Application of Grey Wolf Optimization in Optimal Control of DC Motor and Robustness Analysis

Upma Bhatnagar, Abhishek Gupta
Department of Electrical Engineering
Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, India
Email: upmabhatnagar93@gmail.com

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Abstract: **The work deals with application of Grey Wolf Optimization (GWO) algorithm in determining the optimal parameters of proportional-integral derivative(PID) controller for speed control of DC motor.GWO is a bio inspired heuristic algorithm. Here, integral of time multiplied absolute error (ITAE) has been taken as an objective function for tuning the parameters of PID controller by GWO. Comparison of proposed GWO/PID schemewith other existing techniques has also been shown. It has been observed that proposed GWO/PID approach with ITAE as an objective function gives comparable overshoot and other parameters such as; settling and rise times are lesswhen compared with existing approaches in the literature.The robustness analysis of proposed GWO/PID approach has also been carried out with variations in the parametersof DC motor and the results are compared.**

Keywords: **DC Motor, PID-Controller, Grey Wolf Optimization, Optimal Control, ITAE.**

1. INTRODUCTION

Mainly two types of dc motors are used in the industries.The first one is conventional dc motor where fluxis produced by the current through the field coil of stationary pole structure. The second type is brushless DC Motor (BLDC Motor) where the permanent magnet providesnecessary air gap flux instead of the wire-wound fieldpoles [1]. Due to the advantages of smaller volume, high force and simple structure of BLDC motor, itis widely applied in the areas which needs high performance drive[1].

The PID controllers maintain the output at a level so that there is no difference between the process variable and set point. PID controllers are broadly used in industrial plants due to their robustness and ease of implementation. Various algorithms are available in literature to tune the parameters of PID controllers, such as; Ziegler Nichols, Cohen-coon tuning and Z-N step response, etc. But, all of these classical methods have some limitations [2].

Also, Genetic Algorithm (GA) [3], Particle Swarm Optimization (PSO) [1, 4], Invasive Weed Optimization (IWO) [5], and SFS algorithms [6-7] are already available in the literature to tune the parameters of PID controller for speed control of DC motor.

The present work deals with application of GWO algorithm in tuning the parameters of PID controller for speed control of DC motor, where in ITAE has been used as an objective function. GWOis a bio inspired heuristic algorithm inspired by both the social hierarchy of wolves as well as their hunting behavior. The search starts with population of randomly generated wolves (solutions) in GWO. During hunting (optimization) process, these wolves estimate the prey's (optimum) location through an iterative procedure [8-11].

2. DC MOTOR – BASIC CONCEPTS

The DC motor converts DC energy into mechanical energy [12-15]. DC motor generates torque directly from the DC power supply to the motor by using internal communication, stationary permanent or electromagnets, and rotating electrical magnets. The basic model of DC motor is shown in Figure 1 [6].

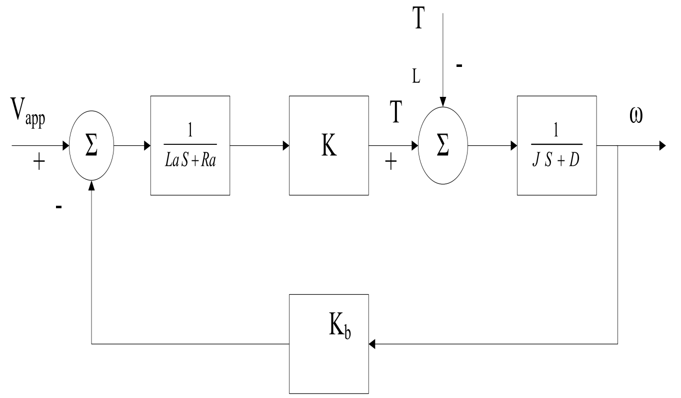

Figure 1: Model of DC motor

For simulation, the parameters and their values for DC motor used in present work have been given in Table 1[5-7].

Table 1: DC motor parameters

Parameter	Value
R_a	0.4 ohm
L_a	2.7 H
J	0.0004 kg.m2
D	0.0022 N.m.sec/rad.
K	15 e-3 Kg.m/A
K_b	0.05 V.sec

Now, the objective is to obtain response/speed of DC motor close to the ideal/set point state. Figure 2 shows the equivalent circuit of DC motor with a PID controller.

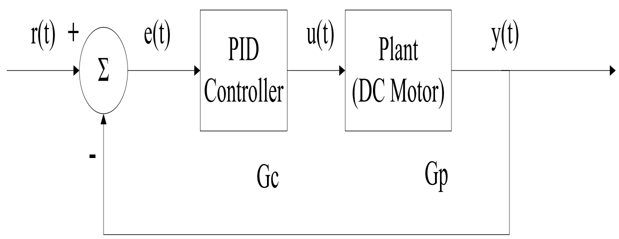

Figure 2:Equivalent circuit of DC motor with PID controller

3. STATEMENT OF PROBLEM

In general, the Eq. of PID controller is given as :

$$G_C = K_P + \frac{K_I}{s} + K_D s \quad \text{(i)}$$

For obtaining the unknown parameters of PID controller in (i) for speed control of DC motor to ideal/set point state, the fitness/objective function taken is ITAE and error is the output velocity of DC motor. Here, ITAE has been taken as an objective function because it gives smaller overshoots and oscillations than the other performance indices [7]. This ITAE is given by :

$$ITAE = \int_{0}^{\infty} t\left|e(t)\right| dt \quad \text{(ii)}$$

The simulink model representation of above ITAE in MATLAB is shown in Figure 3.

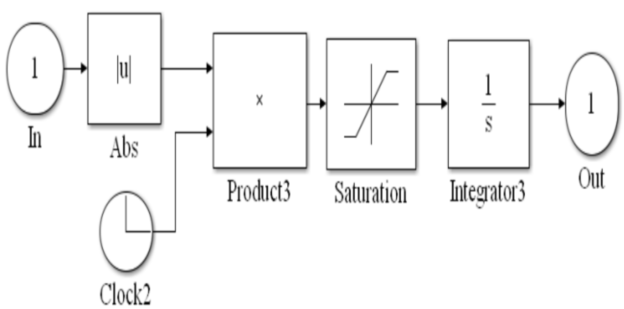

Figure 3:Simulink model representation of ITAE

The complete simulink model of DC motor with PID controller with ITAE as fitness function has been shown in Figure 4.

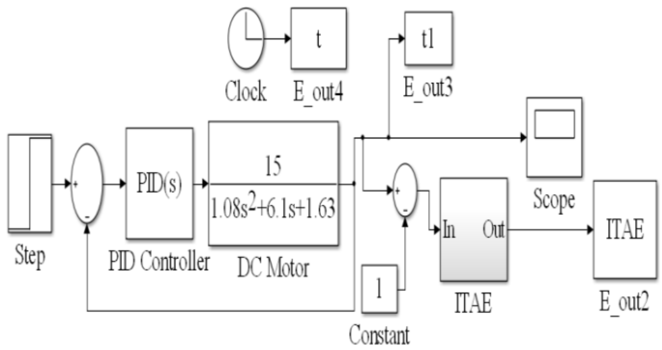

Figure 4:Complete simulink model of DC motor with PID controller and ITAE as an objective function

4. GREY WOLF OPTIMIZATION

Similar to the social hierarchy of grey wolves, there are four groups defined in GWO algorithm namely [8-10] :

- **Alpha (α)**-The leaders are a male and female, called alphas. The alpha is mostly responsible for making decisions about hunting, sleeping place, time to wake, and so on.
- **Beta (β)**-The second level in the hierarchy of grey wolves is beta. The betasare subordinate wolves that help the alpha in decision-makingor other pack activities.
- **Omega (ω)**-The lowest ranking grey wolf is omega. The omega plays the role of scapegoat. Omega wolves always have to submit to all the other dominant wolves. If a wolf is not an alpha, beta, or omega, he/she is called subordinate (or delta in some references).
- **Delta (δ)**-Delta wolves have to submit to alphas and betas, but they dominate the omega. Scouts, sentinels, elders, hunters, and caretakers belong to this category.

The functions of each group have also been defined in Figure 5 [10].

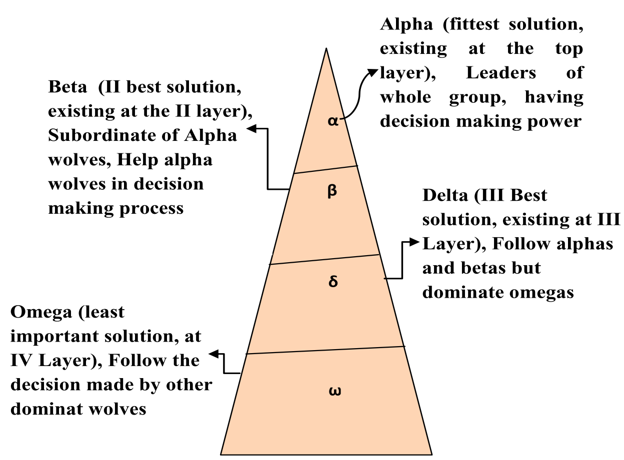

Figure 5:Social hierarchy of GWO and functions of each group

The main phases of grey wolf hunting are as follows [11] :

- Tracking, chasing, and approaching the prey.
- Pursuing, encircling, and harassing the prey until it stops moving.
- Attack towards the prey.

5. IMPLEMENTATION OF GWO/PIDAPPROACH

The GWO algorithm has been run in Matlabfor the simulink model shown in Figure 4 for 30 iterations and obtained parameters of PID controller are given by :

$$G_C = 6.8984 + \frac{0.5626}{s} + 0.9293\ s \qquad \text{(iii)}$$

For obtaining the above parameters of PID controller, the convergence of objective function; ITAE by GWOis shown in Figure 6.

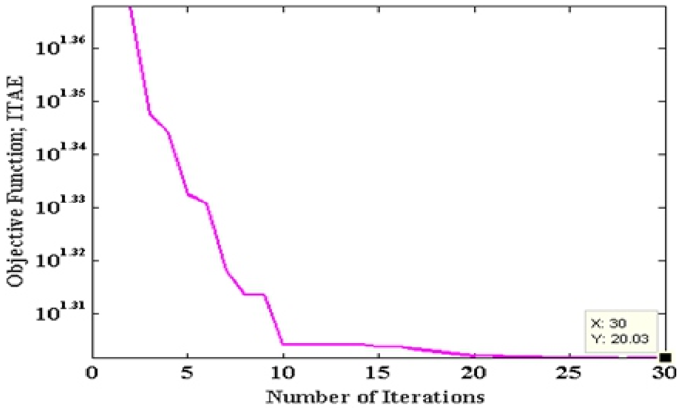

Figure 6:Convergence of objective function

In Table 2, the parameters of PID controller obtained by other existing techniques in literature [5, 7] for the same DC motor have also been given.

Table 2: Parameters of PID controller for DC motor obtained by GWO, IWO, PSO and SFS

Algorithm	K_p	K_I	K_D
GWO (Proposed)	6.8984	0.5626	0.9293
IWO [5]	1.5782	0.4372	0.0481
[1]PSO [5]	1.5234	1.3801	0.0159
SFS [7]	1.6315	0.2798	0.2395

In Figure 7, comparison of speed of DC motor without and with PID controller tuned by GWO with ITAE as an objective function is shown. It can be seen in Figure 7 that, the speed of DC motor approaches to set point immediately with the PID controller tuned by GWO.

The comparison of speed of DC motor with other existing approaches has also been shown in Figure 8. It can be seen in Figure 8 that, GWO/PID approach with ITAE gives less settling and rise times in comparison to existing approaches. In Table 3, comparative analysis of proposed GWO/PID scheme with IWO [5], PSO[5] and SFS[7] has also been shown in terms of transient response's parameters. It can be seen in Table 3 that, the proposed GWO/PID approach gives less settling and rise times in comparison to existing techniques. Also, the obtained overshoot by GWO is comparable with other approaches.

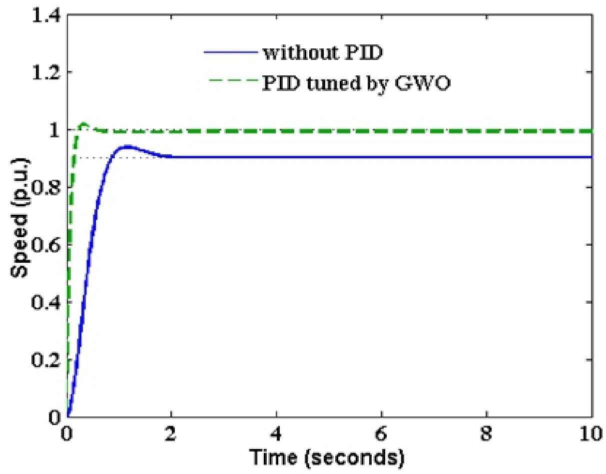

Figure 7: Speed comparison of DC motor without and with PID controller

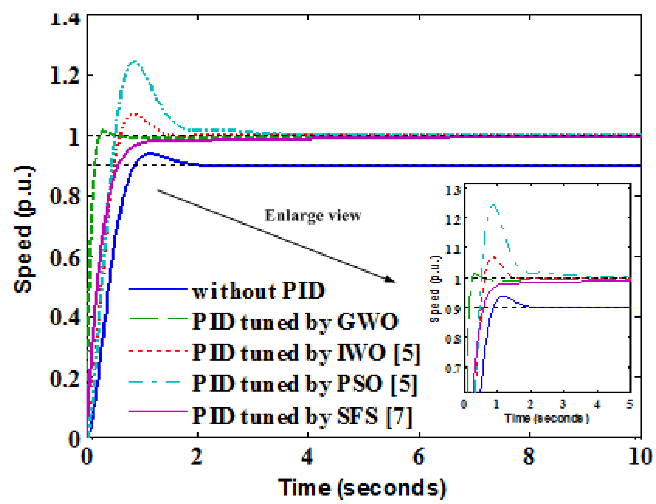

Figure 8: Speed comparison of DC motor without and with PID controller with other approaches

Table 3: Comparison of transient response's parameters

Algorithm	Over Shoot (%)	Settling Time (sec)	Rise Time (sec)
GWO	1.51	0.205	0.139
IWO [5]	6.98	1.25	0.419
PSO [5]	24.2	1.8	0.356
SFS [7]	0	1.45	0.544

6. ROBUSTNESS ANALYSIS

For evaluating the performance of the proposed GWO/PID scheme, different operating points in time domain have been tested. For this, operating points of Table4 according to the changes in electrical resistance and K parameter in DC motor have been used[5, 7] and thereafter comparative analysis has been carried out. These operating points are shown in Table 4.

Table 4: Operating points

Case No.	R_a	K
1	0.4	0.015
2	0.2	0.012
3	0.1	0.014
4	0.3	0.015

For all the above cases, the PID controller of (iii) has been used which is obtained by GWO with minimization of objective function; ITAE. Now, the above operating points have been considered separately and simulation results have been shown.

Case No. 1

In case – 1, operating point is given as :

$$R_a = 0.4; \qquad K = 0.015 \qquad \text{(iv)}$$

For this, the transfer function of DC motor is given by:

$$G_M = \frac{15}{1.08\,s^2 + 6.1s + 1.63} \qquad \text{(v)}$$

The closed loop transfer function of DC motor with PID and unity feedback for GWO using (iii) is given by :

$$G_{CL}(GWO) = \frac{13.9395s^2 + 103.476s + 8.439}{1.08s^3 + 20.0395s^2 + 105.106s + 8.439} \qquad \text{(vi)}$$

For comparison with other existing approaches; IWO [5], PSO [5] and SFS [7], the parameters of PID controllergiven in Table 2have been used.Therefore, the G_{CL} obtained by IWO [5], PSO [5] and SFS [7] is obtained as :

$$G_{CL}(IWO) = \frac{0.7215s^2 + 23.673s + 6.558}{1.08s^3 + 6.8215s^2 + 25.303s + 6.558} \qquad \text{(vii)}$$

$$G_{CL}(PSO) = \frac{0.2385s^2 + 22.851s + 20.7015}{1.08s^3 + 6.3385s^2 + 24.481s + 20.7015} \qquad \text{(viii)}$$

$$G_{CL}(SFS) = \frac{3.5925s^2 + 24.4725s + 4.197}{1.08s^3 + 9.6925s^2 + 26.1025s + 4.197} \qquad \text{(ix)}$$

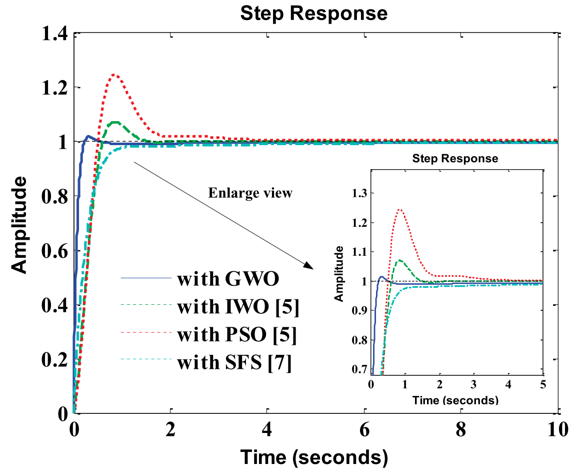

Figure 9:Comparison of step responses for operating point 1; R_a = 0.4; K = 0.015

The comparison of step responses for (vi) – (ix) has been shown in Figure 9. Also, in Table 5, comparative analysis of proposed GWO/PID scheme with IWO [5], PSO [5] and SFS [7] has been shown in terms of transient response's parameters for operating point 1.

Table 5: Comparison of transient response's parameters for operating point 1 ; R_a = 0.4 ; K = 0.015

Algorithm	Over Shoot (%)	Settling Time (sec)	Rise Time (sec)
GWO (Proposed)	1.51	0.205	0.139
IWO [5]	6.98	1.25	0.419
PSO [5]	24.2	1.8	0.356
SFS [7]	0	1.45	0.544

Case No. 2 :

In case – 2, operating point is given as :

$$R_a = 0.2 \quad ; \quad K = 0.012 \qquad \text{(x)}$$

For these parameters, the transfer function of DC motor is given by :

$$G_M = \frac{12}{1.08\,s^2 + 6.02s + 1.04} \qquad \text{(xi)}$$

Therefore, the closed loop transfer functions of DC motor with PID & unity feedback for GWO [Proposed], IWO [5], PSO [5] and SFS [7] as per parameters given in Table 2, are given by :

$$G_{CL}(GWO) = \frac{11.1516s^2 + 82.7808s + 6.7512}{1.08s^3 + 17.1716s^2 + 83.8208s + 6.7512} \quad \text{(xii)}$$

$$G_{CL}(IWO) = \frac{0.5772s^2 + 18.9384s + 5.2464}{1.08s^3 + 6.5972s^2 + 19.9784s + 5.2464} \quad \text{(xiii)}$$

$$G_{CL}(PSO) = \frac{0.1908s^2 + 18.2808s + 16.5612}{1.08s^3 + 6.2108s^2 + 19.3208s + 16.5612} \quad \text{(xiv)}$$

$$G_{CL}(SFS) = \frac{2.874s^2 + 19.578s + 3.3576}{1.08s^3 + 8.894s^2 + 20.618s + 3.3576} \quad \text{(xv)}$$

Figure 10 shows the comparison of step responses for (xii) - (xv). In Table 6, comparative analysis of proposed GWO/PID scheme with IWO [5], PSO [5] and SFS [7] has been shown in terms of transient response's parameters for operating point 2.

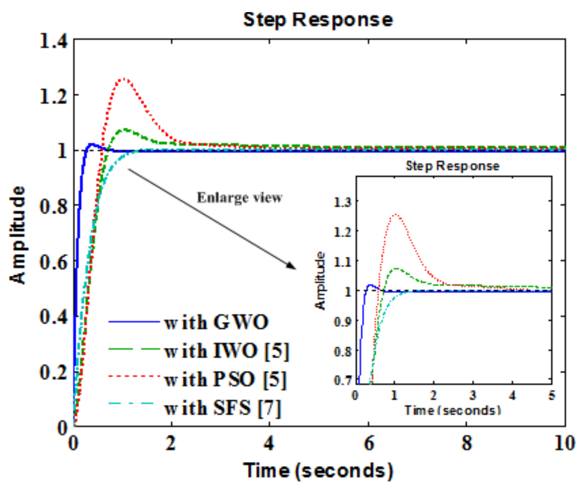

Figure 10:Comparison of step responses for operating point 2 ;R_a = 0.2;K = 0.012

Table 6: Comparison of transient response's parameters for operating point 2 ; R_a = 0.2 ; K = 0.012

Table 5: Comparison of transient response's parameters for operating point 1 ; R_a = 0.4 ; K = 0.015

Algorithm	Over Shoot (%)	Settling Time (sec)	Rise Time (sec)
GWO (Proposed)	1.8	0.244	0.167
IWO [5]	7.16	1.95	0.493
PSO [5]	25.5	2.38	0.409
SFS [7]	0	1.06	0.638

Case No. 3 :

In case – 3, operating point is given as :

R_a = 0.1; K = 0.014 (xvi)

Forthese parameters, the transfer function of DC motor is given by:

$$G_M = \frac{14}{1.08s^2 + 5.98s + 0.92} \quad \text{(xvii)}$$

Therefore, the closed loop transfer functions of DC motor with PID & unity feedback for GWO [Proposed], IWO [5], PSO [5] and SFS [7] as per parameters in Table 2, are given by :

$$G_{CL}(GWO) = \frac{13.0102s^2 + 96.5776s + 7.8764}{1.08s^3 + 18.9902s^2 + 97.4976s + 7.8764} \quad \text{(xviii)}$$

$$G_{CL}(IWO) = \frac{0.6734s^2 + 22.0948s + 6.1208}{1.08s^3 + 6.6534s^2 + 23.0148s + 6.1208} \quad \text{(xix)}$$

$$G_{CL}(PSO) = \frac{0.2226s^2 + 21.3276s + 19.3214}{1.08s^3 + 6.2026s^2 + 22.2476s + 19.3214} \quad \text{(xx)}$$

$$G_{CL}(SFS) = \frac{3.353s^2 + 22.841s + 3.9172}{1.08s^3 + 9.333s^2 + 23.761s + 3.9172} \quad \text{(xxi)}$$

The comparison of step responses for (xviii) – (xxi)has been shown in Figure 11. In Table 7, comparative analysis has been shown in terms of transient response's parameters for operating point 3.

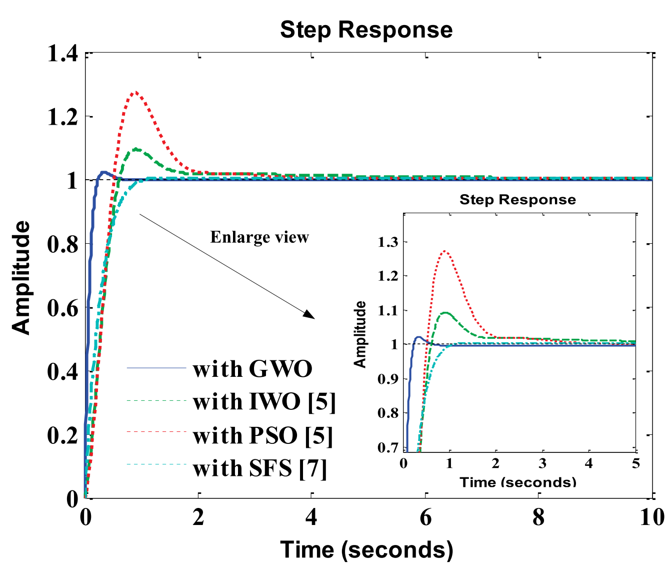

Table 5: Comparison of transient response's parameters for operating point 1 ; $R_a = 0.4$; K = 0.015

Algorithm	Over Shoot (%)	Settling Time (sec)	Rise Time (sec)
GWO (Proposed)	2.18	0.384	0.145
IWO [5]	9.33	1.7	0.428
PSO [5]	27.2	2.06	0.365
SFS [7]	0.438	0.852	0.539

Case No. 4 :

In case – 4, operating point is given as :

$$R_a = 0.3; \qquad K = 0.015 \qquad \text{(xxii)}$$

For these parameters, the transfer function of DC motor is given by :

$$G_M = \frac{15}{1.08\, s^2 + 6.06\, s + 1.41} \qquad \text{(xxiii)}$$

Therefore, the closed loop transfer functions of DC motor with PID and unity feedback forGWO [Proposed], IWO [5], PSO [5] and SFS [7] as per parameters in Table 2, are given by :

$$G_{CL}(GWO) = \frac{13.9395 s^2 + 103.476 s + 8.439}{1.08 s^3 + 19.9995 s^2 + 104.886 s + 8.439} \qquad \text{(xxiv)}$$

$$G_{CL}(IWO) = \frac{0.7215 s^2 + 23.673 s + 6.558}{1.08 s^3 + 6.7815 s^2 + 25.083 s + 6.558} \qquad \text{(xxv)}$$

$$G_{CL}(PSO) = \frac{0.2385 s^2 + 22.851 s + 20.7015}{1.08 s^3 + 6.2985 s^2 + 24.261 s + 20.7015} \qquad \text{(xxvi)}$$

$$G_{CL}(SFS) = \frac{3.5925 s^2 + 24.4725 s + 4.197}{1.08 s^3 + 9.6525 s^2 + 25.8825 s + 4.197} \qquad \text{(xxvii)}$$

The comparison of step responses for (xxiv) – (xxvii) has been shown in Figure 12. In Table 8, comparative analysis has been shown in terms of transient response's parameters for operating point 4.

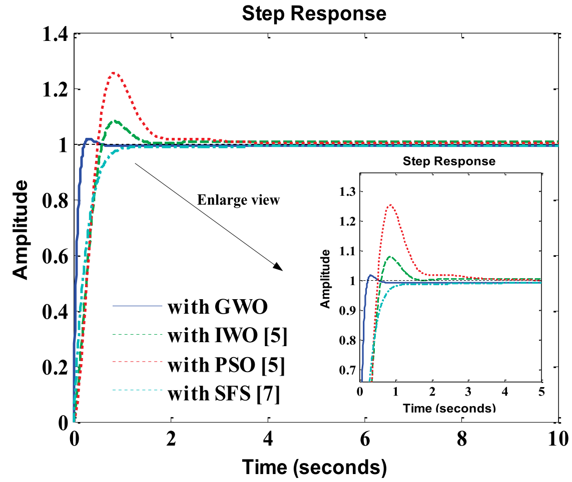

Figure 12:Comparison of step responses for Operating point 4 ;Ra = 0.3 ; K = 0.015

Table 5: Comparison of transient response's parameters for operating point 1 ; $R_a = 0.4$; K = 0.015

Algorithm	Over Shoot (%)	Settling Time (sec)	Rise Time (sec)
GWO (Proposed)	1.74	0.203	0.138
IWO [5]	7.92	1.32	0.414
PSO [5]	25.3	1.83	0.353
SFS [7]	0	0.968	0.53

The complete robustness analysis of the DC motor with PID controller tuned by GWO with ITAE as an objective function for all operating points has been shown in Figure 13. It can be seen in Figure 13 that, step response of DC motor for all operating points is matching, i.e. there is no affect of variations in the parameters of DC motor on the performance of PID controller once it is tuned by GWO.

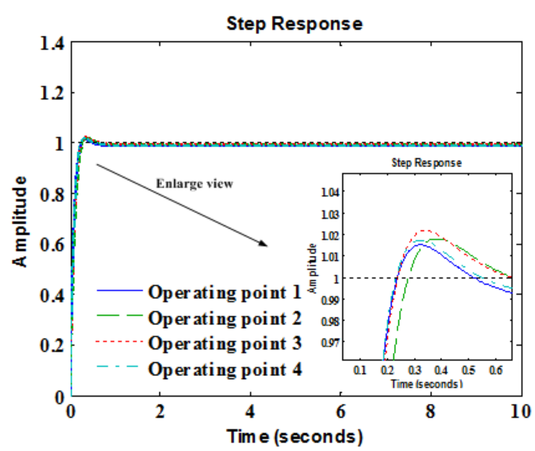

Figure 13: Speed comparison of DC motor for all operating points

figure 13:speed comparison of DC motor

7. CONCLUSIONS

The application of GWO algorithm in optimal speed control of DC motor has been shown. The ITAE has been taken as an objective/fitness function. Comparison of proposed GWO/PID scheme with ITAE has also been shown with other existing techniques; such as IWO/PID [5], PSO/PID [5] and SFS [7]. The simulation results reveal that GWO/PID scheme with ITAE as an objective function gives comparable overshoot and other parameters such as; settling time and rise time are lessin comparison to existing approaches. The robustness analysis of proposed GWO/PID scheme has also been carried out with variations in the parametersof DC motor along with comparative analysis. It has been observed that, there is no affect of variations in the parameters of DC motor on the performance of PID controller.

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