İSTANBUL UNIVERSITY CERRAHPAŞA

ORIGINAL ARTICLE
Electrica 2024; 24(2): 327-335

A Novel Fractional Order Proportional Integral-Fractional Order Proportional Derivative Controller Design Based on Symbiotic Organisms Search Algorithm for Speed Control of a Direct Current Motor

Yahya Danayiyen[1], Kerim Dinçer[2], Yasin Nuhoğlu[3]

[1]Department of Electrical and Electronics Engineering, Karadeniz Technical University, Faculty of Engineering, Trabzon, Türkiye
[2]Department of Energy Systems Engineering, Karadeniz Technical University, Faculty of Engineering, Trabzon, Türkiye
[3]Department of Electronics and Automation, Ordu University, Vocational School of Technical Sciences, Ordu, Türkiye

Cite this article as: Y. Danayiyen, K. Dincer and Y. Nuhoğlu, "A novel fractional order proportional integral-fractional order proportional derivative controller design based on symbiotic organisms search algorithm for speed control of a direct current motor," *Electrica*, 24(2), 327-335, 2024.

ABSTRACT

In this study, the effectiveness of symbiotic organisms search (SOS) algorithm including Zwee Lee Gaing (ZLG) objective function in determining the fractional order (FO) proportional integral and FO proportional derivative (FOPI-FOPD) controller parameters is investigated. To this aim, an FOPI-FOPD controller is designed to control speed of a direct current motor. To calculate the controller parameters in an optimal manner, the SOS algorithm is used and the ZLG function is included within this algorithm as a cost function. The performance of the SOS algorithm is compared with a number of different algorithms to substantiate the method's superiority, including the atomic search optimization (ASO), opposition-based hybrid manta ray foraging optimization (OBL-MRFO), chaotic atom search optimization (ChASO), equilibrium optimizer (EO), arithmetic optimization algorithm (AOA), and gorilla troops optimizer (GTO) algorithms. For performance evaluation, settling time, maximum overshoot, and rise time of the motor speed are chosen as evaluation criteria. The results indicate that the minimum settling time (0.0118 s) and minimum rise time (0.0071 s) are obtained with the SOS-based FO controller compared to the other optimization methods. Thus, the SOS algorithm provides superior system performance, as evidenced by reduced overshoot, shorter settling time, and faster rise time. This highlights the effectiveness of the SOS-based controller in achieving optimal system response. In addition, to verify the robustness of the proposed method, the impact of disturbance effects such as changes in the motor dynamics and load variations are evaluated. The findings reveal that the proposed method surpasses previous techniques in terms of robustness, demonstrating its superior resilience to disturbances in the motor system.

Index Terms— DC motor control, FOPI-FOPD controller, fractional order (FO), metaheuristic algorithms, symbiotic organisms search (SOS) algorithm

Corresponding author:
Yahya Danayiyen

E-mail:
yahya@ktu.edu.tr

Received: June 6, 2023

Revision Requested: September 20, 2023

Last Revision Received: November 20, 2023

Accepted: December 24, 2023

Publication Date: April 17, 2024

DOI: 10.5152/electrica.2024.23076

I. INTRODUCTION

A. Background

Due to their simplicity of control, advantageous torque-speed characteristics, and affordable solutions, direct current (DC) motors are widely employed in a variety of industries, from household appliances to industrial applications [1]. Ward Leonard first used voltage modulation to control the speed of this type of motor in 1891 [2]. Even though there has been a lot of research done on managing the speed of traditional AC motors over a wide range, AC motors have not yet been able to match the inherent flexibility and practicality of DC motors [3]. Due to their operational resemblance to conventional DC motors and their exemption from requiring supplemental components such as commutators and brushes, permanent magnet brushless DC motors have garnered considerable favor in contemporary engineering applications. The need for conventional DC motors will therefore continue in the future as they maintain their competitive position in industrial applications [4]. In order for DC motors to be utilized effectively and with optimal efficiency in industrial settings, it is imperative that their speeds are controlled in a precise and controlled manner. To do so, classical and advanced control techniques have been implemented in the literature.

B. Literature Review

The various speed control techniques for DC motors include classical PID controllers, model-based controllers [5, 6], and artificial neural network-based controllers [7, 8]. On the other hand, the fractional order proportional integral (FOPI) and fractional order proportional derivative (FOPD) controllers have gained more attention due to their superior performance over classical proportional integral derivative (PID) controllers, quick response, low cost, and simplicity of implementation [9-12]. However, the optimal calculation of these parameters is complicated by the fact that FOPI-FOPD has more parameters than classical PID controllers. Metaheuristic algorithms have recently started to be applied successfully to get around this [13-20, 21-24].

Coronavirus optimization algorithm (CVOA), harmony search (HS) optimization and genetic algorithm (GA) [15], particle swarm optimization (PSO) [20], chaotic atom search optimization (ChASO) [25], and opposition-based hybrid manta ray foraging optimization (OBL-MRFO) [26] have found their place in the design of FOPID controllers for DC motor speed control. In 2014, the symbiotic organisms search (SOS) algorithm was proposed as an effective metaheuristic that emulates the symbiotic relationships found among living beings, including mutualism, commensalism, and parasitism, in order to successfully adapt to and thrive within an ecosystem [27]. However, this algorithm has not been thoroughly investigated in the literature for the speed control of DC motors [28], particularly FOPI and FOPD controllers.

C. Research Gap and Motivation

Optimal determination of parameters in FOPI-FOPD controllers constitutes the most important stage of controller design. While designing, internal disturbances such as model uncertainties and external disturbances such as load variation should be taken into account. The applied method must respond optimally to these parameters. Studies conducted in recent years have proven that metaheuristic algorithms are effective in the design of the controllers. Nowadays, it is important that new algorithms constantly emerge, these algorithms are tested on existing systems and their effectiveness is validated. To do so, in this study, the SOS algorithm with ZLG function-based FOPI-FOPD is designed and the DC motor speed is controlled for the first time.

D. Challenges

Controller design is challenging because of disturbance effects on the system that need to be managed. Thus, a comprehensive analysis of the system dynamics is necessary to properly design the parameters of the controllers. Robust optimization techniques are necessary for systems that are especially vulnerable to both external and internal disturbances. As a result, consideration of system disturbances is crucial for the efficacy of the controller while assessing algorithmic effectiveness during the system design.

E. Contribution

After an exhaustive review of relevant literature, this study stands as the inaugural application of the SOS algorithm in the design of a FOPI-FOPD controller for DC motor speed control. The primary goal of this article is to implement the ZLG-based SOS algorithm to design the controller for DC motor speed control application. The most significant originality of this study lies in the utilization of the SOS algorithm in conjunction with the mentioned controller, as well as the initial application of the ZLG objective function in tandem with the SOS algorithm. In order to demonstrate the effectiveness of the proposed method, parameter variations such as torque constant and armature resistance are considered, and comparative results are presented. These results show the robustness of the system in the face of such changes and its ability to yield a fast transition response. To investigate the effectiveness of the SOS algorithm, the method is compared with atomic search optimization (ASO)-PID [25], OBL-MRFO-FOPID [26], ChASO-FOPID (fractional order proportional integral derivative) [25], equilibrium optimizer (EO)-FOPID, gorilla troops optimizer (GTO)-FOPID, and arithmetic optimization algorithm (AOA)- FOPID [29].

F. Paper Organization

The rest of the article is organized as follows: Section 2 explains the DC motor model, FOPI-FOPD controller, and the SOS algorithm. Results and discussion, including robustness analysis and transient response, are given in Section 3. Finally, conclusions are given in Section 4.

II. MATERIALS AND METHODS

In this section, the detailed mathematical derivations of the DC motor model, FO controller and the SOS algorithm are defined.

A. DC Motor Model

Fig. 1 shows the equivalent circuit model of a DC motor. In the circuit, R_a, L_a, i_a, V_a, and e_b are the armature resistance and inductance, armature current, terminal voltage, and the back emf. J is the moment of inertia, B is the motor friction constant, θ is the rotor position, τ is the motor torque, and K_m and K_b are the motor torque constant and motor back emf constant, respectively [30, 31].

To control the speed of the motor, the open loop transfer function from input to output can be defined as in (1).

$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{(L_a s + R_a)(Js + B) + K_m K_b} \quad (1)$$

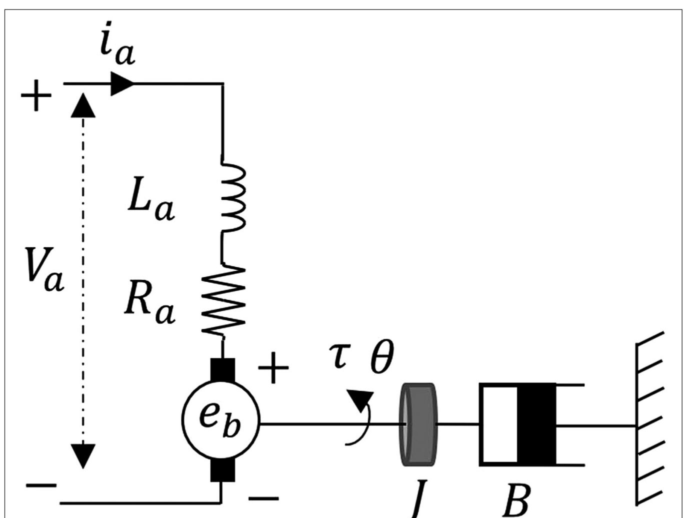

Fig. 1. DC motor equivalent circuit.

B. FOPI-FOPD Controller Design

The controller is designed by adding two different fractional order controllers (FOPI and FOPD) one after the other. Fig. 2 shows the general representation of the FOPI-FOPD controller.

The transfer function of the controller is defined as follows.

$$\left(K_{P_1}+K_I s^{-\lambda}\right)\Big/\left(K_{P_2}+K_D s^{\mu}\right) \tag{2}$$

Here, λ and μ are the fractional degrees of the integral term and derivative term respectively. K_{P_1}, K_{P_2}, K_I, and K_D are the proportional, integral, and derivative gains. These parameters will be determined optimally using SOS algorithm. It is noted that the FOPI-FOPD controller is a type of FOPID controller [22, 24].

To get the maximum performance from the proposed control system, an objective function defined in (3) named Zwee Lee Gaing (ZLG), which is proposed in [32], is used. This function minimizes the settling and rise time, and overshoot. In order to minimize this objective function, the optimal parameters are determined by the SOS.

$$\min\left(ZLG\right)=\left(1-e^{-\beta}\right)\left(M_p+E_{ss}\right)+e^{-\beta}\left(t_s-t_r\right) \tag{3}$$

Here M_p, E_{ss}, t_s, t_r, and β are the maximum overshoot, steady state error, settling time, rise time, and weight factor, respectively. $F=[K_{P1},K_{P2},K_I,K_D,\lambda,\mu]$ is the stabilizing gain vector.

C. Symbiotic Organisms Search (SOS) Algorithm

The symbiotic interactions that exist between two different types of organisms in an ecosystem serve as the basis for the SOS technique [27]. By creating a symbiotic relationship between two organisms, this technique establishes which organism is most suited to mate with a certain creature. Similar to other population-based algorithms, SOS starts with a randomly generated baseline population known as an ecosystem and uses potential solutions from the search space iteratively to find the best overall solution. Each organism in the ecosystem is a potential remedy, and its fitness value indicates how well suited it is to the specified function.

The SOS algorithm generates unique solutions by exploiting the symbiotic link between two ecosystem components. As a framework, it mimics actual biological interactions and includes a flowchart with stages for mutualism, commensalism, and parasitism, as depicted in Fig. 3. The algorithm takes into account E_s, or the number of creatures in the ecosystem, to minimize the objective function J_s.

1) Mutualism

Mutualism is a symbiotic relationship in which two different species benefit from one another. P_j is the *i*th organism in the ecosystem. P_j is another organism chosen at random from the ecosystem to interact with P_i. These two organisms interact to mutually increase their chances of survival in the ecosystem. Equations (4) and (5), which are based on the mutualism relationship between these two organisms, are used to calculate new candidate solutions for P_i and P_j.

$$P_i' = P_i + rand\left(0,1\right)\left(P_{best}-MVxE_{u1}\right) \tag{4}$$

$$P_j' = X_j + rand\left(0,1\right)\left(P_{best}-MVxE_{u2}\right) \tag{5}$$

$$MV=\frac{P_i+P_j}{2} \tag{6}$$

The utility factors E_{u1} and E_{u2} are used to determine the extent of utility acquired by organisms in mutualistic relationships.

2) Commensalism

At this stage, modeling is done in accordance with commensalism, which is a symbiotic relationship in which one of two species living together benefits from the other without harming the other. Only P_i benefits from the combination of these two organisms, with P_j in the mutualism stage being a randomly chosen organism from the ecosystem that will interact with P_i. Accordingly, new candidate solutions for P_i are calculated using (7) modeled according to the commensalism relationship.

$$P_i' = P_i + \text{rand}\left(-1,1\right)x\left(P_{best}-P_j\right) \tag{7}$$

3) Parasitism

The parasitism stage is a form of symbiotic relationship in which one of the two species benefits by harming the other. The organism P_i is used to generate a parasite vector, a type of artificial parasite. While creating the parasite vector, P_i is first amplified and then modified randomly within the boundaries of the search space. The P_j organism, on the other hand, is randomly selected from the ecosystem as in the previous stages and used as the host of the parasite. P_j is replaced in the ecosystem by the parasite vector. By comparing the fitness values of both organisms, if the parasite vector has a better fitness value, it replaces P_j in the ecosystem. If P_j has a better fitness value, it becomes immune to this parasite, and the parasite vector is no longer able to survive in the ecosystem.

III. PERFORMANCE ANALYSES

In order to verify the proposed SOS-FOPI-FOPD controller, various simulation studies have been carried out in the MATLAB environment by comparing it with ASO-PID [25], and ChaSO-FOPID [25], OBL-MRFO-FOPID [26], EO-FOPID [29], GTO-FOPID [29], and AOA-FOPID [29]. The nominal parameters of the permanent magnet DC motor, taken from the R730T-042EL7 model motor produced by Sanyo Denki and given in Table I, are used in the simulation studies.

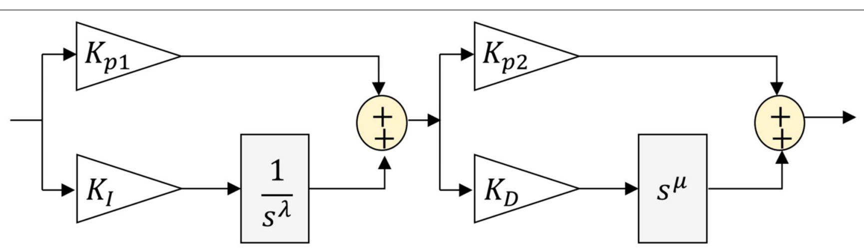

Fig. 2. Block diagram of the FOPI-FOPD controller.

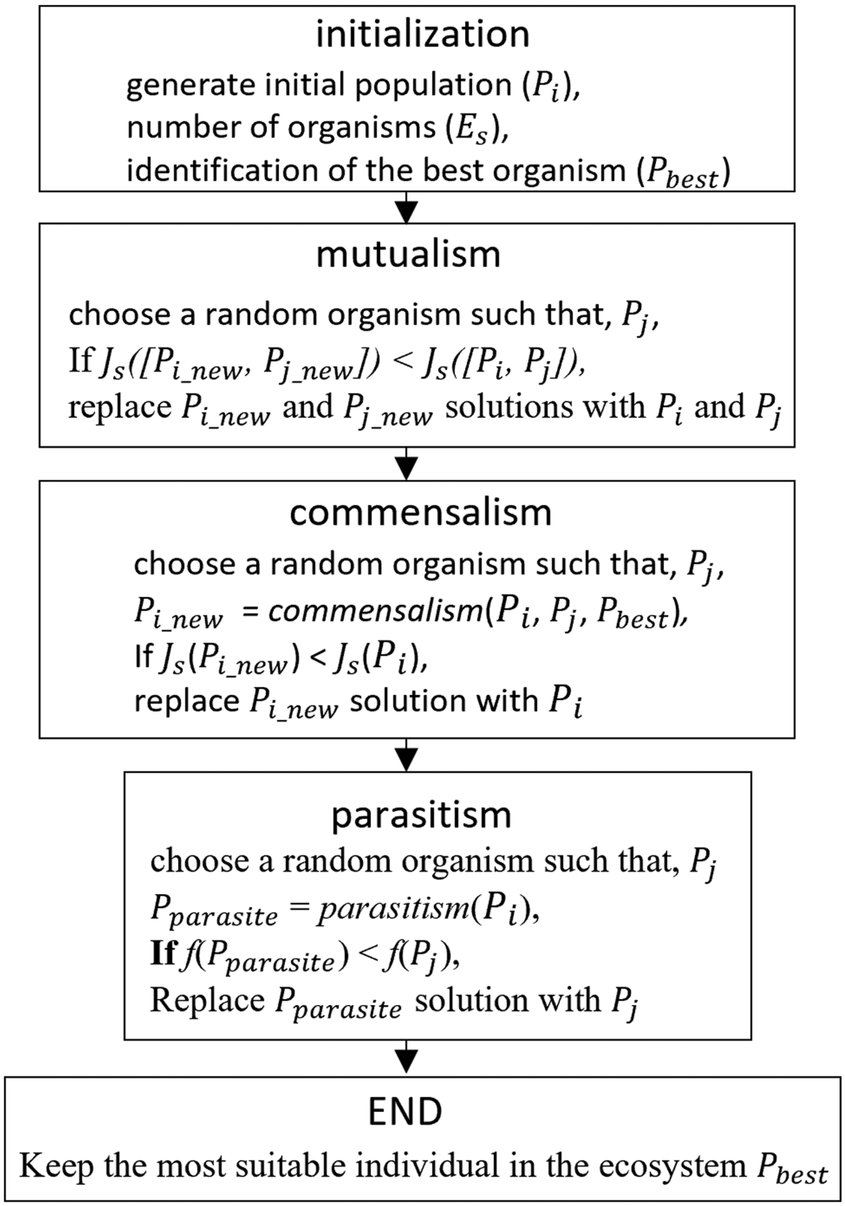

Fig. 3. General flow chart of the SOS algorithm.

When the nominal values are replaced in the transfer function, (1) becomes as follows.

$$\frac{\Omega(s)}{V_a(s)} = \frac{15}{1.08s^2 + 6.1s + 1.63} \tag{8}$$

Fig. 4 shows the general block diagram of the SOS-based FOPI-FOPD control system. The output of the system is the measured speed Ωm, the input of the system is the reference speed Ωr. The error between the reference and measured speed is the input of the controller. The optimum values of $F = [K_{P1}, K_{P2}, K_I, K_D, \lambda, \mu]$ are determined by the SOS algorithm as offline. To find the optimal controller parameters, the search space is defined for each parameter. The search space given in Table II is determined based on the papers [25, 26, 29] for a fair comparison. The SOS algorithm works on this space depending on the objective function. The population size

TABLE I. NOMINAL SYSTEM PARAMETERS

Parameters	Values
R_a	0.4 Ω
L_a	2.7 H
J	0.0004 kgm^2
B	0.0022 Nms/rad
K_m	0.015 Nm/A
K_b	0.05 Vs/rad

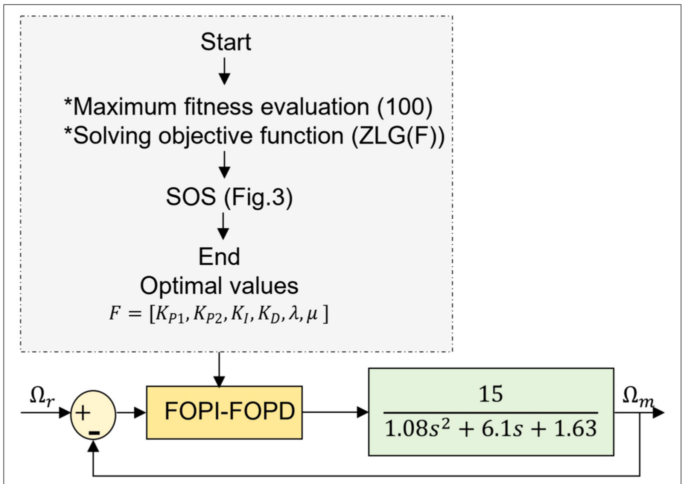

Fig. 4. Block diagram of SOS based FOPI-FOPD controller system.

specifies the number of solution candidates in the algorithm. It is chosen as 30 in the SOS. Fitness evaluation specifies how many times the objective function (3) is used within the algorithm loop. In this study, the fitness evaluation value is chosen as 100. Based on these parameters, the optimal values obtained in the optimization process are given in Table III.

Considering the values in Table III, the transfer function of the FOPI-FOPD controller (2) can be written as follows.

$$\frac{14.1464s^{1.8018} + 0.0017375s^{44.4347}s^{0.8018} + 0.0054576}{s^{0.8018}} \quad (9)$$

Following the determination of the system parameters in an optimal manner, firstly, to verify the open loop performance of the control system, a unit step function is applied as a reference speed to the input without a controller. It has been observed that the system output does not reach its reference value in a steady state as seen in Fig. 5.

It can be seen from Fig. 5 that the performance criteria do not satisfy the system requirements. These criteria are settling time (t_s), rise time (t_r), peak time (t_p), and steady state error (E_{ss}) which are given in Table IV.

A. Transient Response Analyses

The transient response of the proposed SOS-based FOPI-FOPD method is evaluated using performance criteria such as maximum overshoot (M_p), settling time (t_s), and rise time (t_r). The method is compared with ASO-PID [25], ChaSO-FOPID [25], OBL-MRFO-FOPID [26], EO-FOPID [29], GTO-FOPID [29], and AOA-FOPID [29] controllers. The comparative results given in Table V show that the proposed method yields better rise (0.0071 s) and settling (0.0118 s) times compared to other methods.

To see the transient response of the algorithms given in Table V, a step function is applied to the DC motor system as a reference speed in p.u. Fig. 6 shows that the proposed SOS-FOPI-FOPD method yields a faster transient response. It is noted that the performances of the last three methods in Table V are not included in the figure since they are not satisfactory at the desired level.

TABLE II. INTERVAL OF THE SELECTED VALUES

Parameters	Intervals
K_{P_1}	0.001–20
K_{P_2}	0.001–20
KI	0.001–20
KD	0.001–20
λ	0.1–1
μ	0.1–1

TABLE III. OPTIMAL VALUES BASED ON THE SOS ALGORITHM

Parameters	Optimal Values
K_{P_1}	8.1418
K_{P_2}	5.4576
KI	0.0010
KD	1.7375
λ	0.8018
μ	1.0000

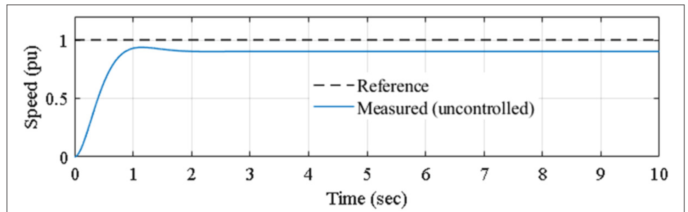

Fig. 5. Uncontrolled DC motor speed response.

TABLE IV. SPEED RESPONSE ANALYSES WITHOUT CONTROLLER

Reference	t_s	t_r	t_p	E_{ss}
1 p.u.	1.6085	0.7280	1.1530	0.0980

TABLE V. COMPARATIVE RESULTS FOR TRANSIENT RESPONSES

Controllers	Max. Over shoot (%)	Settling Time (s) (±%5)	Rise Time (s) (0.1 –0.9)
SOS-FOPI-FOPD	0	0.0118	0.0071
ASO-PID	0	0.1535	0.0692
ChASO-FOPID	0	0.0405	0.0253
OBL-MRF-FOPID	0	0.0339	0.0214
EO-FOPID	0.190	0.0354	0.0206
AOA-FOPID	0.005	0.0396	0.0207
GTO-FOPID	0.150	0.0356	0.0206

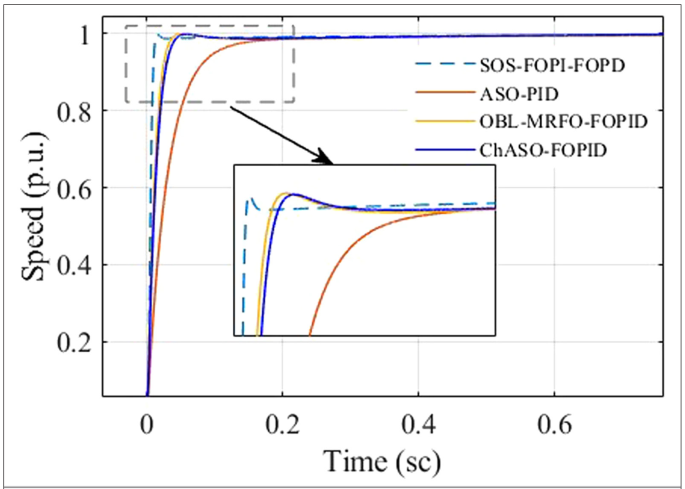

Fig. 6. Transient response comparison.

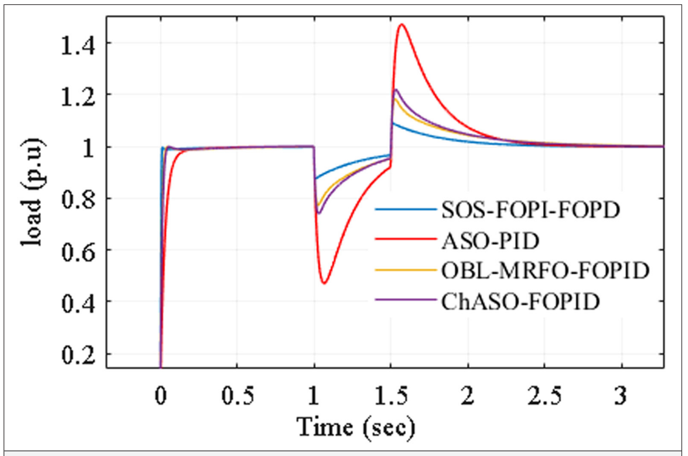

Fig. 7. Robustness analysis under load change.

B. Robustness Analysis

During the operation of the DC motor applications, some external factors such as load change, heat, etc. may cause the motor parameters torque constant (K_m) and armature resistance (R_a) to change. In such cases, it is not desirable to deteriorate the stability of the control system. To verify the effectiveness of the proposed method in the presence of parameter change, K_m and R_a are changed at the rates of −50%, −25%, 25%, and 50% from the nominal values. For these different rates of change, Table VI shows the performance criteria (rise time, settling time, and maximum overshoot). The parameter change does not significantly affect the performance of the controller despite the −50%, −25%, 25%, and 50% deteriorations of R_a and K_m. The highest rise time is 0.0190 s (−50% K_m), the highest maximum overshoot is 7.6214% (+50% K_m) and the highest settling time is 0.1046 s (−50% K_m). Based on the data given in Table VI, it can be said that the proposed method yields better robustness in the presence of parameter change.

Secondly, the robustness analysis is carried out based on the load change which acts as an external disturbance to evaluate the effectiveness of the proposed method. A load step (T_{load}) is applied to the DC motor model at time intervals of 1–1.5 s as a disturbance load. Fig. 7 shows the comparative results of the transient response of ASO-PID, OBL-MRFO-FOPID, ChASO-FOPID, and SOS-FOPI-FOPD controllers. It is clear that the proposed method is more robust since the maximum overshoot is smaller compared to other methods during the load change.

TABLE VI. ROBUSTNESS ANALYSIS

P.	Rate of Change (%)	Rise Time (s) (0.1–0.9)	Max. Over shoot (%)	Settling Time (s) (±%5)
K_m	−50	0.0190	0	0.1046
	−25	0.0107	0	0.0235
	+25	0.0054	3.395	0.0137
	+50	0.0044	7.621	0.0133
R_a	−50	0.0071	0	0.0118
	−25	0.0071	0	0.0118
	+25	0.0071	0	0.0118
	+50	0.0071	0	0.0118

TABLE VII. FREQUENCY RESPONSES OF DIFFERENT ALGORITHMS

Controllers	Gain Margin (dB)	Phase Margin (deg.)	Bandwidth
SOS-FOPI-FOPD	20.2	69.2	0.2646
ASO-PID [25]	Infinite	180	32.9113
ChASO-FOPID [26]	Infinite	179.3515	84.7989
OBL-MRFO-FOPID [29]	Infinite	179.5836	99.4956

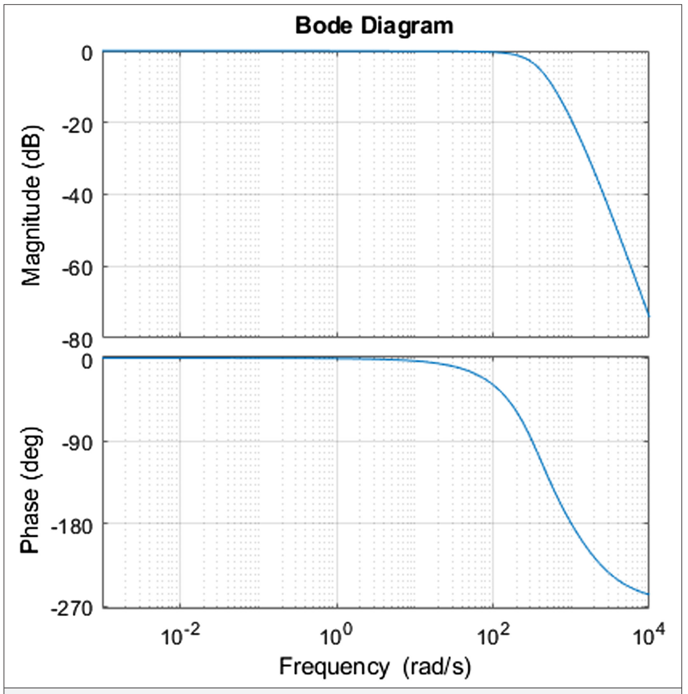

Fig. 8. Bode analyses of SOS-based controller.

C. Frequency Response Analysis

The system's distance from instability is indicated by the phase and gain margins. The bandwidth of the system, which is relevant and inversely connected with the rise time, is essential for a quick response. The stability analysis of the proposed method, based on the SOS algorithm, is conducted by evaluating the phase and gain margins. A comparative analysis with existing studies [25, 26] is presented in Table VII. Furthermore, the Bode diagram illustrating the characteristics of the proposed method is depicted in Fig. 8. The frequency domain analysis is not carried out in [29]. Table VII encapsulates the Bode analysis outcomes of both extant literature studies and the proposed method. In particular, the controller devised in this study manifests comparatively lower results in the gain margin when evaluated with alternative controllers. Nevertheless, the bandwidth value achieved by the proposed controller stands notably favorable in contrast to its counterparts. The phase margin of the proposed controller closely aligns with those attained in antecedent studies. Consequently, the discernible attributes of the proposed controller include a low rise time, indicative of prompt responsiveness to dynamic changes, and an overall stable structural configuration.

IV. CONCLUSION

This article presents an SOS algorithm-based FOPI-FOPD controller to control the speed of a DC motor. The proposed method is compared with other metaheuristic algorithms [25, 26, 29] considering model uncertainties and disturbance load effect to verify the effectiveness of the control system. The results show that the proposed SOS-FOPI-FOPD controller performed better than 89% of ASO-PID, 67% better than the OBL-MRFO-FOPID, and 72% better than the ChASO-FOPID in terms of rise time. Moreover, the proposed method performed 92%, 65%, and 71% better than the other controllers in terms of seating time. In addition, the method is more robust since the maximum overshoot is smaller compared to other methods during the disturbance load change.

This study represents a pioneering endeavor in the realm of DC motor speed control, introducing the design of a FOPI-FOPD controller through the utilization of the SOS algorithm. Moreover, the incorporation of the ZLG function with SOS is introduced for the first time, demonstrating its application in tandem. Through a comprehensive analysis of the results, it is discerned that the ZLG-based SOS methodology facilitates the optimal identification of the controller parameters, thereby establishing a foundation for their effective utilization in motor speed control applications.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – K.D, Y. N.; Design – Y.D., K.D., Y.N.; Supervision –Y.D.; Materials –Y.D, Y.N., K.D.; Data Collection and/or Processing – K.D., Y.N.; Analysis and/or Interpretation – Y.D., Y.N.; Literature Review – K.D., Y.N.; Writing –Y.D., K.D., Y.N.; Critical Review –Y.D

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: The authors declared that this study has received no financial support. .

REFERENCES

1. V. Lechappe et al., "Delay estimation and predictive control of uncertain systems with input delay: Application to a DC motor," *IEEE Trans. Ind. Electron.*, vol. 63, no. 9, pp. 5849–5857, 2016. [CrossRef]
2. O. Bingol, and S. Pacaci, "A virtual laboratory for fuzzy logic controlled DC motors," *International Journal Of Physical Sciences*, vol. 5, no. 16, pp. 2493–2502, 2010. Available: https://academicjournals.org/journal/IJPS/article-abstract/C522C1D34615
3. M. Kushwah, and P. A. Patra, "'Tuning PID Controller for Speed Control of DC Motor Using Soft Computing Techniques-A Review," *Research India Publications*, vol. 4, no. 2, pp. 141–148, 2014. Available: http://www.ripublication.com/aeee.htm
4. Z. Y. Tong, Z. Y. Dong, and M. Li, "A new entropy bi-cepstrum based-method for dc motor brush abnormality recognition," *IEEE Sens. J.*, vol. 17, no. 3, pp. 745–754, Feb. 2017. [CrossRef]
5. J. A. Niembro-Ceceña, R. A. Gómez-Loenzo, J. Rodríguez-Reséndiz, O. Rodríguez-Abreo, and Á. Odry, "Auto-regression model-based off-line PID controller tuning: An adaptive strategy for DC motor control," *Micromachines (Basel)*, vol. 13, no. 8, 2022. [CrossRef]
6. M. Vidlak, P. Makys, and M. Stano, "Comparison between model based and non-model based sensorless methods of brushed DC motor,", in *Transp. Res. Procedia*. Elsevier B.V., vol. 55, pp. 911–918, 2021. [CrossRef]
7. A. Traue, G. Book, W. Kirchgassner, and O. Wallscheid, "Toward a reinforcement learning environment toolbox for intelligent electric motor control," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 33, no. 3, pp. 919–928, 2022. [CrossRef]
8. K. H. Al-Waeli, R. Ramli, S. M. Haris, Z. B. Zulkoffli, and M. S. Amiri, "Offline ANN-PID controller tuning on a multi-joints lower limb exoskeleton for gait rehabilitation," *IEEE Access*, vol. 9, pp. 107360–107374, 2021. [CrossRef]
9. F. Oliva-Palomo, A. J. Muñoz-Vázquez, A. Sánchez-Orta, V. Parra-Vega, C. Izaguirre-Espinosa, and P. Castillo, "A fractional nonlinear PI-structure control for robust attitude tracking of quadrotors," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 55, no. 6, pp. 2911–2920, 2019. [CrossRef]
10. H. Li, Y. Luo, and Y. Chen, "A fractional order proportional and derivative (FOPD) motion controller: Tuning rule and experiments," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 2, pp. 516–520, Mar. 2010. [CrossRef]
11. A. Tepljakov, E. A. Gonzalez, E. Petlenkov, J. Belikov, C. A. Monje, and I. Petráš, "Incorporation of fractional-order dynamics into an existing PI/PID DC motor control loop," *ISA Trans.*, vol. 60, pp. 262–273, 2016. [CrossRef]
12. V. P. Shankaran, S. I. Azid, U. Mehta, and A. Fagiolini, "Improved performance in quadrotor trajectory tracking using MIMO PI-D control," *IEEE Access*, vol. 10, pp. 110646–110660, 2022. [CrossRef]
13. A. Idir, K. Khettab, and Y. Bensafia, "Design of an optimally tuned fractionalized PID controller for DC motor speed control via a henry gas solubility optimization algorithm," *Int. J. Intell. Eng. Syst.*, vol. 15, no. 3, pp. 59–70, 2022. [CrossRef]
14. B. B. Acharya, S. Dhakal, A. Bhattarai, and N. Bhattarai, "Pid speed control of dc motor using meta-heuristic algorithms," *IJPEDS*, vol. 12, no. 2, pp. 822–831, 2021. [CrossRef]
15. M. A. Shamseldin, "Optimal coronavirus optimization algorithm based pid controller for high performance brushless dc motor," *Algorithms*, vol. 14, no. 7, 2021. [CrossRef]
16. D. A. Souza, V. A. de Mesquita, L. L. N. Reis, W. A. Silva, and J. G. Batista, "Optimal LQI and PID synthesis for speed control of switched reluctance motor using metaheuristic techniques," *Int. J. Control Autom. Syst.*, vol. 19, no. 1, pp. 221–229, 2021. [CrossRef]
17. W. Aribowo, S. Supari, and B. Suprianto, "Optimization of PID parameters for controlling DC motor based on the aquila optimizer algorithm," *IJPEDS*, vol. 13, no. 1, pp. 216–222, 2022. [CrossRef]
18. L. Yin, X. Cao, and L. Chen, "High-dimensional multiple fractional order controller for automatic generation control and automatic voltage regulation," *Int. J. Control Autom. Syst.*, vol. 20, no. 12, pp. 3979–3995, 2022. [CrossRef]
19. X. Li, and L. Gao, "Robust fractional-order PID tuning method for a plant with an uncertain parameter," *Int. J. Control Autom. Syst.*, vol. 19, no. 3, pp. 1302–1310, 2021. [CrossRef]
20. J. Y. Jhang, C. J. Lin, C. T. Lin, and K. Y. Young, "Navigation control of mobile robots using an interval Type-2 fuzzy controller based on dynamic-group particle swarm optimization," *Int. J. Control Autom. Syst.*, vol. 16, no. 5, pp. 2446–2457, 2018. [CrossRef]
21. D. İzci, and S. Ekinci, "Comparative performance analysis of slime mould algorithm for efficient design of proportional–integral– derivative controller," *Electrica*, vol. 21, no. 1, pp. 151–159, 2021. [CrossRef]
22. D. İzci, S. Ekinci, M. Kayri, and E. Eker, "A novel enhanced metaheuristic algorithm for automobile cruise control system," *Electrica*, vol. 21, no. 3, pp. 283–297, 2021. [CrossRef]

23. Y. Arya, "A new optimized fuzzy FOPI-FOPD controller for automatic generation control of electric power systems," *J. Franklin Inst.*, vol. 356, no. 11, pp. 5611–5629, 2019. [CrossRef]
24. K. Peddakapu, P. Srinivasarao, M. R. Mohamed, Y. Arya, and D. J. K. Kishore, "Stabilization of frequency in Multi-Microgrid system using barnacle mating Optimizer-based cascade controllers," *Sustain. Energy Technol. Assess.*, vol. 54, no. Dec., 2022. [CrossRef]
25. B. Hekimoglu, "Optimal tuning of fractional order PID controller for DC motor speed control via chaotic atom search optimization algorithm," *IEEE Access*, vol. 7, pp. 38100–38114, 2019. [CrossRef]
26. S. Ekinci, D. Izci, and B. Hekimoğlu, "Optimal FOPID speed control of DC motor via opposition-based hybrid manta ray foraging optimization and simulated annealing algorithm," *Arab. J. Sci. Eng.*, vol. 46, no. 2, pp. 1395–1409, 2021. [CrossRef]
27. M. Y. Cheng, and D. Prayogo, "Symbiotic Organisms Search: A new metaheuristic optimization algorithm," *Comput. Struct.*, vol. 139, pp. 98–112, 2014. [CrossRef]
28. E. Çelik, and N. Öztürk, "First application of symbiotic organisms search algorithm to off-line optimization of PI parameters for DSP-based DC motor drives," *Neural Comput. Appl.*, vol. 30, no. 5, pp. 1689–1699, 2018. [CrossRef]
29. K. Dincer, and H. Kahveci, "Yapay goril birlikleri optimizasyonu, aritmetik optimizasyon algoritması ve denge optimize edici ile doğru akım motoru uygulaması," Selçuk Zirvesi 7. Uluslararasi Uygulamali Bilimler Kongresi. Konya, Turkey, 2022, pp. 165–177.
30. B. Çavdar, E. Sahin, and F. Nuroglu, "SSA-based fractional order PI-PD cascade controller design for DC motor speed control," *J. Polytech.*, 2022. [CrossRef]
31. S. N. Norman, *Control Systems Engineering*, 6th ed. Chichester, UK: Wiley, 2010.
32. Z.-L. Gaing, "A particle swarm optimization approach for optimum design of PID controller in AVR system," *IEEE Trans. Energy Convers.*, vol. 19, no. 2, pp. 384–391, 2004. [CrossRef]

Yahya Danayiyen is currently a lecturer with the Department of Electrical and Electronics Engineering, Karadeniz Technical University, Trabzon, Türkiye. He received the B.S., M.S., Ph.D. degrees in electrical and electronics engineering from the Karadeniz Technical University, in 2009, 2013, and 2021, respectively. In 2015, he was a visiting PhD researcher with the University of Southampton, Southampton, UK, and from 2017 to 2018, with Seoul National University of Science and Technology, Seoul, South Korea. His research interests include model predictive control, power electronic converters, and optimal control.

Kerim Dinçer is currently a research assistant with the Department of Energy Systems Engineering, Karadeniz Technical University, Trabzon, Türkiye. He received the B.S. and M.S. degrees in Electrical and Electronics Engineering from the Karadeniz Technical University in 2018 and 2022, respectively. In 2019, he was a visiting exchange student with the University of Kassel, Kassel, Germany. He is currently a PhD in Electrical and Electronics Engineering at Karadeniz Technical University. His research interests include metaheuristic algorithms, control theory, power systems, and converters.

Yasin Nuhoğlu is currently a lecturer with the Department of Electronics and Automation, Vocational School of Technical Sciences, Ordu University, Ordu, Türkiye. He received the B.S. degree in Electrical and Electronics Engineering from Atatürk University in 2016. He received the M.S. degree in Electrical and Electronics Engineering from Erzurum Technical University in 2019. He is currently a PhD in Electrical and Electronics Engineering at Karadeniz Technical University. His research interests include control systems, renewable energy systems, biomedical image processing, and machine learning.