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SFS based Fractional Order PID Controller (FOPID) for Speed Control of DC Motor

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ABSTRACT

In the present work, Stochastic Fractal Search (SFS) based Fractional Order Proportional Integral Derivative (FOPID) has been proposed for optimal speed control of DC motor. For speed control, a fractional order PID (FOPID) controller has been incorporated and its parameters have been tuned by SFS algorithm using the minimization of Integral Time Absolute Error (ITAE) as an objective function. The application of SFS to tune the FOPID controller's parameters for optimal speed control of DC motor is referred as an approach: SFS-FOPID. SFS is a powerful metaheuristic algorithm based upon the concept of Fractal in which, the particle explores the search space more efficiently by using the diffusion property. The superiority of SFS algorithm has been established by comparing its results with some popular approaches in literature such as: GWO-FOPID, IWO-PID, PSO-PID and SFS-PID for the same system. A robustness analysis of SFS based FOPID controller for the investigated system has also been carried out and compared with other well known aforesaid approaches in which no alteration has been found for the step responses in accordance with the four cases of system parametric variation and 10% step load change in the torque which shows that the controller designed by the proposed algorithm SFS is more robust as compared to other algorithms/approaches. The simulation results show that the proposed approach SFS-FOPID gives the less ITAE, less settling times and less undershoots while comparing with other well known approaches.

Key words : Integral Time Absolute Error (ITAE), DC motor speed control, Fractional Order PID (FOPID) controller, Stochastic Fractal Search (SFS),

1. INTRODUCTION

The control of DC motors has become an interesting topic of research all around the world because of its extreme flexibility and versatility in aspects of excellent speed control. It is widely used in areas like Robotic Manipulators, Automation Systems, Industries, Defense Industry and many [1].

PID controller is used for industrial control due to its easy implementation and better performance and it is broadly used in industrial applications to improve time domain characteristic i.e. the transient and steady state behaviors of a plant [2].

Now a days, fractional calculus is being applied to design and modify the PID controller for improving its working in various industrial systems and it is then known as Fractional-Order-PID Controller (FOPID) [3]**.** FOPID is a sophisticated version of conventional PID controller offering an excellent mechanism for the portrayal of fundamental and innate properties of the diverse techniques and materials of traditional PID along with enhanced response, improved stability and robustness of performance [4]. FOPID has two more parameters along with three parameters of the PID that are Derivative (μ) and Integer (λ) orders which add flexibility and robustness to the system [5]. Due to these two parameters, FOPID controllers have become extremely popular and are being widely used in application of DC motor control [6]. The Table 1 enumerates how FOPID controllers are better than conventional PID Controllers.

Generally, tuning the controller parameters is a complicated task and it refers to the tuning of its various parameters (K_P, K_I, K_D, in case of PID and K_P, K_I, K_D, μ, λ in case of FOPID) to achieve an optimized value of the desired response. The additional two parameters for the FOPID (μ and λ) make it superior than PID controller by offering numerous time and frequency domain techniques for tuning [12] which can be categorized into Rule-based, Traditional and Optimization Algorithm based techniques [7-8]**.** Well Known method for tuning the gain parameters of PID controller in literature is Ziegler-Nichols method [13] however, this method is best suited for online calculations and is used as basic guidelines for tuning of PID controllers but it involves trial-and-error method which sometimes makes the process time consuming. So, the various soft computing algorithms as alternatives of Zeigler Nichol's method have come in the picture to reduce the time and efforts such as: Invasive Weed Optimization [14], Grey Wolf Optimization [15-16] and Stochastic Fractal Search [17-18].

Table 1: Comparison of FOPID controller with PID Controller

Property	PID Controller	FOPID Controller
Parameters [7]	Three	Five
Iso-damping	Achieved with difficulty	Easily attainable
Performance for higher order systems [8]	Performance deteriorates	Performance improves
Time Delay systems [9]	Results deteriorate with long time delays	Results are improved with long time delay
Robust Stability [10]	Lower	Much higher
Control of the system with nonlinearities [11]	Difficult to control	Easy to control
Non-minimum response system	Scanty response	Much better response
Non-Linear System	Linearization with different controllers at every step.	One FOPID controller is sufficient.

Controller tuning can also be achieved using Artificial Intelligence (AI) techniques such as: Fuzzy logic [19], Particle Swarm Optimization (PSO) [20], Bacterial Swarm Optimization (BSO) [21]. Genetic Algorithm [22], Hybrid GWO with PS [23], Hybrid PSO with Pattern search [24], PSO [25] and Constrained PSO [26].

Various soft computing algorithms have already come in the picture for different engineering applications [34-36] Recently, a powerful Meta-Heuristic algorithm based on the concept of fractal, named Stochastic Fractal Search (SFS) algorithm has been proposed by [30] which is highly accurate and convergence and obtained in few iterations. SFS algorithm has proved its distinction in designing various controllers over other well-known algorithms [17, 27-29].

In this paper, tuning of FOPID's Parameters using SFS algorithm has been dealt for the speed control of DC motor.

2. DC MOTOR

A DC Motor works on the principal of rotational motion, achieved through attraction and repulsion of magnetic poles of permanent magnet and the electromagnet. Elctrical energy is converted into mechanical energy by means of passing the Direct Current through the coil windings, generating electromagnetic poles, which interact with poles of permanent magnet making the motor rotate and hence generating mechanical energy. Current speed is the main factor in attaining the desired outputs, which can be attained either manually by means of voltage variation, armature resistance and field flux or by means of automated control devices, wherein controllers are used to regulate the current speed for attaining desired outputs (Figure 1).

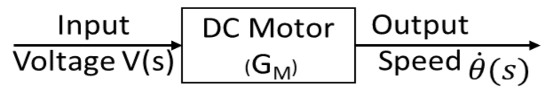

Figure: 1 TF model of DC Motor (G_M)

The Specifications of the DC motor have been shown in Table 2 [14, 15, 17] and the same literature show mathematical expressions for the same. The SIMULINK modal of DC motor is shown in Figure 2.

Table 2: Specifications of DC Motor [14,15,17]

Specifications	Value
Armature resistance; R_a	0.40 ohm
Inductance of armature winding; L_a	2.70 H
Equivalent moment of inertia of motor; J	0.00040 kg m2
Equivalent friction coefficient of motor; *D*	0.00220 N.m.sec/rad
Motor torque constant; *K*	15 e-3 kg m/A
Back EMF constant; K_b	0.050s

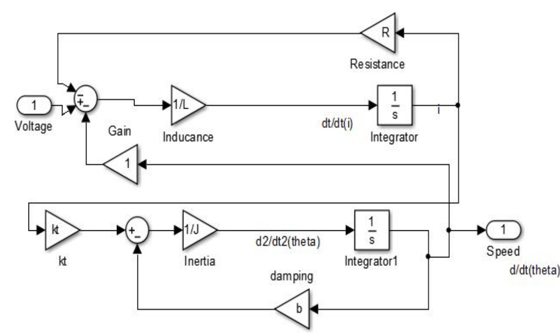

Figure 2: SIMULINK diagram of DC motor

Using specifications given in Table 2, DC motor transfer function (G_m) can be generated in MATLAB as follows:

$$G_M = \frac{0.015s}{0.00108s^3+0.0061s^2+0.00163s} \quad (1)$$

The expression in "(1)" can be given as:

$$G_M = \frac{15}{1.08s^2+6.1s+1.63} \quad (2)$$

Which yields the transfer function of DC Motor.

3. STOCHASTIC FRACTAL SEARCH ALGORITHM

The Stochastic Fractal Search (SFS) algorithm has been proposed by Salami, et al., 2015 [30] and it exploits diffusion property existing in random fractals to determine the search space. The procedures in the SFS algorithm can be divided into two processes: Diffusion Process and Update Process. Steps of SFS algorithm involve the followings:

- Initialization
- Computation of fitness function
- Diffusion Process:
- Updating Process

The parameters of SFS algorithm used for simulation of the speed control of DC motor is given in Table 3. The flow chart of SFS algorithm is shown in Figure 3.

Table: 3: Simulation Parameters Used for SFS Algorithm

Parameters	**Value**
Number of particles (population)	50
Maximum iterations	30
S. diffusion	3
S. walk	1
Lower bounds (K_P, K_D,K_I,λ, μ)	[0 0 0 0 0]
Upper bounds (K_P, K_D,K_I,λ, μ)	[20 10 10 2 2]

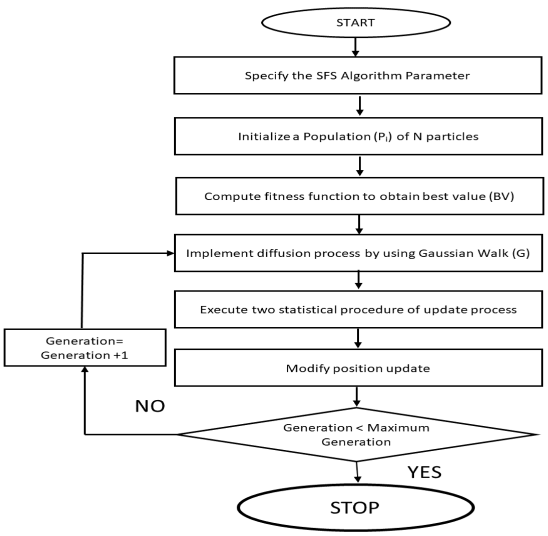

Figure 3: Flow Chart of SFS Algorithm

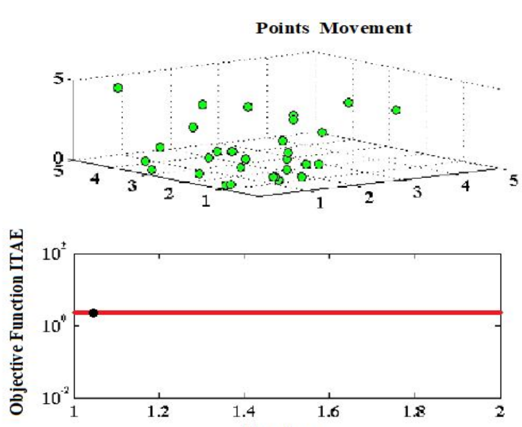

Figure 4: Convergence of ITAE as Objective Function at Start.

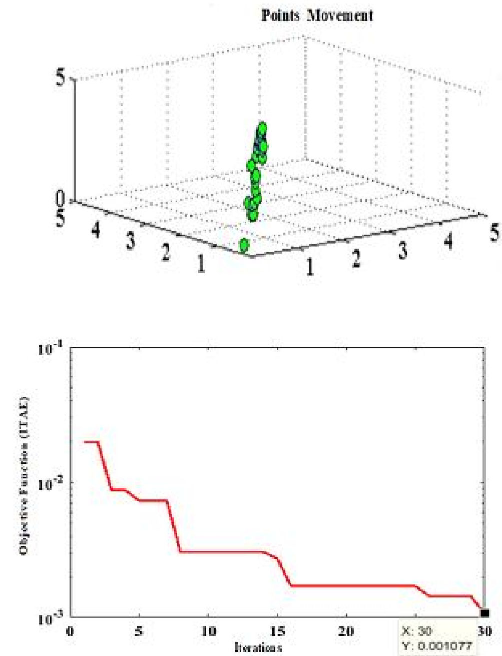

Figure 5: Convergence of ITAE as An Objective Function at End

The convergence of objective function ITAE using SFS algorithm has been shown in Figure 4-5. The more details about SFS including mathematical modeling of each step can be found in [30].

4. PERFORMANCE INDICES AND OBJECTIVE FUNCTION

Various kind of performance indices have been used as objective function such as: Error-Based criteria including Integral Time Absolute Error (ITAE), Integral Absolute Error (IAE), Integral Time Square Error (ITSE), Integral Square Error (ISE) etc. and transient performance-based criteria including Rise Time (t_r), Settling Time (t_s), Maximum Peak Overshoot (M_P) etc. In the present study, Settling Time (t_s), Rise Time (t_r), Maximum Peak Overshoot (M_P) and ITAE for speed control of DC motor are considered since all of these will lead to enhance the output response of the proposed system. The details of all performance indices are found in [17].

In the present work, the ITAE is taken as an objective function instead of all other performance indices aforesaid and its SIMULINK model is shown in Figure 6.

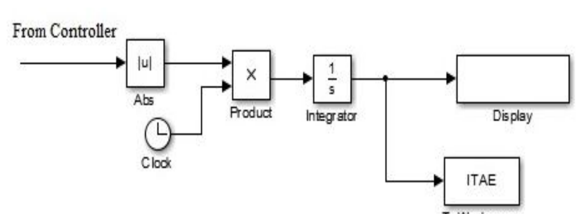

Figure 6: SIMULINK Model of ITAE as An Objective Function

5. FOPID CONTROLLER

The FOPID controller reported in 1994 by Podlubny, et al., [32] can achieve iso-damping property very easily [33].

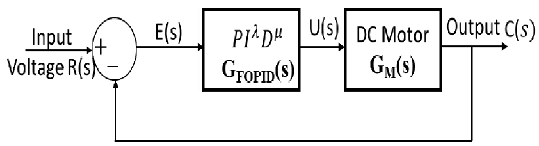

Figure 7: Block Diagram of FOPID Controller with DC Motor.

The transfer function of FOPID controller with DC motor is as follow:

$$G(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1+H(s)} \quad (3)$$

where, C(s) is the output of system; U(s) is the output of FOPID controller; E(s) is the error; H(s) is Feedback transfer function and G(s) is closed loop transfer function of overall system.

The transfer function of DC motor is given in equation "(1)" and transfer function of FOPID Controller is given as follow:

$$G_{FOPID} = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} \quad (4)$$

Where

K_P = proportional gain constant; K_I = integral gain constant: K_D = derivative gain constant; λ = order of fractional integration should be greater than 0; μ = order of fractional derivative should be greater than 0..

6. PROBLEM FORMULATION

Modelling and simulations have been carried out using MATLA SIMULINK environment which yields the transient replication, frequency replication and robustness analysis on a Dell laptop with Intel (R) Core (TM) i3-8145U CPU @ 2.10GHz processor with 4 GB RAM and utilizing software version MATLAB (R2013b) with toolboxes .

6.1 Proposed SFS-FOPID Approach for Speed Control of DC Motor

To improve the time response characteristics as rise time (t_r), settling time (t_s), maximum overshoot (M_p) and steady state error (E_{ss}), the optimum values of FOPID controller parameters can be obtained using the proposed SFS algorithm, which has excellent intensification and diversification characteristics. Figure 8 shows the SIMULINK model of the same using proposed approach: SFS-FOPID with ITAE. Followings are the steps for proposed SFS-FOPID approach:

- For optimization, the parameters of the controllers based on SFS algorithm are first coded into particle.
- The particles are tuned by following the main steps of the SFS algorithm corresponding to the minimum objective function (OF).
- For each particle, the time domain simulation for present work is made and the system response of the dc motor is achieved.
- It is expected that every particle shall give a different output curve with the associated objective function values.
- Then ITAE is calculated for every particle and subsequently, every particle is returned to the optimization unit for updating and next iteration.
- This process is repeated number of times between investigated system and SFS unit to approach the maximum number of iterations.
- Finally, the best fit particle with minimum objective function values are considered as the optimal parameters.

The SIMULINK model of present work SFS-FOPID approach is shown in Figure 8.

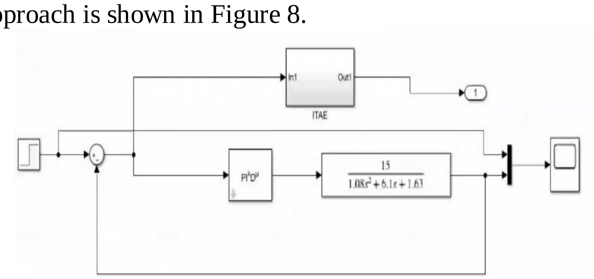

Figure 8: SIMULINK Model of Present Work with SFS-FOPID Approach (Proposed)

6.2 SFS–PID Approach for DC Motor Speed Control Using ITAE

The SIMULINK model of present work SFS-PID approach is also shown in Figure 9 with the same OF: ITAE.

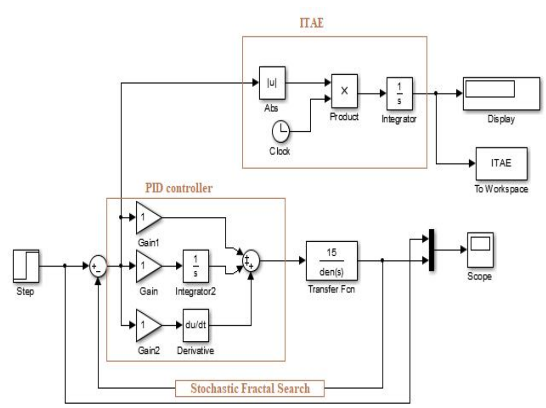

Figure 9: SIMULINK Model of Present Work with SFS-PID Approach

The PID controller's parameters are given as [18]:

$$K_p = 1.6315 \quad K_I = 0.2798 \quad K_D = 0.2395 \tag{5}$$

Hence, the CLTF of the above model is given by (H(s) = 1):

$$G_{CL} = \frac{3.592545s^2 + 24.47s + 4.2}{1.08\,s^3 + 9.6925s^2 + 26.1025\,s + 4.197} \tag{6}$$

6.3 SFS–FOPID Approach for DC Motor Speed Control Using ITAE

SIMULINK model of DC motor speed control using SFS-FOPID approach by minimizing ITAE as objective function is shown in Figure 10.

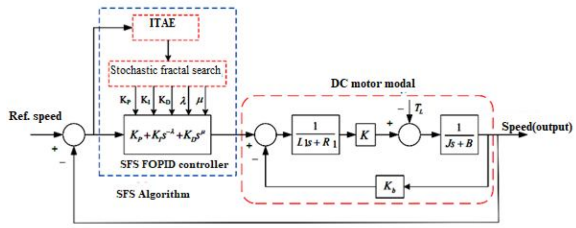

Figure 10: Functional Block Diagram of Speed Control of DC Motor Using SFS - FOPID with ITAE as An Objective Function

The unknown parameters of FOPID controller are obtained as follow:

$$K_P = 18.101;\ K_I = 4.8307;\ K_D = 3.1630;\ \lambda = 1.0009;\ \mu = 0.9968 \tag{7}$$

$$G_{FOPID} = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} \tag{8}$$

Hence, the transfer function of FOPID controller is given by

$$G_{FOPID} = \frac{3.163s^{1.9977} + 18.101s^{1.0009} + 4.8307}{s^{1.0009}} \tag{9}$$

Consequently, OLTF of DC motor with FOPID controller is obtained as: .

$$G_{OLFOPID} = G_{FOPID} * G_M \tag{10}$$

$$G_{OLFOPID} = \frac{47.45s^{1.9977} + 271.51s^{1.0009} + 72.5}{1.08s^{4.0009} + 6.1s^{3.0009} + 1.105s^{2.0009}} \tag{11}$$

Hence, CLTF of the above model is obtained as:

$$G_{CLFOPID} = \frac{47.45s^{1.9977} + 271.51s^{1.0009} + 72.5}{1.08s^{4.0009} + 6.1s^{3.0009} + 1.105s^{2.0009} + 47.45s^{1.9977} + 271.51s^{1.0009} + 72.5} \tag{12}$$

Step response of investigated system by SFS-FOPID approach with ITAE as an OF is shown in Figure 10. .The approach SFS-FOPID has been compared with the approach SFS-PID for the same system and is shown in the Figure 12.

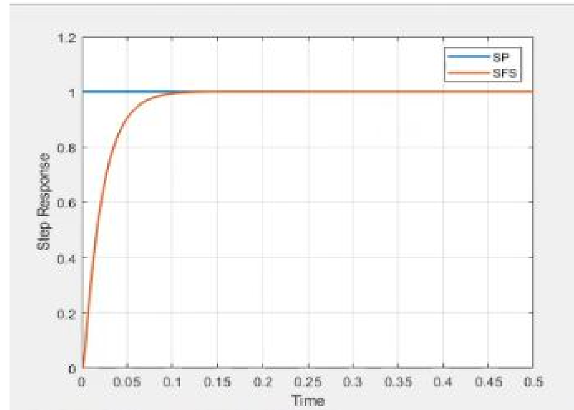

Figure 11: Step Response of Investigated System By SFS-FOPID Approach with ITAE as An OF

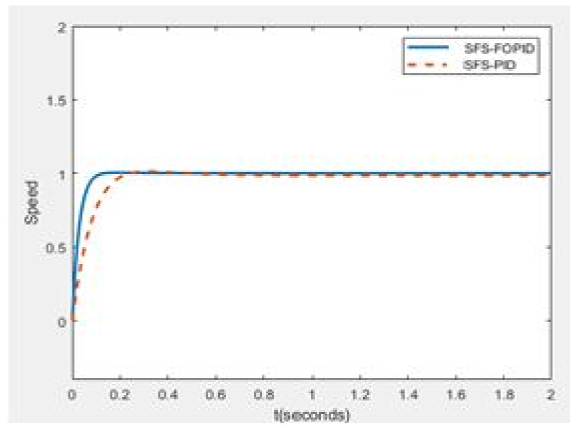

Figure 12: Step Response of Investigated System By SFS-FOPID and SFS-PID Approach with ITAE as An OF

7. RESULTS

The following results are discussed below:

7.1 Convergence of ITAE

The convergence of objective function at starting and ending point using SFS algorithm are shown in Figure 13-14. The results show that the lowest value of ITAE (0.001077) has been achieved with minimum number of iterations (30 iterations).

7.2 Comparison with Different Approaches

The unknown parameters of controller obtained by different approaches have been compared with the proposed approach SFS-FOPID for the same system: speed control of DC motor and this comparative study is shown in Figure 15. The obtained parameters controllers from different approaches are given in Table 4. It is clear from the comparative study that the proposed SFS-FOPID approach for investigated system gives better stability indices and small overshoot while comparing with other approaches available in the literature.

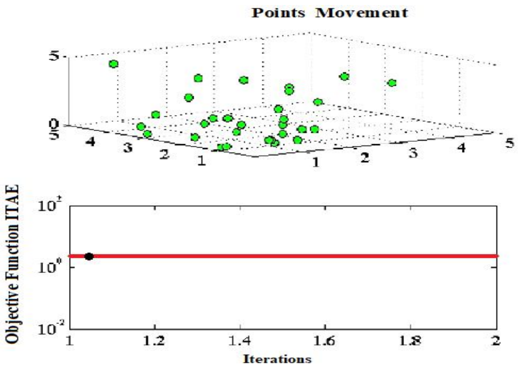

Figure 13: Convergence of ITAE Objective Function at Starting Point

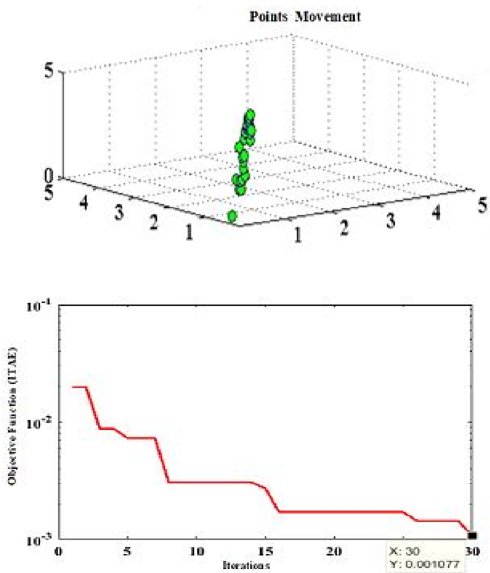

Figure 14: Convergence of ITAE Objective Function at Ending Point.

Table 4: Comparison for Unknown Parameters Obtained By Different Approaches for Ra=0.4, K=0.015

Algorithm-Controller	K_P	K_I	K_D	λ	μ
SFS-FOPID (Proposed)	18.101	4.8307	3.1630	1.0009	0.9968
GWO-FOPID [15]	18.328	4.9418	3.2612	0.9998	0.9845
GWO-PID [15]	6.8984	0.5626	0.9293	1	1
IWO-PID [14]	1.5781	0..437	0.0481	1	1
SFS-PID [17]	1.6314	0.2797	0.2395	1	1

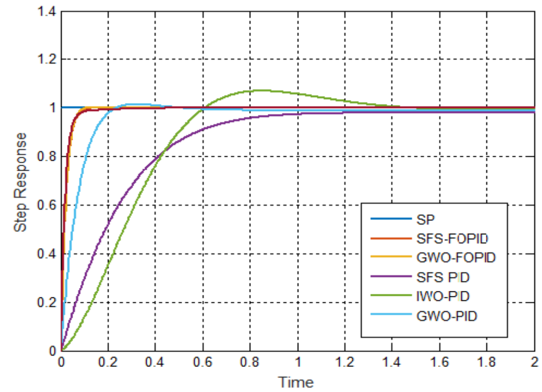

Figure 15: Comparison of Step Responses for Speed Control of DC Motor Using Different Approaches

7.3 Robustness Analysis

A controller is said to be robust when its behavious is not altered in accordance with the parametric variations. In the robustness analysis, the step responses of the PID/FOPID controller using SFS and other algorithm for considered system has been studied with parametric variation of DC Motor i.e. variation in torque constant (*k)* and the electrical resistance (R_a). There are four cases of parametric variations (Given in Table 5) for which the step responses have been evaluated and shown in Figures 16-19. The transient response parameters obtained for all four cases are given in Table 5-8. These results justify the robustness of the SFS based FOPID controller for investigated system.

Table 5: Different Cases for Parameters of DC Motor

Case No.	R_a	K
1.	0.40	0.0150
2.	0.20	0.0120
3.	0.10	0.0140
4.	0.30	0.0150

Table 6: Transient Response Parameters Obtained by Different Approaches For Case1. (*Ra=0.4, K=0.015*)

Algorithm-Controller	**Max. overshoot (%) (M_p)**	**Settling time (s)(t_s) (2-5)%**	**Rise time (s)(t_r) (0.10-0.90)**
SFS-FOPID (Proposed)	0.06410	0.08040	0.04490
GWO-FOPID [15]	0.3150	0.0814	0.0490
GWO-PID [15]	1.450	0.2050	0.1390
IWO-PID [14]	6.980	1.250	0.4190
PSO-PID [14]	24.20	1.8010	0.3560
SFS-PID [17]	0	1.450	0.5440

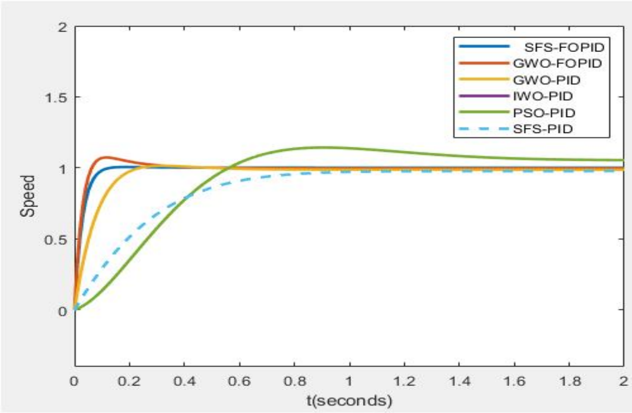

Figure 16: Step Response Parameters Obtained by Different Approaches For Case1. (*Ra=0.40, K=0.0150*)

Table 7: Transient Response Parameters Obtained by Different Approaches for Case 2 (Ra=0.20, K=0.0120)

Algorithm-Controller	**Max. overshoot (M_p)**	**Settling time (t_s) (2-5)%**	**Rise time (t_r) (0.10-0.90)**
SFS-FOPID (Proposed)	0.2910	0.12620	0.0530
GWO-FOPID [15]	0.510	0.1172	0.0580
GWO-PID [15]	1.060	0.2540	0.1710
IWO-PID [14]	7.160	1.950	0.4930
PSO-PID [14]	25.50	2.380	0.4090
SFS-PID [17]	0	1.060	0.6380

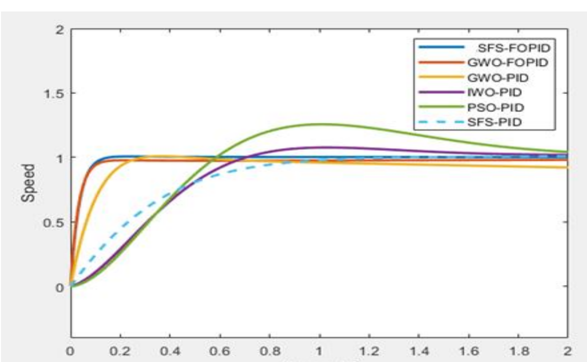

Figure 17: Step Response Parameters Obtained by Different Approaches for Case 2 (Ra=0.20, K=0.0120)

Table 8: Transient Response Parameters Obtained by Different Approaches for Case 3 (Ra=0.10, K=0.0140)

Algorithm-Controller	**Max. overshoot (M_p)**	**Settling time (t_s) (2-5)%**	**Rise time (t_r) (0.10-0.90)**
SFS-FOPID (Proposed)	0.03120	0.04610	0.04010
GWO-FOPID [15]	0.570	0.8510	0.270
GWO-PID [15]	2.180	0.3840	0.1450
IWO-PID [14]	9.330	1.70	0.4280
PSO-PID [14]	27.20	2.060	0.3650
SFS-PID [17]	0.4380	0.8520	0.5390

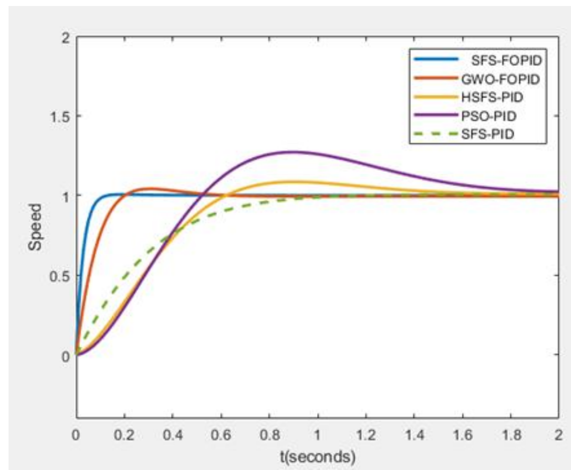

Figure 18: Step Response Parameters Obtained by Different Approaches for Case 3 (Ra=0.10, K=0.0140)

Table 9: Transient Response Parameters Obtained by Different Approaches for Case 4 (Ra=0.30, K=0.0150)

Algorithm-Controller	Max. overshoot (M_p)	Settling time (t_s) (2-5)%	Rise time (t_r) (0.10-0.90)
SFS-FOPID (Proposed)	0.0710	0.03140	0.0190
GWO-FOPID [15]	0.3300	0.10150	0.0550
GWO-PID [15]	1.740	0.2030	0.1380
IWO-PID [14]	7.920	1.320	0.4140
PSO-PID [14]	25.30	1.830	0.3530
SFS-PID [7]	0	0.9680	0.530

When the step responses obtained by SFS-FOPID approach for all four cases of parametric variations are compared to each other for the same considered system, it has been found that each step response meets each other after a short time which yield that the FOPID controller based on SFS algorithm approach is more resilient or robust to model uncertainties and once the controller's parameters are tuned then there is no need to reset these parameters again under the wide range of parametric variation. It is shown in Figure 20 .

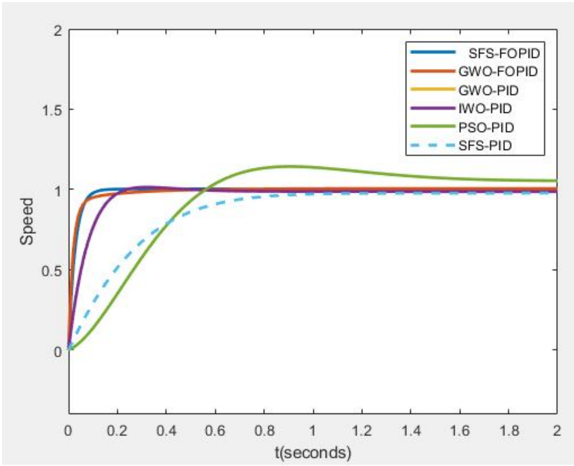

Figure 19: Transient Response Parameters Obtained by Different Approaches for Case 4 (Ra=0.30, K=0.0150)

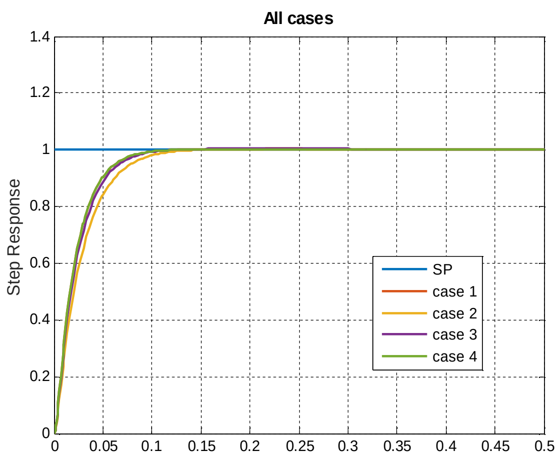

Figure 20: Comparison of Step Responses Obtained by SFS-FOPID Approach for All Four Cases of Parametric Variations

7.4 Dynamic System Response with Step Load Change in Torque

Change in load torque disturbs the step response of speed control of DC motor. Therefore, the disturbance needs to be eliminated immediately. Figure 21 shows the SIMULINK model and Figure 22 shows the step responses of speed control of DC motor by different approaches under the same 10% SLP. Figure 21 yields that the proposed SFS-FOPID approach has exhibited the system dynamic response with level of satisfaction under the SLP in torque in terms of minimum undershoot and settling time while comparing with some approaches available in the literature. Hence, the proposed approach SFS-FOPID is more effective as well as robust in suppressing the load disturbances occurred in torque as compared to other approaches for the same speed control of DC motor.

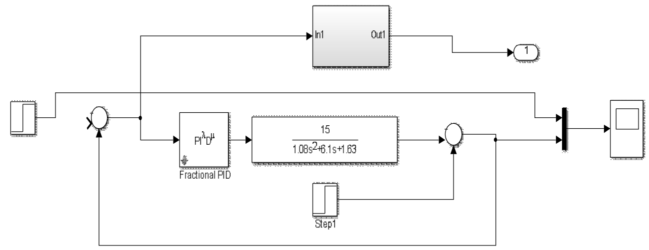

Figure 21: SIMULINK Model of DC Motor Speed Control When Subjected to a 10% Step Load Disturbance in Torque

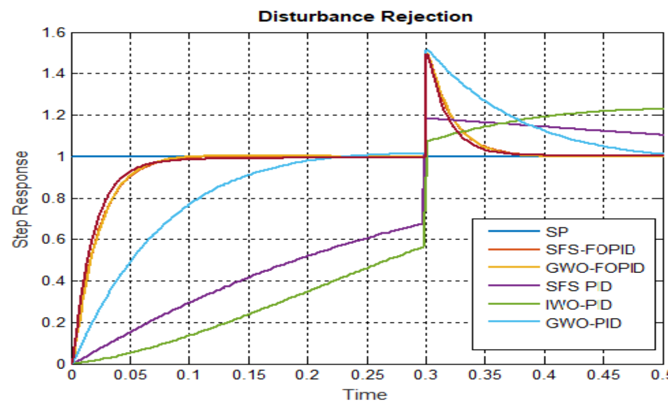

Figure 22: System Dynamic Responses of DC Motor Speed Control Obtained by Different Approaches When Subjected to a 10% Step Load Disturbance in Torque

8 CONCLUSION

In the present work, FOPID controller has been used in speed control of DC motor and the parameters of FOPID have been evaluated using the SFS algorithm by minimizing the ITAE as an objective function. The implementation of SFS to tune the FOPID controller's parameters is abbreviated as SFS-FOPID approach throughout the present work. The convergence of ITAE has been studied. The system dynamic response (step response) obtained by the proposed approach SFS-FOPID for the speed control of DC motor has also been compared with some other approaches available in the literature and the results show that the proposed approach exhibits the far better results in comparison of different existing approaches and gives less settling times, minimum undershoots and less ITAE values. The robustness of the FOPID controller using SFS for the same investigated system has also been carried out under the system parametric variations and the results show that the controller designed using SFS algorithm for aforesaid system is more robust as compared to other existing approaches and it is also investigated that once the controller's parameters are tuned using SFS-FOPID approach then there is no need to reset these parameters again under the wide range of parametric variation. The system dynamic response obtained by SFS-FOPID approach has also been studied with 10% step load change in torque and compared with some other popular approaches. It is found that the proposed approach SFS-FOPID is more effective as well as robust in suppressing the load disturbances occurred in torque as compared to other approaches for the same speed control of DC motor.

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