International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

A hybrid optimization scheme for tuning fractional order PID controller parameters for a DC motor

Ruby Chinyere Beremeh [1], Adunola Fatai Olatunde [1], Joshua Sokowonci Mommoh [2, *], Abel Airoboman [1], Solomon Obhenbhen Ibharunujele [3] and Dada Anuoluwapo Emmanuel [1]

[1] *Department of Electrical Electronic Engineering, Nigerian Defence Academy, Kaduna, 800281, Nigeria.*
[2] *Department of Software Engineering, Mudiame University Irrua, Edo, 310112, Nigeria.*
[3] *Department of Electrical &Electronic Engineering, Ambrose Alli University, Ekpoma, Edo, 310101, Nigeria.*

International Journal of Science and Research Archive, 2024, 13(02), 2779–2789

Publication history: Received on 31 October 2024; revised on 10 December 2024; accepted on 12 December 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.13.2.2291

Abstract

This paper on a hybrid optimization scheme for tuning fractional order PID (FOPID) controller parameters for a DC motor explored the effectiveness of a hybrid GA-PSO approach in optimizing FOPID controller parameters. The DC motor is faced with the following challenges: brush wear and maintenance, limited speed control range, limited lifespan, size and weight, efficiency complexity of control systems, and spark generation. This problem arises from the poor tuning of the PID controller used in the systems. First, a DC motor was modelled along with an FOPID controller in a MATLAB environment. Secondly, a hybrid scheme (GA-PSO) was designed in MATLAB environment. Furthermore, the performance of the hybrid scheme (GA-PSO) was compared with GA and PSO used distinctly. The GA-PSO hybrid algorithm outperforms other algorithms in terms of rise time of 0.30, settling time of 2.90, overshoot of 5.29, peak to peak of 1.05, and peak values of 0.59. The results show improvements in key performance indicators, offering insights for improving DC motor control.

Keywords: DC MOTOR; HYBRID; FOPID; GA-PSO

1. Introduction

A crucial research area for engineering applications is the design of a proportional-integral-derivative (PID) controller for a variety of practical situations. The PID controller offers the simplest and most efficient solution [1][2]. PID controllers are employed in both high-tech and low-tech industries. Operating in heavy industries such as shipyards and refineries often involves dealing with PID controllers. PID is essentially a combination of three control units. The differential, integral, and proportional controls are what they are. A piece of a system fault is utilized to control the system in proportional control. This action applies an offset to the system. Integral control adds a lag to the system in order to eliminate the offset that proportional action had previously added. To eliminate the lag caused by the integral action, a lead is added to the system in the derivative control action [3]. Maintaining a measured process value at a predetermined point, or intended value, is the primary objective of PID controller implementation. Therefore, it is essential to fine-tune PID controllers to minimize control error variability and optimize their reactions to set point changes and unmeasured disturbances. To increase production and prolong the safe and reliable operation of machinery, a PID controller needs to be appropriately tuned. There are numerous ways to fine-tune the PID controller [4]-[6]. For example, fractional order proportional integral derivation and fuzzy logic controller. A modification of the conventional PID controller, the Fractional Order Proportional-Integral-Derivative (FOPID) controller applies techniques from fractional calculus to enhance control performance in specific applications. Utilizing non-integer differentiation and integration orders is a need for fractional calculus [7]. Proportional (P) in an FOPID controller

* Corresponding author: Joshua Sokowonci Mommoh

responds proportionately to the current error, much like it does in a conventional PID controller. Fractional integration is used in integral (I), which enables the controller to more skillfully handle long-memory effects in system dynamics. Fractional differentiation is incorporated into Derivative (D), allowing the controller to manage systems with non-integer order dynamics. Five parameters make up the Fractional Order PID (FOPID) controller, a unique type of PID controller: Kp, Ki, Kd, and the one to be adjusted. More flexibility in recording complicated system behaviors, particularly those with memory-dependent or non-integer order properties, is provided by the fractional order components [8]-[10]. FOPID controllers are used in applications where typical PID controls would have trouble achieving optimal performance, like biomedical systems, robotics, and chemical reactions. For the controller to respond to particular system dynamics, fine-tuning the fractional order parameters is essential [11]. The goal of the mathematical and computational field of optimization is to solve a problem as well as it can be given a given set of constraints. It is widely applied in a wide range of disciplines and fields, from operations research and machine learning to engineering and economics. The objective function, decision variables, restrictions, and local versus global optimization are some of the various essential ideas in optimization [12]. Two categories under the umbrella of optimization include continuous optimization techniques, which consist of gradient descent, Newton's method, quasi-Newton methods, conjugate gradient methods, and interior point methods, and discrete optimization methods, which consist of swarm intelligence (SI) and evolutionary algorithms (EAs). These have been shown to be effective search and optimization techniques for a variety of engineering applications, which include particle swarm optimization (PSO), bee colony, firefly algorithm, and cuckoo search, prominent algorithms in SI. Others are genetic algorithms (GAs), genetic programming, and differential evolution, which are major algorithms in EAs, which are population-based techniques [13]-[15]. The term "hybrid" in this study generally refers to the combination of elements from different sources or systems, resulting in a mixed or integrated entity. In various contexts, "hybrid" can be used to describe combinations of technologies, systems, or methodologies. The concept of hybridization often aims to leverage the strengths of different approaches, technologies, or systems, creating solutions that are more robust, adaptable, or efficient than their individual components [16,17]. Presently, DC motors are faced with numerous challenges, such as brush wear and maintenance, limited speed control range, limited lifespan, size, weight, efficiency, complexity of control systems, and spark generation [18, 19]. A well-tuned system allows equipment to run longer and safer, whereas a poorly tuned system may increase the frequency of failures, losses, and safety problems. The goal of this research is to solve the problem of limited speed control range, limited lifespan, size and weight, efficiency, complexity of control systems, and spark generation, which results from the poor tuning of the PID controller used in the system by employing a hybrid optimization scheme (GA-PSO).

2. Methodology

2.1. Modelling of DC Motor

A DC motor is an electric machine that transforms DC power into mechanical power in the form of rotation of the rotor. The transfer function of a DC motor describes the relationship between the input voltage and the output angular velocity or position [20].

The implementation involves electrical and mechanical parts of the motor and then combining these models.

2.1.1. Electrical Model

The electrical part of the DC motor is represented by the equation [21]:

$$v(t) = L\frac{di(t)}{d(t)} + R_i(t) + e(t) \quad \text{................ (1)}$$

Where,

L = inductance
R= Resistance
i (t) =the armature current
$v(t)$ = the applied voltage

e(t) = is the back electromotive force, or EMF, which varies with the motor's angular velocity: $e(t) = K_e \varpi(t)$

2.1.2. Mechanical Model

The Mechanical part of the DC motor is represented by the equation 2 [21]:

$$T(t) = J\frac{d\varpi(t)}{d(t)} + B\varpi(t) \quad \text{.................. (2)}$$

Where,

$T(t)$ =is the torque generated by the motor, which is proportional to the armature current $T(t) = K_t i(t)$
J =inertia of the rotor
B =damping coefficient
$\varpi(t)$ = angular velocity

2.1.3. Ccombining Electrical and Mechanical Model

By combining the electrical and mechanical equations (1) and (2), we can derive the transfer function. First, solve the electrical equation for $i(t)$

$$V(t) = L\frac{di(t)}{d(t)} + Ri(t) + K_e\varpi(t) \quad \text{................ (3)}$$

Taking the Laplace transform (assuming zero initial conditions) gives:

$$V(s) = LsI(s) + RI(s) + K_e\Omega(s) \quad \text{................ (4)}$$

$$V(s) = (Ls + R)I(s) + K_e\Omega(s) \quad \text{............. (5)}$$

Solving for I(s) for the armature current:

$$I(s) = \frac{v(s) - K_e\Omega(s)}{Ls + R} \quad \text{.......... (6)}$$

Substitute I(s) into the mechanical equation:

$$J(s)\Omega(s) + B\Omega(s) = K_t I(s) \quad \text{............... (7)}$$

$$J(s)\Omega(s) + B\Omega(s) = K_t\frac{v(s) - K_e\Omega(s)}{Ls + R} \quad \text{...................... (8)}$$

Rearranging and solving for $\frac{\Omega(s)}{v(s)}$:

$$(Js + B)\Omega(s)(Ls + R) = K_t V(s) - K_t K_e\Omega(s) \quad \text{................. (9)}$$

$$K_t V(s) = (Js + B)(Ls + R)\Omega(s) + K_t K_e\Omega(s) \quad \text{................... (10)}$$

$$\frac{V(s)\times K_t}{(Js + B)(Ls + R)\Omega(s) + K_t K_e\Omega(s)} \quad \text{............................ (11)}$$

Finally, the transfer function[10] for is $\frac{\Omega(s)}{v(s)}$:

$$\omega(s) = \frac{\theta(s)}{v(s)} = \frac{k}{(Las + Ra)[(Js + b) + K_t k_b]} \quad \text{.................. (12)}$$

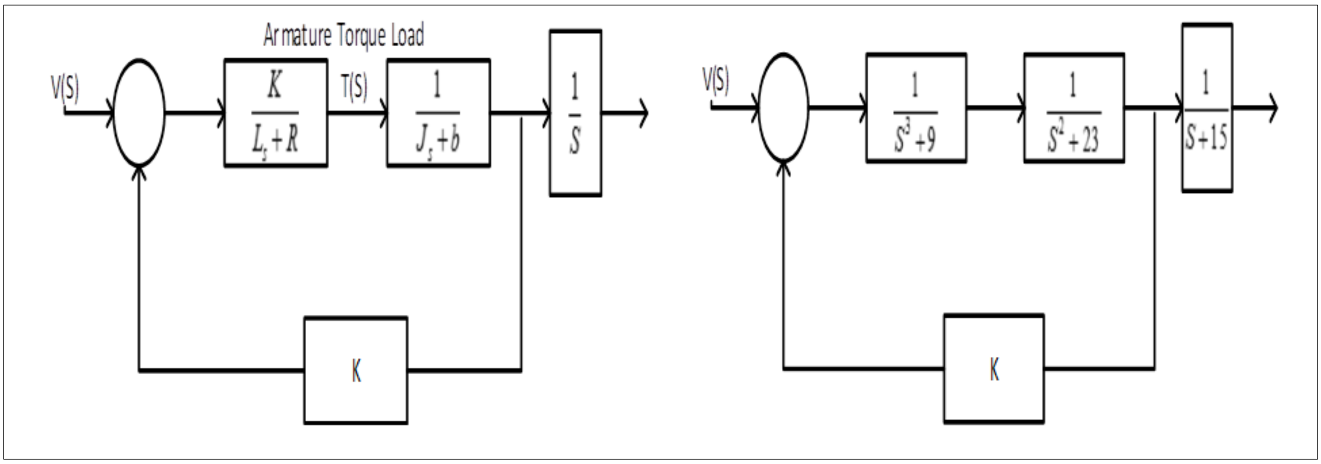

Figure 1 Block diagram of the DC motor transfer function

$$G(s) = \frac{1}{(s^3 + 9)(s^2 + 23)(s + 15)} \quad \text{................. (13)}$$

The transfer function captures the dynamics of the DC motor and is used to show the efficacy of the presented method. The transfer function was gotten from [11] for the modelling of a DC motor and is defined in equation 14.

$$G(s) = \frac{1}{s^3 + 9 \times s^2 + 23 \times s + 15} \quad \text{........................ (14)}$$

A controller based on a closed-loop feedback control is designed to stabilize the closed-loop system based on predefined characteristics of equality. Digital PID controller can be described by discrete transfer function as defined in Equation 15.

$$U(s) = \frac{K_d \times s^2 + K_P \times s + K_i}{s} \quad \text{............. (15)}$$

2.2. Design of FOPID Controller

A fractional order proportional-integral-derivative (FOPID) controller was used to regulate the DC motor. The system will have the ability to modify the DC motor's control. The following procedures were followed in order to apply a fractional order proportional integral derivative (FOPID) controller to a DC motor.

Model Identification: Identify the transfer function of your DC motor system, which was analyzed in equations 13 and 14, where (K) is the gain and (s) is the time constant.

Select FOPID Parameters: Select the derivative, integral, and proportional terms' fractional orders (α, β). These figures were either 1.5 or 0.5. To match the FOPID structure, modify the conventional PID parameters (proportional gain Kp, integral gain Ki, and derivative gain Kd), which represent the integrator and differentiator orders, respectively.

Formulate FOPID Controller: The FOPID controller is represented in equation 16 [5].

$$PI^{\lambda}D^{\mu} = K_P + K_I \times S^{-\lambda} + K_d \times S^{\mu} \quad \dots\dots\dots \ (16)$$

Combine System and Controller: Formulate the open-loop transfer function

$$Gc(s) = C(s)G(s). \quad \dots\dots\dots\dots\dots \ (17)$$

Analyze and Tune: Analyze the open-loop system and tune the FOPID parameters to achieve the desired performance of the overshoot, settling time Rise time, etc.

Simulate and Implement: Simulate the closed-loop system using MATLAB software or Simulink. Implement the controller on an uncontrolled DC motor system and observe its behavior.

Iterative Tuning: Fine-tune the parameters iteratively based on the system response until satisfactory performance is achieved.

2.2.1. Design of GA-PSO FOPID Controller

Designing a GA-PSO FOPID (GA-PSO Fractional Order Proportional Integral Derivative) controller involves hybridization of genetic algorithms and particle swarm optimization to become one algorithm with a fractional order control strategy. The parameters used in the single GA and PSO parameters are shown in tables 1 and 2, where the algorithm was combined to produce one algorithm, a step-by-step procedure used in the simulation of a GA-PSO FOPID controller for a DC motor.

Table 1 Parameter Setting For GA-FOPID

Parameter	**Value**
Population Size	100
Mutation Fraction	0.1
Beta	1
Gamma	0.1
Sigma	0.1
Crossover Fraction	0.8
Lower boundary	0
Upper boundary	100
Iteration	100

Table 2 Parameter Setting For PSO-FOPID

Parameter	**Value**
Swarm size	100
Inertia weight (ω)	0.99
Lower boundary	-100
Social parameter (β)	2.0
Upper boundary	100
Iteration	100
Cognitive parameter(α)	1.5

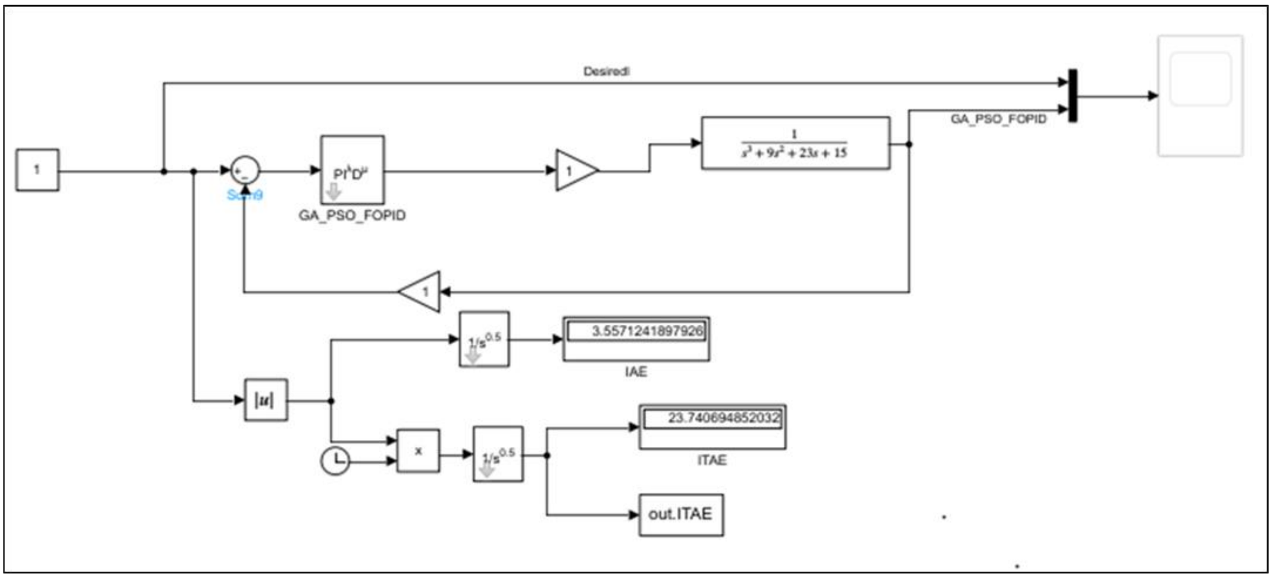

Figure 2 Simulink diagram of GA-PSO -FOPID for a DC motor

Figure 2 shows the Simulink diagram of GA-PSO-FOPID, illustrating a step-by-step process on how the GA-PSO was implemented on MATLAB. These Simulink states have an FOPID controller, a gains transfer function, a scope that displays a step of time response, and the IAE and ITEA, which are the fitness function analysis of the error of the DC motor.

2.2.2. Implementation GA-PSO FOPID Optimization Process

- Initialization: Initialize populations for both GA and PSO components with random solutions (individuals or particles). Defines the initial exploration space for both components.
- Evaluation: Evaluate fitness for each individual or particle in both populations using the fitness function. Determines the quality of solutions in both populations.
- GA Operations: Apply genetic operations (crossover and mutation) to individuals in the GA population. Evolutionary processes in the GA component.
- PSO Operations: Update velocities and positions of particles in the PSO population. Swarm-based optimization processes in the PSO component.
- Combining Solutions: Combine solutions from both populations to form a hybrid population Integrates diverse search strategies from both GA and PSO components.
- Convergence Check: Check convergence criteria, such as reaching a target fitness or a maximum number of iterations. Determines when the optimization process should stop.
- Iteration: Repeat steps ii to v for a predefined number of iterations or until a convergence criterion is met in each iteration which evolves the swarm toward a better optimal solution.

3. Results

3.1. DC Motor with FOPID Controller

The FOPID controller's step response is seen in Figure 3. The step response in the FOPID controller offered a measure for the DC motor control system's steady-state performance. Good performance is often shown by exhibiting rising time, settling time, overshoot, and undershoot in addition to minor integral error values (IAE and ITAE). Further information about the dynamics of the system may be gleaned from the peak time and peak value.

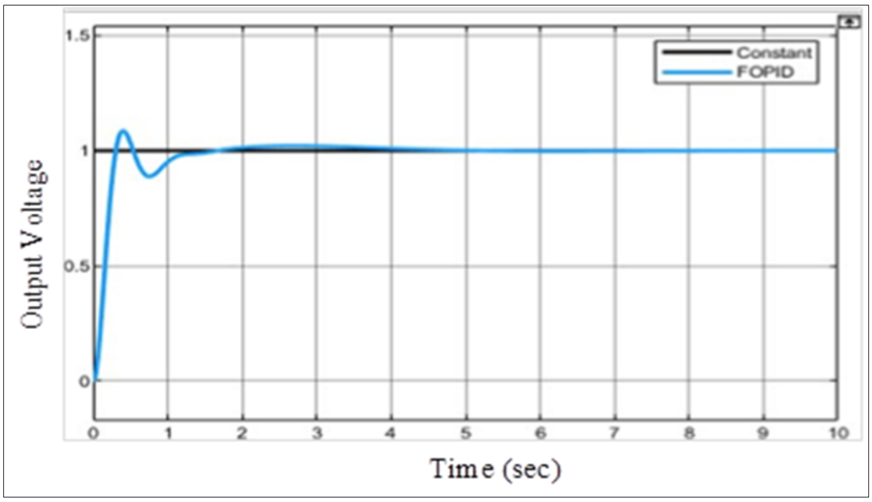

Figure 3 Step Response for a controlled FOPID system without algorithm

The FOPID controller applied to the DC motor performs reasonably well, with a fast rise time, minimal overshoot, and settling time within an acceptable time frame. The IAE and ITAE values are low, indicating good control performance. The system's response is analyzed using a range of settling times, with a peak value of 1.08 and a peak time of 0.412, providing insights into the transient behavior of the system. The system's overshoot percentage is 8.52, indicating moderate overshooting. The system's peak value is represented by a peak time of 1.08 and 0.412 seconds. The Integral of Absolute Error (IAE) and Integral of Time-weighted Absolute Error (ITAE) values are 0.026 and -0.011, respectively, indicating good control performance. However, in this paper further analysis is to be carried out to get a better performance.

Table 3 Closed-Loop system performance of an FOPID using 100 iterations

Performance metric	**Iteration (100)**
Risetime (sec)	0.20
Settling Time(sec)	2.99
Settling Min(sec)	0.88
Settling Max(sec)	1.08
Overshoot (%)	8.52
Undershoot (%)	0
Peak(sec)	1.08
Peak Time(sec)	0.412
IAE	0.026
ITAE	-0.011

3.1.1. DC Motor Using GA-PSO FOPID Controller

The GA-PSO FOPID controller's step response is displayed in Figure 4. The step response in the GA-PSO FOPID controller offered a metric for the DC motor control system's steady-state performance. The GA-PSO FOPID controller shows a step response that measures the steady-state behavior of a DC motor control system. The system's performance is measured by various parameters, including the rise time, setting time, overshoot, undershoot, peak value, peak time, IAE, and ITAE.

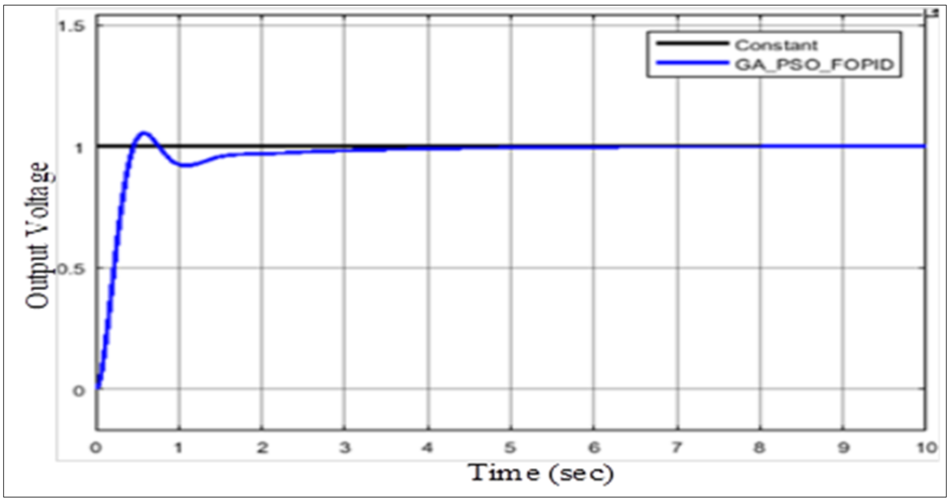

Figure 4 Step Response for the System using GA-PSO FOPID Controller

The result shows a rise time of 0.30 seconds indicates a quick response to input changes, and the settling time of 2.90 seconds meets the desired settling time criteria. The system has a 5.29% overshoot, indicating slight deviation beyond the final value, and no undershoot, indicating good stability. The peak value (1.05) and peak time (0.59 seconds) indicate the system reaches its maximum value quickly and efficiently. The low values of IAE and ITAE (0.006) indicate the FOPID controller effectively minimizes error over time, contributing to good overall system performance. Table 4 illustrated the control system performance metrics, showing a balance between speed and stability. The system responds quickly to changes, taking 0.30 seconds to reach 90% of its final value. The settling time is 2.90 seconds, indicating the system stays within a certain percentage of its final value. The system's response stays between 0.92 and 1.05 during the settling time, demonstrating stability without excessive oscillations. Depending on the application, a little transient reaction that exceeds the final steady-state value, as indicated by the overshoot of 5.29%, can be acceptable. A stable reaction is facilitated by the absence of undershoot, which indicates the system does not fall below the ultimate steady-state value. The peak value of 1.05 is reached at 0.59 seconds, indicating the system's transient behavior. The system's performance in minimizing error over time is excellent, indicating a fast response.

Table 4 A Closed-Loop System Performance Using GA-PSO Using 100 Iteration

Performance metrics	**Iteration (100)**
Risetime(sec)	0.30
Settling Time(sec)	2.90
Settling Min(sec)	0.92
Settling Max(sec)	1.05
Overshoot (%)	5.29
Undershoot (%)	0
Peak(sec)	1.05
Peak Time(sec)	0.59
IAE	0.006
ITAE	0.006

4. Validation

The results obtained from the research of [22] was compared with the developed hybrid scheme (GA-PSO) for Controlling DC motor is presented in Table 5. Equation 18 shows the percentage improvement of developed hybrid scheme (GA-PSO) over the research of [22], which was solely based of PSO.

$$Percentage\ Improvement = \frac{Developed - Existing}{Existing} \text{ X } \frac{100}{1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

Table 5 Comparative Analysis of developed Hybrid Scheme and Most recent Related Research

Metric performance	[22] PSO	Developed Hybrid Scheme GA-PSO	Percentage Improvement
Rising Time(sec)	0.49	0.30	-38.78%
Setting Time(sec)	0.76	2.90	−281.58%
Overshoot (%)	0	5.29	0
Peak value(sec)	1	1.05	5.00%
Peak time(sec)	0.99	0.59	-40.40%

Table 5 reveals that the developed hybrid scheme outperformed the existing PSO by decreasing the rising time by 38.78%, decreasing the setting time by 281.58%, and decreasing the peak time by 40.40%. This result indicates an optimized and faster response in controlling a DC motor.

5. Conclusion

In this paper, a DC motor was designed using the transfer function, which serves as a mathematical representation. The constants, like armature resistance and inductance, shape the motor's performance and stability. To enhance system stability and the DC motor's performance, a FOPID (Fractional Order Proportional-Integral-Derivative) controller was introduced. These controllers offer more flexibility in tuning and better performance compared to traditional PID controllers. The integration of the hybrid scheme algorithm (GA-PSO) led to improved control and step response of the DC motor. The hybrid scheme algorithm (GA-PSO) achieved a rising time of 0.30, setting time of 2.90, an overshoot of 5.29, a peak of 1.05, and a peak time of 0.59. However, this paper was limited to the hybridization of the GA-PSO algorithm; future studies can consider integrating algorithms such as the Mountain Gazelle Optimizer Algorithm (MGO) along with other types of Proportional-Integral-Derivative (PID).

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Qi, J. Deng Z, and Li. Y (2007) "Design of fuzzy PID controller and application in glass furnace,"In 2007 8th International Conference on Electronic Measurement and Instruments, ICEMI, 2007, pp. 4224–4227. doi: 10.1109/ICEMI.2007.4351123.

[2] Gao, Z., He, L., and Yue, X. (2018). "Design of PID controller for greenhouse temperature based on Kalman," in ACM International Conference Proceeding Series, New York, NY,USA: ACM, 2018, pp. 1–4. doi: 10.1145/3232116.3232117.

[3] Subrata, R. H., Gozali, F., and Djuana, E. (2022). "Computational and Intelligent Optimization Tuning Method for PID Controller," Journal of Theoretical and Applied Information Technology (JATIT), vol. 100, no. 7, pp. 2007–2017, 2022.

[4] Salem, A., Hassan, M. A. M., and Ammar, M. E. (2014). "Tuning PID Controllers Using Artificial Intelligence Techniques Applied to DC-Motor and AVR System," Asian Journal of Engineering and Technology, vol. 02, no. 02, pp. 2321–2462, [Online]. Available: www.ajouronline.com.

[5] Samara, R., Hikmarika, H., Dwijayanti, S., and Suprapto, B. Y. (2019). "Comparison of Inverted Pendulum Control System using Proportional – Integral – Derivative (PID) and Proportional – Integral (PI)," in 2019 International Conference on Electrical Engineering and Computer Science (ICECOS), Oct. 2019, pp. 316–320. doi: 10.1109/ICECOS47637.2019.8984451.

[6] Widya, S.E and Ma'arif, A. (2021). "Tuning of PID Controller Parameters with Genetic Algorithm Method on DC Motor," Internation Journal of Robotics and Control Systems, Vol. 1, no. 1, pp. 4 1–53,doi: 10.31763/ijrcs.v1i1.249.

[7] Kannan, G. Saravanakumar, G. and Saraswathi, M.. (2018). Two-degree of freedom PID Controller in time delay system using hybrid controller model. International Journal of Automation and Control. 12. 399. 10.1504/IJAAC.2018.092852.

[8] Aleksei T., Baris B. A, Celaleddin Y,Gonzalez E, Hassan S. A, and Eduard P. (2018). FOPID Controllers and Their Industrial Applications: A Survey of Recent ResultsThis study is based upon works from COST Action CA15225, a network supported by COST (European Cooperation in Science and Technology).,IFAC PapersOnLine, Volume 51, Issue 4, Pages 25-30,ISSN 2405-8963,https://doi.org/10.1016/j.ifacol.2018.06.014

[9] Tejado I, Vinagre B. M, Traver J. E, Prieto-Arranz J, and Nuevo-Gallardo, C. (2019) Back to Basics: Meaning of the Parameters of Fractional Order PID Controllers. MDPI journal of Mathematics; 7(6):530. https://doi.org/10.3390/math706053

[10] Saleh M. A, Ahmad B. M, Touqeer A. J, Ilyas, K. Nawaf, N. H, and Afrasyab K. (2024). Optimal design of Fractional order PID controller based Automatic voltage regulator system using gradient-based Optimization algorithm, Journal of King Saud University - Engineering Sciences, Volume 36, Issue 1, Pages 32-44, ISSN 1018-3639,https://doi.org/10.1016/j.jksues.2021.07.009.

[11] Bharat, S., Ganguly, A., Chatterjee, R., Basak, B., Sheet, D., and Ganguly, A. (2019). "A Review on Tuning Methods for PID Controller," Asian Journal of Convergence in Technology, vol. Issue I, no. I, pp. 1–4, [Online]. Available: www.asianssr.org.

[12] Padamwar, B. and Pandey, H. (2019). Optimization techniques in operations research: a Review. Turkish Journal of Computer and Mathematics Education (TURCOMAT). 10.746-752. 10.61841/turcomat.v10i1.14604.

[13] Sun, S. Cao, Z. Zhu, H. and Zhao, J. (2019). A Survey of Optimization Methods From a Machine Learning Perspective. ArXiv. Pp. 1-29

[14] Janga M. R and Nagesh D. K (2020). Evolutionary algorithms, swarm intelligence Methods, and their applications in water resources engineering: a state-of-the- art review. H2Open Journal. January; 3 (1): 135–188. doi: https://doi.org/10.2166/h2oj.2020.128

[15] Selvarajan, S. A (2024). Comprehensive study on modern optimization techniques for engineering Applications. Artifificail Intelligence Review,57, 194. https://doi.org/10.1007/s10462-024-10829-9

[16] Harish G. (2016). A hybrid PSO-GA algorithm for constrained optimization problems, Applied Mathematics and Computation,Volume 274, Pages 292-305, ISSN 0096-3003,https://doi.org/10.1016/j.amc.2015.11.001.

[17] Cherki I, Chaker A, Djidar Z, Khalfallah N, Benzergua F. (2019) A Sequential Hybridization of Genetic Algorithm and Particle Swarm Optimization for the Optimal Reactive Power Flow. MDPI Journal of Sustainability.; 11(14):3862. https://doi.org/10.3390/su11143862

[18] Kanojiya, R. G. and Meshram, P. M. "Optimal tuning of PI controller for speed control of DC motor drive using particle swarm optimization," in 2012 International Conference on Advances in Power Conversion and Energy Technologies, APCET 2012, 2012, pp. 1–6. doi: 10.1109/APCET.2012.6302000.

[19] Deepak, M & Aruldavid, Ranjeev & Verma, Rajesh & Sathyasekar, K. & Barnawi, Abdulwasa & Bharatiraja, C. & MIHET-POPA, Lucian. (2022). A Review of BLDC Motor:State of Art, Advanced Control Techniques, and Applications. IEEE Access. 10.1109/ACCESS.2022.3175011.

[20] Kuczmann M (2024). Review of DC Motor Modeling and Linear Control: Theory with LaboratoryTests.MDPI Journal of Electronics; 13(11):2225. https://doi.org/10.3390/electronics13112225

[21] Mishra, N. Bajpai, S and Narayan, E. (2020). "Speed Control of DC Motor using PID Controller FED H-Bridge," International Journal of Innovative Technology and Exploring Engineering (IJITEE) vol. 9, no. 10, pp. 274–282, doi: 10.35940/ijitee.f3967.0891020

[22] D. Maddi, A. Sheta, D. Davineni, and H. Al-Hiary, "Optimization of PID Controller Gain Using Evolutionary Algorithm and Swarm Intelligence," 2019 10th Int. Conf. Inf. Commun. Syst. ICICS 2019, pp. 199–204, 2019, doi: 10.1109/IACS.2019.8809144.