Fractional Order PID Controller Design for Speed Control DC Motor based on Artificial Bee Colony Optimization

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ABSTRACT

A proportional–integral–derivative (PID) controller is very popular in applications that require an easy and comprehensive control. In this project, the application of soft-computing algorithm design based on Artificial Bee Colony (ABC) optimization technique is integrated with Fractional order PID controller (FOPID) . It is an advancement of conventional PID controller in which the derivative and integral order are fractional rather than integer. Apart from the usual tuning parameters of PID, it has two more parameters λ (integer order) and μ (derivative order) which are infractions. This increases the flexibility and robustness of the system and gives a better performance .The aim of this work is to design a speed controller of a DC motor by selection of proper FOPID parameters using bio-inspired optimization technique of Artificial Bee Colony Optimization (ABC). The application of ABC to the FOPID controller imparts it the ability of tuning itself automatically in an on-line process while the application of optimization algorithm to the PID controller makes it to give an optimum output by searching for the best set of solutions for the PID parameters.

Keywords

Fractional Order PID Controller (FOPID), Artificial Bee Colony Optimization; Tuning Algorithm

1. INTRODUCTION

During the past decades there is a considerable interest in designing high efficiency motor drives due to widely used of drives in industrial applications such as rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills, excavators and cranes. These applications demand adjustable speed, good speed regulations, frequent starting, braking and reversing. To match these demanded industrial criteria a robust and high performance motor control system should be designed. Although so many research works have been done in field of design of motor control system, however, the development and further improvement in performance of the motor drives is still a target of many engineers and research centers.

Direct Current (DC) motor is among various electric motors that can provide excellent control of speed for acceleration and deceleration. The DC motors have been popular in drive application field as the power supply of the system is directly fed to motor which allows for a precision in current control. In addition, their high start torque characteristic and high response performance enabled them in speed and torque control applications. Moreover, these motors are also able to provide starting and torques for loads up to 400% than rate [1][2].

Efficient speed control systems can be easily implemented based on DC motors as these DC electric devices are considered as single-input single-output (SISO) systems the property which makes the motors controllable over a wide range of speed by providing a precise adjustment control signal. In this study, an armature current controlled scheme is considered for speed control. Proportional-Integral-Derivative (PID) technique is adopted to implement the controller of speed control system for a DC motor due to its simplicity and performance characteristics [3][4]. This technique has a simple structure and yet easy to realize for SISO systems since the control gain parameters are relatively independent [5]. Good performance of PID controller in various industrial applications makes it be the most famous controller among industrial players [5][6]. Recent studies revealed an elegant and effective way of enhancing the performance of PID controller by doing a new extension to the controller structure with the help of integrations and differentiations based on Fractional Calculus [7] and it is termed as fractional order (FO) PID controller [8]. In FOPID controller, apart from proportional (K_p), integral (K_i) and derivative (K_d) integer constants, there are two non-integer more adjustable parameters: order of derivative (μ) and order of integral (λ). Therefore, this controller technique is generalizations of PIDs and consequently has a wider scope of design, while retaining the advantages of classical ones. Based on this new technique, better and robust performance can be achieved if the FOPID controller parameters ($K_p, K_i, K_d, \lambda, \mu$) are tuned properly. In this paper, ABC tuning algorithm is used to optimize both of PID and FOPID controllers for the DC motor plant through obtaining optimum values for their gain parameters. The proportional gain makes the controller respond to the error while the integral derivative gain helps to eliminate steady state error and prevent overshoot respectively [9]. Speed control of DC motor has been attracting a considerable interest by many researchers, hence, there are many studies and researches have been published in this issue. Mickky and Tewari [10] proposed speed control system for DC motor using FOPID controller and Linear Quadratic Regulator (LQR) controller. Simulation results of the controllers are presented and then compared. However, the controller parameters of FOPID controller and weighting matrices R, Q elements of LQR controller are not calculated properly as they obtained based on hit and error method. In 2017, Kumar et. al. [11] introduced a speed control system for DC servo motor based on PID/FOPID controller. The parameters of PID controller are optimized with the help of genetic algorithm (GA) method, while FOPID controller parameters are tuned based on genetic algorithm (GA),

Simulated Annealing (SA) and frequency domain design (FDD) method. The time response of both of controllers is presented on the basis of unit step response. The performance of PID/FOPID controller is compared based on control criteria parameters.

Classical PID Fractional order PID controllers are proposed by [12] for DC motor based on GA optimization method. The time response of the controllers is demonstrated and their performance is compared to evaluate the proposed control system. Simulation results showed that shortest rise time achieved based on FOPID controller is 0.3 s. Anguluri et. al introduced DC motor control system using PID and FOPID controller based on artificial bee colony algorithm (ABC) optimization method. Simulation results of the control system are demonstrated and then compared. However, effect of friction coefficient of motor is not taken into consideration in the modeling of their proposed system. Furthermore, the performance of the control system showed overshoot and not short enough rise time. Moreover, control input of the system is not calculated.

In this paper, a good performance and robust speed control system for a DC motor using PID and FOPID controller based on high efficient ABC optimization method is introduced.

The rest of paper is organized as follows. Section II presents mathematical modeling dynamics of DC motor drive. Theory of fractional order systems is introduced in Section III. Section IV deals with Artificial Bee Colony optimization algorithm. A detailed explanation of ABC-based PIP/FOPID control system design is stated in Section V. Finally, simulation design of speed control system and results are presented in section VI followed by conclusions and future work details in Section VII.

2. SYSTEM PLANT MODELING

All Consider a DC motor with a single rigid rectangular coil constituted by a single wire where a current i flows, suitably located in a uniform exogenous magnetic field (B), then the torque (T) exerted at the center of the coil is given by:

$$T = ildB \tag{1}$$

Where l is the length of the wire perpendicular to the magnetic field B (m), d is the length of an edge of coil (m). The flux ϕ flowing through the rotor of DC motor is proportional to magnetic field B, the above torque expression can be rewritten as follows:

$$T = K_\phi \phi i \tag{2}$$

Where $K_\phi = ld / A$. In this work, the magnetic field B is assumed constant, hence ϕ is constant, and then the motor torque can be written as:

$$T = K_T i \tag{3}$$

Where $K_T = K_\phi \phi$ is a motor torque constant. Based on Farady's law, the back electromotive force (EMF) induced in the wire is given by:

$$E_a = \frac{d\phi_c}{dt}, \tag{4}$$

where ϕ_c is the flux flowing in the internal surface of a closed wire (Wb). Similarly to the case studied in (2) and (3), the back EMF can be written as follows:

$$E_a = K_a w \tag{5}$$

where K_a is the motor electromotive factor constant and w is the angular velocity of the motor (m/s)

In SI units, the motor torque and back emf constants are equal, that is, $K_T = K_a$, therefore, the constant K is used to represent both the constants i.e $K = K_a = K_T$.

The equation of the system dynamic is derived based on second Newton's law and is given by:

$$J \frac{dw}{dt} + Bw = Ki \tag{6}$$

While the electric equation of the system is formulated based on Kirchhoff's voltage law as follows:

$$L \frac{di}{dt} + Ri = E_a - Kw, \tag{7}$$

where J is motor inertia (kgm^2), B is the motor viscous friction coefficient (Nms), w is the angular velocity of the motor (rad/s) and L, R and E_a is the inductance (H), resistance (Ω) and voltage (V) of the coil respectively.

Applying the Laplace transform, the above system dynamic equations (6) and (7) can be expressed in s-domain as follows:
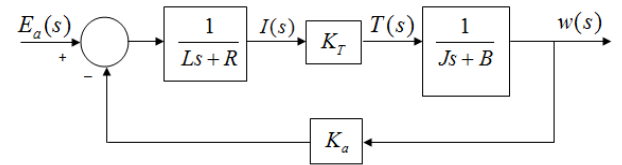
$$(Js + B)w(s) = KI(s) \tag{8}$$

Fig 1: Block diagram of a current controlled DC motor.

$$(Ls + R)I(s) = E_a(s) - Kw(s) \tag{9}$$

In this paper, the block diagram of the armature current controlled DC motor is shown in Figure 1. Based on (8) and (9), the open loop transfer function with the motor voltage $E_a(s)$ as the system input and the angular velocity $w(s)$ of the motor as the system output is as follows [13]:

$$\frac{w(s)}{E_a(s)} = \frac{K}{(R + Ls)(Js + B) + K^2} \tag{10}$$

Applying the realistic parameters values of DC motor system, which are listed in Table 1, the final transfer function of DC motor approximately becomes

$$\frac{w(s)}{E_a(s)} = \frac{0.023}{0.005s^2 + 0.01s + 0.000559} \tag{11}$$

Table 1. Typical parameters values for DC motor

Parameter	Symbol	Typical Value
Motor inertia	J	$0.01 \ kg.m^2$
Coil inductance	L	$0.5 \ H$
Coil resistance	R	$1 \ \Omega$
Motor constant	K	$0.023 \ Nm/A$
Friction	B	$0.00003 \ Nms$

3. THEORY OF FRICTIONAL ORDER SYSTEM

3.1 Fractional Order Calculus

Please Fractional order calculus is an area of calculus which generalizes the derivative or integral of a function to non-integer (fractional) order. Fractional calculus evaluates ($\dfrac{d^n y}{dt^n}$), n-fold integrals where n is fractional, irrational or complex [3]. This mathematical operation allow to establish a more concise and accurate model than the classical integer-order method. Moreover, the Fractional order calculus can also provide a good tool for describing dynamic process for control systems.

Fractional order calculus is a generalization of differentiation and integration to non-integer order fundamental operator which is denoted by aD_t^α where a and t are the operation limits and $\alpha(\alpha \in \Re)$ is the order of the operation. The formula of continuous differ-integral operator aD_t^α is defined as follows [3]:

$$aD_t^\alpha = \begin{cases} \dfrac{d^\alpha}{dt^\alpha} & \alpha > 0 \\[2mm] 1 & \alpha = 0 \\[2mm] \displaystyle\int_a^t (d\tau)^{-t} & \alpha < 0 \end{cases} \quad (12)$$

There are two commonly used definitions for general fractional differ-integral aD_t^α which are used for realization of control problem algorithm:

- Grunwald – Letnikov (GL) definition

$$aD_t^\alpha f(t) = \lim_{h \to 0} h^{-\alpha} \sum_{j=0}^{[\frac{t-a}{h}]} (-1)^j \binom{\alpha}{j} f(t-jh) \ (13)$$

Where $[.]$ denotes the integer part of operator

- Riemann-Liouville definition

$$aD_t^\alpha f(t) = \frac{1}{\Gamma(1-\alpha)} \frac{d^n}{dt^n} \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau$$

(14)

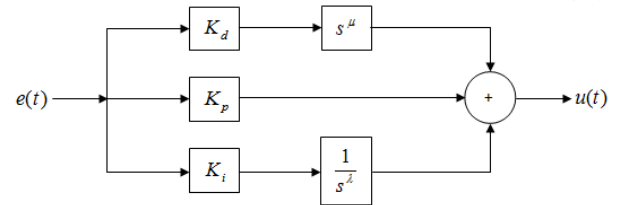The condition for above equation is $n-1 < \alpha \le n$, $\Gamma(.)$ is called *Gamma* function.

The definition of *Gamma* function is given by
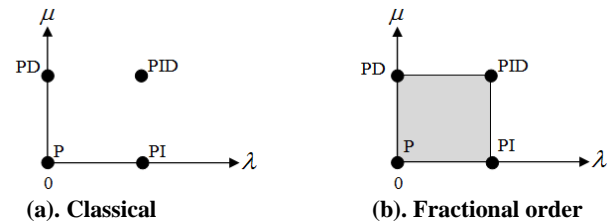
$$\Gamma(x) = \int_0^\infty z^{x-1} e^{-z} dz \quad (15)$$

Laplace transform of differ-integral operator aD_t^a is given by expected form

$$L[{}_0D_t^\alpha f(t)] = \int_0^\infty e^{-st} {}_0D_t^\alpha f(t) dt \quad (16)$$

$$L[{}_0D_t^\alpha f(t)] = s^\alpha F(s) - \sum_{m=0}^{n-1} s(-1)^j {}_0D_t^{\alpha-m-1} f(t)$$

(17)

Fig 2: The basic block diagram structure of a fractional order PID

(a). Classical   (b). Fractional order

Fig 3: PID controllers with fraction oredrs

Where $F(s) = L\{f(t)\}$ is the normal Laplace transformation and n is an integer number that satisfies $n-1 < \alpha \le n$ and $s = jw$ denotes the Laplace transform variable.

3.2 Fractional Order PID Controller

Fractional order PID controller denoted by $PI^\lambda D^\mu$ was proposed by Igor Podlubny [4] in 1997. It is an extension of conventional PID controller where λ and μ have non-integer fractional values. Figure 2 shows the block diagram of fractional order PID controller.

The integer-differential equation defining the control action of a fractional order PID controller is given by:

$$u(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{-\mu} e(t) \quad (18)$$

Based on the above equation, it can be expected that the FOPID controller can enhance the performance of the control system due to more tuning knobs introduced. Taking the Laplace transform of (18), the system transfer function of the

FOPID controller is given by:

$$G_{FOPID}(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \qquad (19)$$

Where λ and μ are an arbitrary real numbers. Taking $\lambda = 1$ and $\mu = 1$, a classical PID controller is obtained. Thus, FOPID controller generalizes the classical PID controller and expands it from point to plane as shown in Figure 3. This expansion provides us much more flexibility in designing PID controller and gives an opportunity to better adjust the dynamics of control system. This increases the robustness of the system and makes it more stable. [5]. A number of optimization techniques can be implemented for getting the best values of the gain parameters of the controller. In this research, Artificial Bee Colony Optimization (ABC) technique is recommended to tune the controller due to its ability to obtain optimum controller parameters, hence achieve best system response.

4. ARTIFICIAL BEE COLONY OPTIMIZATION METHOD

The Artificial Bee Colony is a bee swarm algorithm described by Karaboga in 2005. It considers one of the more recent population based optimization algorithm for solving the multivariable numerical functions [1]. The ABC optimization algorithm has advantages of fast convergence high flexibility, strong robustness and fewer control parameters. [16] [17]. In a real bee colony, there are some tasks performed by specialized individuals. These specialized bees try to maximize the nectar amount stored in the hive by performing efficient division of labor and self-organization. The colony of artificial bees consists of three groups of bees: employed bees, onlookers and scouts. First half of the colony consists of the employed artificial bees and the second half includes the onlookers.

Employed bees determine a food source within the neighbourhood of the food source, onlooker bees wait on the dance area for making the decision to choose a food source within the neighbourhood of the food sources chosen by themselves, while scouts are responsible for random search of new food sources. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose the food source has been abandoned by the bees becomes a scout. The position of a food source represents a possible solution of the optimization problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. The number of the employed bees or the onlooker bees is equal to the number of solutions in the population [7].

Detailed pseudo code of the ABC optimization algorithm is as follows [18]:

1. Initialize the population of solutions $x_{i,j}$, $i = 1,2,.....SN$ (SN is the number of food sources) $j = 1,2,.....D,$ (D is the dimension of problem, for optimization of PID controller $D = 3$ [namely K_p, K_i and K_d], and for FOPID controller $D = 5$ [namely K_p, K_i, K_d, λ and μ]).

2. Evaluate the population.

3. Cycle=1.

4. Repeat.

5. Produce new solutions (food source positions) v_{ij} in the neighborhood of x_{ij} for the employed bees using the formula $v_{ij} = x_{ij} + \psi_{ij}(x_{ij} - x_{kj})$ (k is a solution in the neighborhood of i, ψ is a random number in the range [-1,1]) and evaluate them

6. Apply the greedy selection process between x_{ij} and v_{ij}.

7. Calculate the probability values P_i for the solutions x_i by means of their fitness values using the following equation:

$$P_i = \frac{fit_i}{\sum_{i=1}^{SN} fit_i} \qquad (20)$$

In order to calculate the fitness values of solutions we employed the following equation:

$$fit_i = \begin{cases} \dfrac{1}{1+f_i} & if\ f_i \geq 0 \\ 1 + abs(f_i) & if\ f_i < 0 \end{cases} \qquad (21)$$

Normalize P_i values into [0,1].

8. Produce the new solutions (new positions) v_i for the onlookers from the solutions x_i, selected depending on P_i, and evaluate them

9. Apply the greedy selection process for the onlookers between x_i and v_i.

10. Determine the abandoned solution (source), if exists, and replace it with a new randomly produced solution xi for the scout using the following equation:

$$x_{i,j} = \min_j + rand(0,1) * (\max_j - \min_j) \qquad (22)$$

11. Memorize the best food source position (solution) achieved so far.

12. Cycle=Cycle+1.

13. Until Cycle= Maximum Cycle Number (MCN) .

5. SPEED CONTROL SYSTEM DESIGN

In this research, PID and fractional order PID controllers based on ABC optimization method are adopted to design the proposed speed control system for DC motor. The block diagram of the speed control system for DC motor is shown in Figure 4. The ABC tuning algorithm was mainly utilized to determine optimal values for controller parameters K_p, K_i, K_d with the derivative order μ and integral order λ are infractions such that the output speed of motor could follow the demand reference input trajectory. These controller gain parameters can enable the system to achieve a good output response and result in minimization of performance criteria in the time domain which includes rise time (t_r), settling time (t_s), maximum overshoot

$(MO\%)$ and steady state error (e_{ss}). Based on (8) and (18), the closed loop transfer function of the proposed speed DC motor control system can be expressed as follows:

$$G_{cl}(s) = \frac{K_1 s^{\lambda+\mu} + K_2 s^{\lambda} + K_3}{(K_5 + K_4)s^{\lambda} + K_1 s^{\lambda+\mu} + K_3} \quad (23)$$
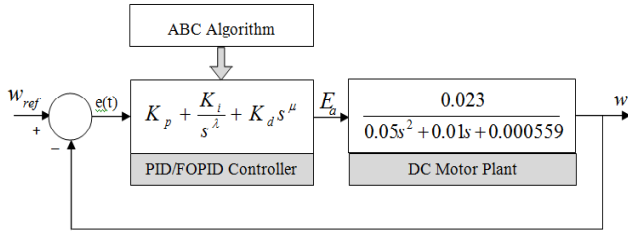

Fig 4: Block diagram of speed control of DC motor

where $K_1 = K_d K, \quad K_2 = K_p K, \quad K_3 = K_i K$ and

$K_4 = K_2 K^2, K_5 = (R + Ls)(Js + B)$.

The controllers are simulated using Matlab environment to validate the proposed system and their performance is evaluated and then compared based on control criteria which includes: rise time and settling time, maximum overshoot, and steady state error parameters. The system under unit step input is designed to achieve the following control criteria: rise time (t_r) less than 1 s, settling time (t_s) less than 2 s, maximum overshoot $(MO\%)$ less than 5% and steady state error (e_{ss}) less than 1%. The proposed Fitness function (F) for the optimization of both PID and FOPID controller parameters is defined as:

$$F = w_{\max}(1 - e^{-(Mo+e_{ss})}) + w_{\min}e^{-(t_s - t_r)} \quad (24)$$

6. SIMULATION AND RESULTS

In this research, controllers based on PID and FOPID techniques of speed motor control system are designed and simulated using Matlab tool. Parameters of controllers are tuned in optimum fashion based on ABC optimization algorithm. The parameter values taken for running the ABC algorithm in Matlab environment are listed in Table 2.

Table 2. Parametric values of ABC algorithm

Parameter	Value
No of food sources SN	100
No of onlooker bees	100
Limit (scout trails)	20
No of iterations	100
Run time (MCN)	50

Table 3 states optimum values of PID and FOPID controller parameters for speed control system. Based on these controller parameters, under unit step input, the output response of PID and FOPID controllers for speed control system are shown in Figures (5) and (6) respectively.

Table 3. Parametric values of PID/FOPID controller

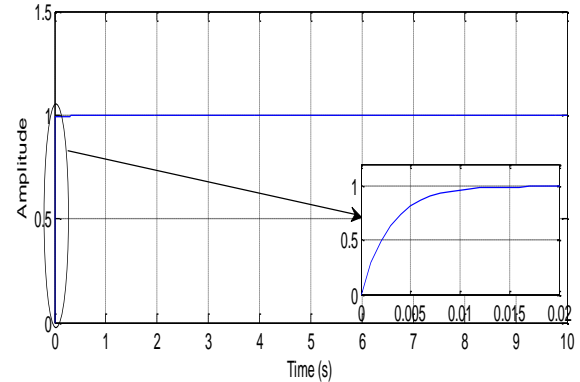| Parameter	PID Controller	FOPID Controller
λ		0.0
μ		2.0116
K_p	2.994	98.0859
K_i	29.75	13.9115
K_d	72.6	100

Fig 5: Unit step response of PID controller for speed control system using ABC tuning algorithm
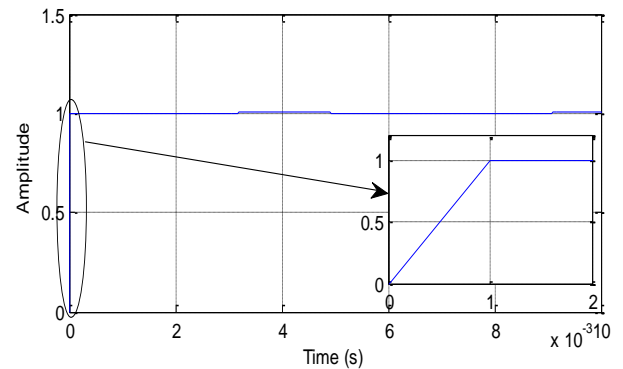

Fig 6: Unit step response of FOPID controller for speed control system using ABC tuning algorithm.

It can be noted from these figures that the ABC optimization method succeeded to tune controllers effectively and hence achieve good output response. Based on mini plots of Figures 5 and 6, the parameters of system performance criteria which include rise time, settling time and overshoot are presented in Table 4. It can be noted from Table 4 that, both controllers based on ABC optimization algorithm satisfied the control requirements, however, there is a good improvement in rise time and settling time is achieved using ABC-FOPID controller. Rise time reduced from 6.5 ms to 0.8 ms while the settling time reduced from 13 ms to 1.9 ms. Consequently, the FOPID controller based on ABC tuning algorithm can be effectively adopted to design a good speed control system for DC motor.

Regarding control system input, Figure 7 shows control effort of speed control system for DC motor using FOPID controller based on ABC tuning algorithm.

It can be seen from mini plot of Figure 7 that steady state value of control input is very small while its initial value is high the reason for this is that the controller parameters are set based on fast response requirement.

Table 4. Performance parameters of PID and FOPID controllers for speed control system
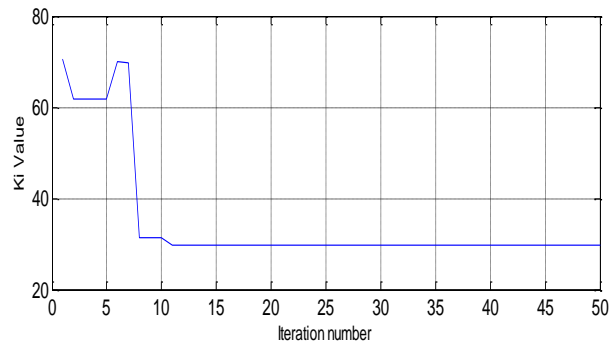
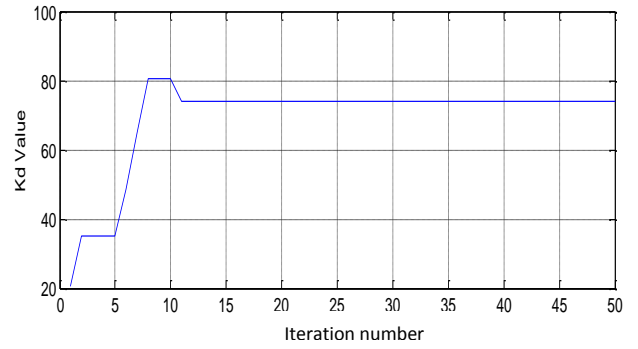| Controller	Performance Parameter		
	t_r	t_s	MO %
ABC-PID	6.5 ms	13.3 ms	0.0
ABC-FOPID	0.8 ms	1.9 ms	0.0
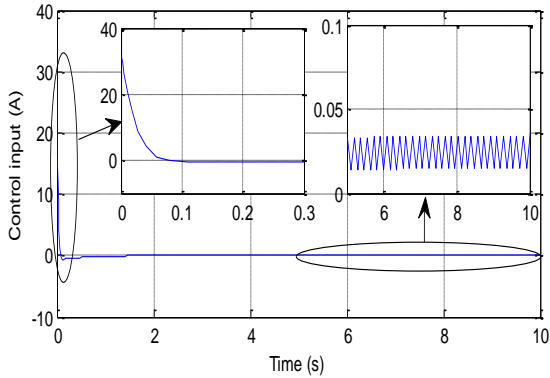
Fig 7: Control effort of FOPID controller
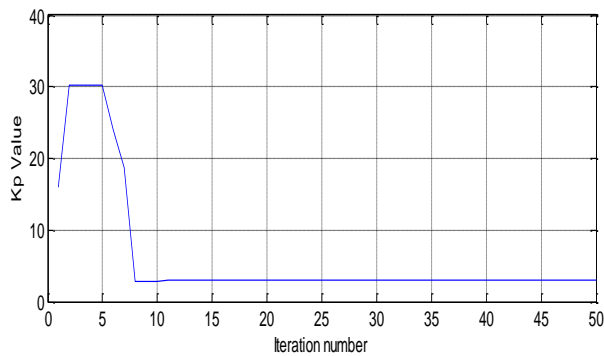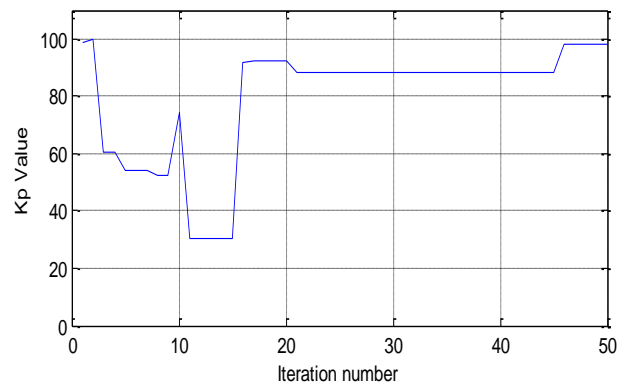

(a). K_p **gain**

(b). K_i **gain**

(c). K_d **gain**

Fig 8: Generation values of PID controller gains.

To achieve an acceptable system behavior a compromise between response speed and control effort of the system should be considered in determine the controller gain parameters. Figures. 8 and 9 present convergence curve of gains parameters for PID and FOPID controllers based on ABC optimization method through iterations respectively.

7. CONCLUSION

This research presents investigation into the development of speed control system for DC motor. The mathematical model of armature current controlled DC motor , which describes the dynamics of the speed control system, was derived. Two controllers, PID and FOPID, were successfully designed and simulated based on Matlab environment for the speed control system. In this study, ABC optimization algorithm has been successfully used to tune the gain parameters of the controllers. Under unit step input, the performance of the optimized ABC-PID and ABC-FOPID controllers was compared based on rise time, settling time and overshoot parameters to evaluate the proposed speed control system. The simulation results have shown that, the FOPID controller based on ABC tuning method had the fastest response with minimal overshoot value. Therefore, FOPID technique can be effectively adopted to design an efficient controller of speed control system for DC motor.
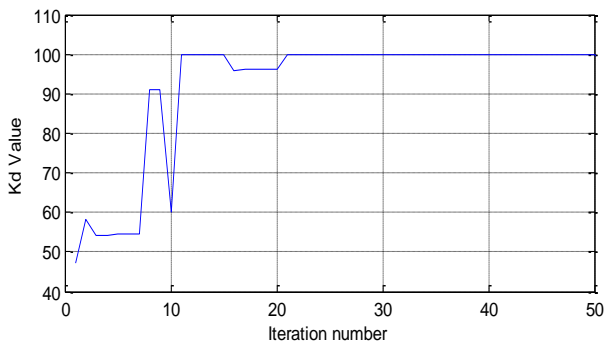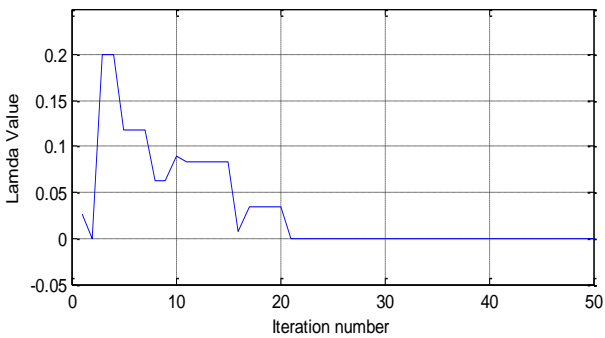

(a). K_p **gain**
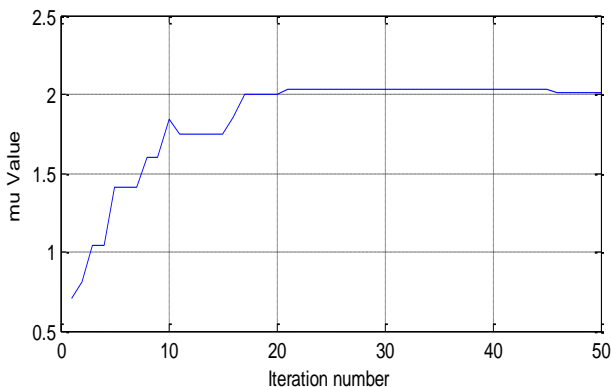
(b). K_i **gain**

(c). K_d **gain**

(d). λ **gain**
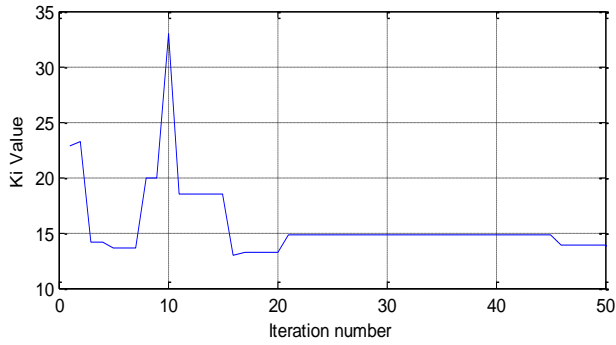
(e). μ **gain**

Fig 9: Generation values of the FOPID controller parameters

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