$T_r(s)$	$T_{set}(s)$ (5%)	E_{ss}	
MPA	**0.55**	**0.0833**	**0.1106**	**1.83e-06**	**0.01108495**
SA-MRFO	1.95	0.1311	0.1760	6.6745e-04	0.02060125
GBO	12.46	0.1081	0.5161	0.0148	0.18305555
ChBWO	3.89	0.0956	0.1266	0.0022	0.02011246
PSO	1.37	0.2231	0.3227	0.0067	0.04346518
NSGA II	42.69	0.2025	1.6800	0.0016	0.62550586

Table 1 showcases the optimal FOPID gains acquired through the MPA-based method and other algorithms, directly sourced from their respective research papers. Consequently, Fig. 3 illustrates the step responses of the terminal voltage derived via the MPA-FOPID controller and other FOPID controllers optimized through recent metaheuristic algorithms. The simulations are conducted over a time span of $t_s = 5$ s, with the desired terminal voltage set at 1.0 per unit (p.u.). It is essential to note that all compared controllers have been re-evaluated, taking into account the experimental parameters established in this study, including Oustaloup approximation, simulation time, and settling time tolerance. Moreover, Table 2 presents the objective function J and the time response specifications obtained by all algorithms. Notably, the proposed MPA method yields the smallest overshoot M_p, fastest rise time T_r, quickest settling time T_{set} and the smaller steady-state error E_{ss} when compared to other algorithms. Additionally, MPA remarkably achieves an outstanding result for J with recorded at 0.01108495 which is the lowest among other methods. In summary, the MPA-based method emerges as the most effective tool for fine-tuning the FOPID controller,



(a)

(b)

Fig. 4. (a) Reference signal for trajectory tracking. (b) Trajectory tracking responses from different algorithms.

Table 3
Comparison of trajectory tracking performances among various FOPID-based controllers.

Algorithm	ITSE	ITAE	ISE	IAE
MPA	**0.2803**	3.651	**0.09773**	0.8451
SA-MRFO	0.5945	4.756	0.2027	1.16
GBO	0.4729	4.254	0.1648	1.042
ChBWO	0.2902	**3.535**	0.1013	**0.8423**
PSO	1.438	7.388	0.4688	1.765
NSGA II	1.385	7.649	0.4715	1.823

demonstrating superior performance in terms of objective function and time response specifications.

Subsequently, a trajectory tracking analysis is carried out to assess the accuracy of the MPA-FOPID controller in following the newly introduced trajectory, which comprises sinusoidal and trapezoidal inputs, as depicted in Fig. 4(a). The FOPID gains outlined in Table 1 are utilized for this trajectory tracking evaluation. Controllers are comparatively evaluated based on their performance criteria, including Integral-Time-Square-Error (ITSE), Integral-Time-Absolute-Error (ITAE), Integral-Square-Error (ISE), and Integral-Absolute-Error (IAE). The simulation time is defined as $t_s = 15$ s during this trajectory tracking analysis. The responses of all controllers to the trajectory are illustrated in Fig. 4(b). The figure distinctly reveals that the MPA-FOPID controller exhibits an exceptional trajectory-tracking response, closely adhering to the reference input with exceptional accuracy. This observation is corroborated by the smallest ISE and ITSE values attained by MPA-FOPID, as indicated in Table 3. Consequently, these results emphasize the superior control efficacy of the MPA-FOPID controller in accurately tracking the desired trajectory.

5. Conclusion

This paper introduces an innovative tuning approach for the FOPID controller in the AVR system, utilizing the MPA. The step response analysis demonstrates that the MPA-FOPID controller beats other FOPID-based controllers, excelling in all time response specifications and achieving the lowest objective function J. Additionally, the trajectory tracking results affirm the superior control efficacy of the proposed controller in accurately following the desired trajectory. Furthermore, the versatility of the proposed MPA extends to nonlinear PID controllers, enabling solutions for practical applications like flexible manipulator systems, twin-rotor system, and gantry crane control systems.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

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