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Speed Control of DC Motor Using Whale Optimization Algorithm Based PID Controller

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Abstract

In this research article, the whale optimization algorithm technique, which is a meta-heuristic technique, has been implemented for the optimization tool of the traditional proportional-integral-derivative controller. The three parameters of the PID controllers have been optimized by the WOA technique to control the speed of the DC motor. For the analysing the propounded controller, the proposed controller has been juxtaposed with the other optimization techniques based PID controller to control the speed for the same investigated DC motor system. The simulation result of the propounded controller has shown superior result collated to other optimization techniques based PID controller as well as the transient response parameters along with objective function value also yielded better outcome than other optimization techniques.

Keywords: DC motor, proportional-integral-derivative controller, whale optimization algorithm, figure of demerits.

Introduction

In industry many controllers are used but one of the most utilized controller is the proportional-integral-derivative controller which is employed for the improvement of the nature of steady state and as well as the transient [1]. The PID controllers are also named in other term i.e. conventional or integer order controllers [2]. Another type of PID controller is

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there, which depends upon the fractional value of the integral and derivative controller, called fractional order PID controller (FOPID) [3]. Along with the conventional PID controller parameters (proportional controller - K_P, integral controller - K_I and derivative controller - K_D), the FOPID has two extra parameters which are λ i.e. fractional value of integration and μ i.e. fractional value of derivative. The system become more robust and it also becomes more flexible when these two parameters, which are having fractional values, gets added with the PID controller [4]. Achieving the correct parameters for the controller is a big challenge and it should be done properly to achieve desired response from the system. The researchers have preferred distinct types of meta-heuristic techniques which comes under the topic of numerical methods. The optimization techniques such as particle swarm optimization (PSO) [5], many optimizing liaisons (MOL) [6], artificial bee colony (ABC) [7], dynamic PSO (dPSO) [2], chaotic ant swarm (CAS) [8], genetic algorithm and bacterial foraging (GA-BF) [9], simulated annealing (SA) [10], local unimodal sampling optimization (LUS) [11], genetic algorithm (GA) [12], cuckoo search (CS) [13] and bacterial swarm optimization (BSO) [14] have been implemented for the optimization job. The techniques should have the capability to search for any random magnitudes in any solution space for a larger area. If the techniques follow this method then the technique will be able to converge near the best value or near to the best values [15].

In engineering applications, the implementation of these techniques are required so that the performance can be boosted up for evaluating the problems. The speed of the DC Motor can be controlled in the real word platform that is mainly implemented as a benchmark functions for the evolutionary optimization techniques. The parameters of the PID controller has been optimized by the different techniques, in literature, such as grey wolf optimization (GWO) [16, 17, 18] another algorithm is stochastic fractal search (SFS) [19], then one algorithm is there which is also being implemented i.e. invasive weed optimization (IWO) [20], genetic algorithm (GA) [21] and ant bee colony (ABC) [22]. For the optimization of the PID controller, the above stated optimization techniques have been used which has shown better results than the conventional Ziegler-Nichols (ZN) method depending on time of rise, time to settle and the percentage of maximum overshoot. From other techniques also, there are some drawbacks which should be eliminated. For any moment, the optimizing technique, *viz.* ABC, PSO and GA, has suffered from various types of flaws such as the burden of computation and the capability of storing in the memory but they can solve the problems in a

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greater way despite having these problems. Here, the modification of the optimization techniques is required, that why new optimization techniques are coming in the market. Through these new techniques, results which are obtained are better than the present techniques [23, 24, 25]. There is no exact technique for the parameters of the controller employed for the control of the speed of DC motor. Hence, the investigation of new optimization techniques is important task.For this research work, the whale optimization technique has been used for the tuning purpose of the system [28]. This algorithm gets inspired from the characteristic of the humpback whales which they use for the hunting purpose. In this algorithm, there is a generation of the group of solutions and for the reference purpose, the solution (candidate solution) has been considered as the new position. Parameter which are internal has to be used for the development of the nature of whale. The authors are expecting a relationship, which has to be good, between two important parts one is exploration and another one is exploitation. The search for the prey is the main requirement for the algorithm. Among these, there are some drawbacks also for this algorithm, one is the convergence which is taking place prematurely and second one is the distribution on which the adaptive parameters is depending randomly [28].

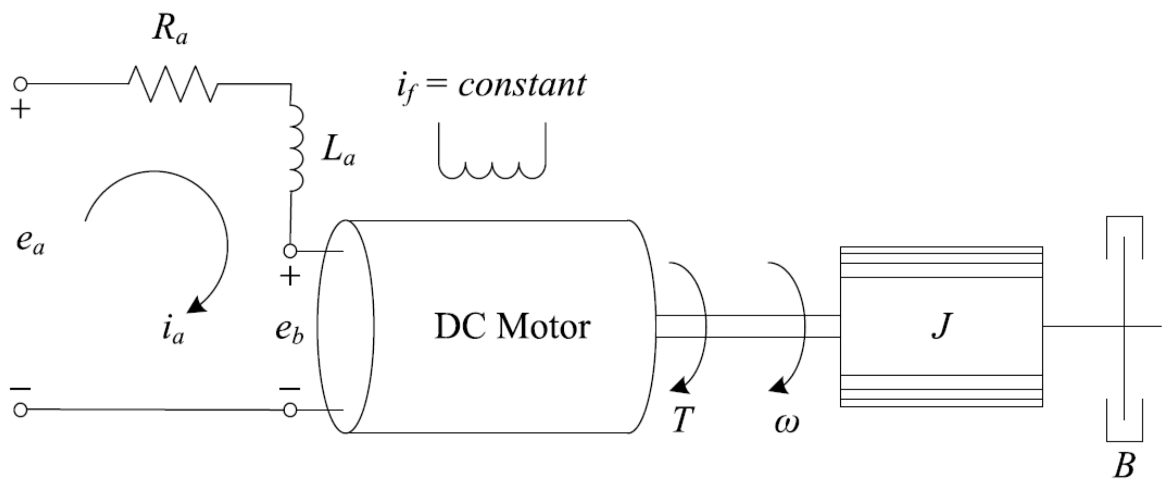

Fig. 1. DC Motor’s Circuit Diagram

Design of DC Motor

The classification of the DC motor can be done on the basis of its excitation method. Depending on the excitation type, the DC motor is classified into separately excited motor and self-excited motor. In present research work, the DC motor, having separate excitation, has been investigated. In **Fig. 1**, the DC motor’s circuit has been displayed for the control of speed.

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The voltage, which is induced, depends upon the flux and further it is angular velocity dependent, whose expression is expressed as $\omega = \frac{d\theta}{dt.}$. If the flux is constant, then in (1), the emf can be expressed.

$$e_b = K_b \frac{d\theta}{dt} = K_b \omega \quad (1)$$

If the armature voltage, e_a, of the DC servo motor is varied, then the speed of the motor will also vary that mean the speed of the motor can be controlled by the variation of the armature voltage. In (2), the expression of the armature circuit can be defined based on the differential equation.

$$e_a = L_a \frac{d\,i_a}{d\,t} + R_a\, i_a + e_b \quad (2)$$

The system's parameters are reported below:

Symbols	**Parameter Name**
R_a	Armature resistance, Ω
L_a	Armature inductance, H
i_a	Armature current, A
i_f	Field Current, A
e_a	Applied armature voltage, V
e_b	Back electromotive force, V
T	Motor torque, N-m
ω	Angular speed of motor shaft, rad/s
J	Inertia torque of motor, Kg.m^2
K_b	Electromotive force constant, V.s/rad
K	Motor torque constant, N-m/ A
B	Motor friction constant, N-m.s/rad

The torque developed by the motor, expressed in (3), depends upon the armature current which is based on the sum of the torque created by friction and the inertia.

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$$T = J\frac{d\omega}{dt} + B\omega = K i_a \tag{3}$$

The speed control of DC motor gets affected by the torque of the load, that's why the torque provided by the load has not taken into account in (3). Now, zero has been taken for the initial conditions, the expressions from (1) to (3) may represented in the following expressions.

$$E_b(s) = K_b\,\omega(s) \tag{4}$$

$$E_a(s) = (L_a s + R_a) I_a(s) + E_b(s) \tag{5}$$

$$T(s) = (J_s + B)\omega(s) = K I_a(s) \tag{6}$$

Table 1. DC Motor's parametric values

Parameter	**Value**
R_a	0.4Ω
L_a	2.7 H
J	0.0004 kg.m^2
B	0.0022 N-m-s/rad
K	0.015 N-m/ A
K_b	0.05 V.s

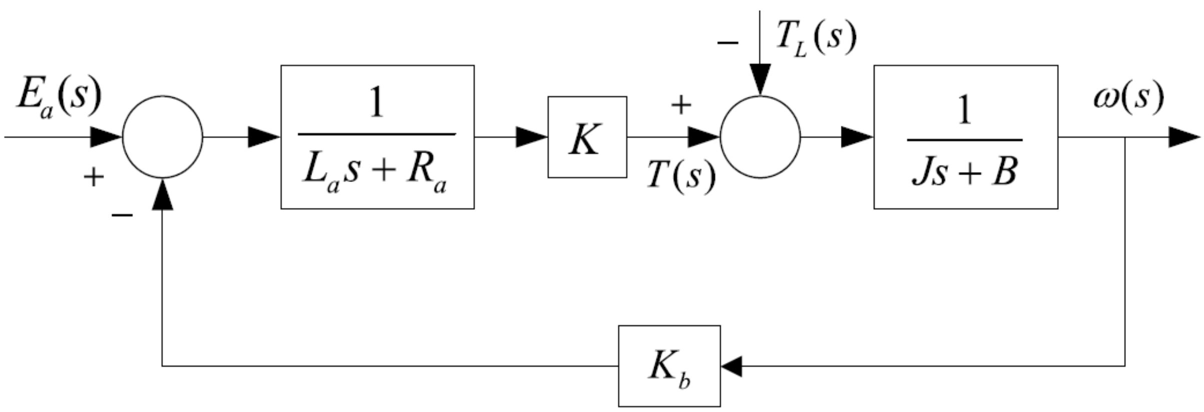

Fig. 2. DC Motor's block diagram

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The DC motor's block diagram is portrayed in **Fig. 2**. In (7), the DC motor's expression in expressed in the terms of Laplace domain.

$$G(s)=\frac{\omega(s)}{E_a(s)}=\frac{K}{(L_a+R_a)(J_s+B)+K_b K} \tag{8}$$

The parameters of the DC motor have some values, which is being reported in Table 1 [16, 19, 20]. These values are used for the simulation purpose.

PID controller

The proportional-integral-derivative controller is one of the simple controller which is easy to use, simple in structure, robust in nature and high degree of adaptability. These characteristics of PID controller encourage the researchers to accept the PID controller for their research purpose and this is the reason that the researchers have preferred the PID controller for the AGC problem also. The PID controller can minimize the steady-state error, the fastness of the responses can be increased by the controller and as well as the improvement of the transient response is also observed which makes the PID controller as a most chosen controller by the researchers [29-31]. The PID controller's model can be designed with the help of a transfer function, and in Laplace domain, it is presented in (9) where the parameters of controller show K_p, K_i and K_d which denotes the gain of proportional, integral and derivative respectively.

$$K_{PID}(s)=K_p+\frac{K_i}{s}+\frac{s K_d}{\xi s+1} \tag{9}$$

A low pass filter has been considered for this research work which has been installed in the path of derivative which helps to eliminate the fluctuation which is occurring in the output of the system. During the simulation, the magnitude of the ξ has been taken as 0.01.

Whale Optimization Algorithm

Whale optimization technique depends upon the hunting mechanism of the humpback whales where they search for the prey and by using the bubbles which they use for reaching the prey and hunt it [28]. The steps of the algorithm have been shown through flowchart and it is displayed in **Fig. 3.**

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1) The first step deals with the initialization of the population number which represents the searching of the agent and as well as the variables.
2) The second step comes up with the calculation of the fitness function which has to be done for each agent used for searching purpose and further the best solution has to be selected for individual variable and the position of the best solution has to be updated.
3) It is necessary to update the position for individual search agents and that can be done by following way:
   a) If P < 0.5, P represents random number
      i) If $|\vec{A}| < 1$

$$X(t+1) = \overrightarrow{X^*(t)} - (\vec{A} * \vec{D}) \tag{10}$$

where $\overrightarrow{X(t+1)}$ is the position updated and $\overrightarrow{X^*(t)}$ is best result.

$$\vec{A} = (2 * \vec{a} * \vec{r}) - (\vec{a}) \tag{11}$$

where $\vec{a}$ is the a value between 0 and 2 and $\vec{r}$ is the random vector which has value between [0, 1].

$$\vec{D} = \left| \left(2 * \vec{r} * \overrightarrow{X^*(t)} \right) - \left(\overrightarrow{X(t)} \right) \right| \tag{12}$$

where $\overrightarrow{X(t)}$ is the position vector.

      ii) If $|\vec{A}| > 1$,

$$X(t+1) = \overrightarrow{X^{rand}} - (\vec{A} * \vec{D}) \tag{13}$$

$$\vec{D} = \left| \left(2 * \vec{r} * \overrightarrow{X^{rand}} \right) - \left(\overrightarrow{X(t)} \right) \right| \tag{14}$$

where $\overrightarrow{X^{rand}}$ is the random position vector.

   b) If P > 0.5

$$\overrightarrow{X(t+1)} = \left(\vec{D} * e^{bl} * \cos(2\pi L) \right) + \overrightarrow{X^*(t)} \tag{15}$$

where *b* is logarithmic spiral shape and *L* is the random number between -1 and 1.

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$$\overline{D'} = \overline{X^*(t)} - \overline{X(t)} \tag{16}$$

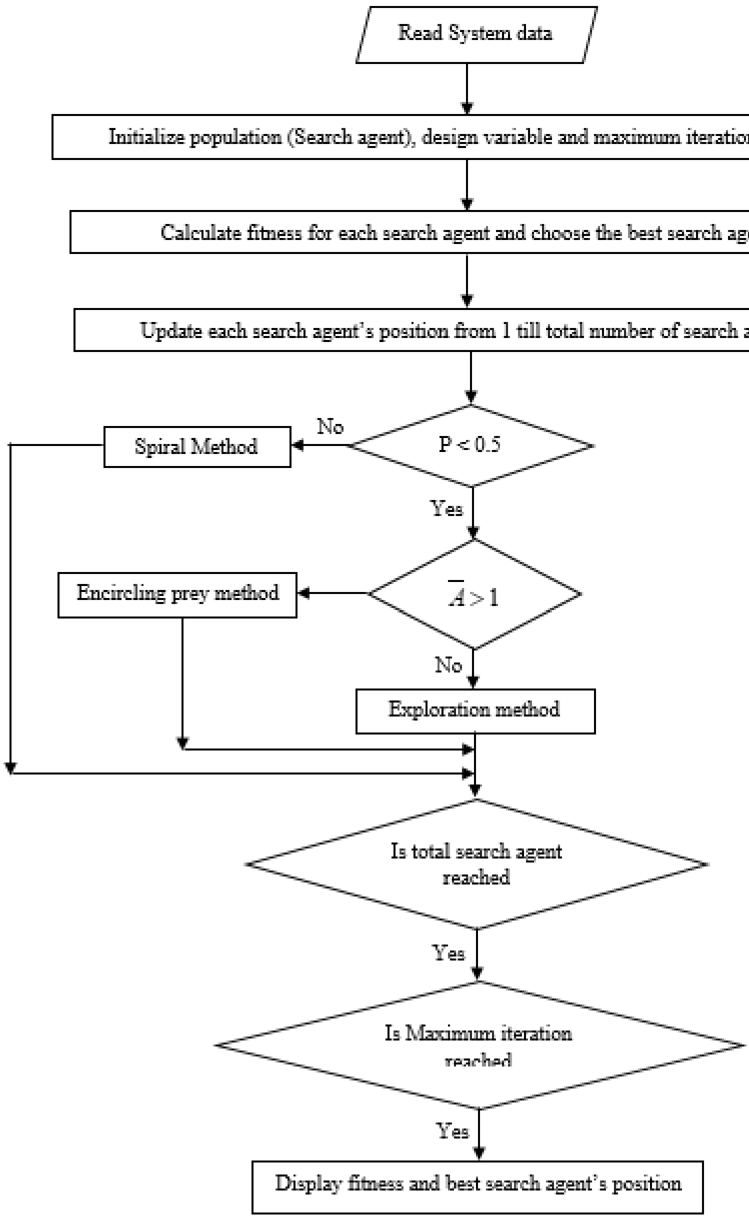

Fig. 3. WOA's Flowchart

The steps number 2 and 3 has to executed every time after the position has been updated and the value of fitness function will be evaluated.

Result and Discussion

For investigating the exhibition of the proposed controller, figure of demerits (FOD) has been utilized which depends upon the performance indices values of the voltage response profiles,

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i.e., maximum overshoot (M_P), rise time (T_R), settling time (T_S) and steady state error (E_{SS}) as stated in (17) [32].

$$FOD = \left(1 - e^{-\beta}\right)\left(M_P + E_{SS}\right) + e^{-\beta}\left(T_S - T_R\right) \tag{17}$$

where the magnitude of β is set as 1 for the current research work.

The MFO strategy need to advance the parameters of the PID controller inside specific limitations which is introduced in (18).

$$\left.\begin{array}{l} K_P^{MIN} \le K_P \le K_P^{MAX} \\ K_I^{MIN} \le K_I \le K_I^{MAX} \\ K_D^{MIN} \le K_D \le K_D^{MAX} \end{array}\right\} \tag{18}$$

where MIN is for the minimum value of the gains and MAX is for the maximum value of the gains.

In this examination work, the WOA procedure is being utilized for the enhancement of the PID controller for controlling the speed of DC Motor framework. The speed response profiles accomplished from the WOA procedure is compared with different methods based PID controller for a similar DC motor framework. The simulation is carried out with population size of 50 and 100 number of iterations in MATLAB/ Simulink. The other techniques such as ASO [33], GWO [18], SFS [21] and IWO [22] has been considered for the comparison purpose to analyse the presentation of the PID controller tuned by MFO method for controlling system.

Table 1. Controller parameters.

Controller Type	Controller Parameters		
	K_P	K_I	K_D
WOA-PID [Proposed]	**13.100**	**3.1011**	**2.2100**
ASO-PID [33]	11.9437	2.0521	2.4358
GWO-PID [18]	6.8984	0.5626	0.9293
SFS-PID [21]	1.6315	0.2798	0.2395
IWO-PID [22]	1.5782	0.4372	0.0481

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In **Fig. 4**, the collation of the speed response profiles has been shown and performance indices along with the FOD value has been delineated in **Table 2** based on the values of parameters of the controller, as reported in **Table 1**. From **Table 2**, it may be written that the FOD value of the PID controller based DC Motorspeed control system tuned by WOA technique is 0.3780 which is far better than the other techniques based PID controller for the same examined system.

Table 2. Transient response parameter and FOD value

Controller Type	Transient response analysis			
	M_P	T_R	T_S	FOD
WOA-PID [Proposed]	**1.0018**	**0.0506**	**0.0788**	**0.3780**
ASO-PID [33]	0.9995	0.0483	0.0813	0.3803
GWO-PID [18]	1.0137	0.1169	0.1801	0.4047
SFS-PID [21]	0.9952	0.5203	1.0743	0.7409
IWO-PID [22]	1.0690	0.4152	1.2489	0.9182

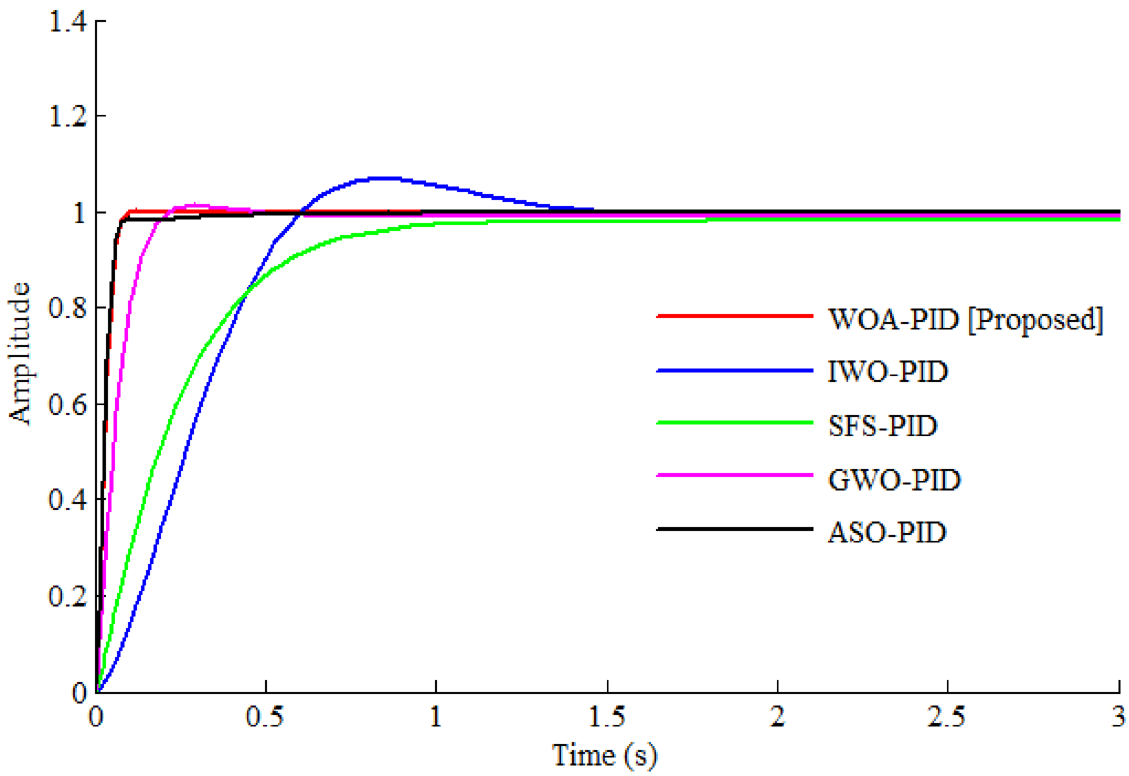

Fig. 4. Speed Response profile of WOA- [Proposed], IWO- [22], SFS- [21], GWO- [18] and ASO- [33] tuned PID controllers

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It may also be reported from the **Fig. 4**, that the speed response profile of the propounded technique yielded better characteristics than other optimization techniques based controller. Thus, from **Fig. 4** and **Table 2**, it may be noted that the propounded PID controller tuned by whale optimization technique has shown superior result than other evolutionary optimization technique based PID controller for controlling the same investigated DC motor speed control system.

Conclusion

The optimization of the parameters of the PID controllers for any application is a task of high challenge. The controller parameters get worsen as well as the system become unstable if the optimization process is not efficient to do the task. In this particular research work, the employment of PID controller for the controlling of the speed of DC motor has been studied. The whale optimization algorithm technique has been employed for the tuning purpose of the PID controller parameters. The objective function value achieved by the propounded controller has yielded exceptional result as compared to the optimization techniques based PID controller as stated in the literature survey. From the simulation results and the transient response parameters, it may be reported that the propounded whale optimization technique based proportional-integral-derivative controller can be employed for the speed control of the DC Motor system.

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