Journal of Circuits, Systems, and Computers
Vol. 27, No. 8 (2018) 1850123 (19 pages)

DOI: 10.1142/S0218126618501232

A Metaheuristic Optimization Approach for Tuning of Fractional-Order PID Controller for Speed Control of Sensorless BLDC Motor*

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Received 21 November 2016
Accepted 19 October 2017
Published 21 November 2017

This paper deals with a novel method for Bat Algorithm (BA) based on optimal tuning of Fractional-Order Proportional Integral Derivative (FOPID) controller for governing the rotor speed of sensorless Brushless Direct Current (BLDC) motor. The BA is used for developing a novel optimization algorithm which can generate five degrees of freedom parameters namely K_p, K_i, K_d, λ and μ of FOPID controller. The desired speed control and robust performance are achieved by using the FOPID closed loop speed controller with the help of BA for optimal tuning. The time domain specifications of a dynamic system for unit step input to FOPID controller for speed response such as peak time (t_r), Percentage of overshoot (PO), settling time (t_s), rise time (t_r) have been evaluated and the steady-state error (e_{ss}) of sensorless speed control of BLDC motor has been measured. The simulation results are compared with Artificial Bee Colony (ABC) optimization method and Modified Genetic Algorithm (MGA) for evaluation of transient and steady state time domain characteristics. The proposed BA-based FOPID controller optimization technique is more efficient in improving the transient characteristic performance and reducing steady state error.

Keywords: Sensorless BLDC motor drive; optimal control; fractional-order PID controller; bat algorithm.

*This paper was recommended by Regional Editor Tongquan Wei.
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1. Introduction

Permanent magnet Brush Less Direct Current (BLDC) motors play a vital role in the modern engineering applications. BLDC motor drives are commonly used for obtaining high efficiency and good controllability. Its applications are in home appliances, medical, aerospace, robotic, automotive equipment,[1] etc. A BLDC motor can achieve the required commutation process with the help of an inverter and a rotor position sensor, i.e., Hall Effect sensor. Hence, the BLDC motor need not to have brushes and commutator. However, the Hall Effect position sensors also have more drawbacks due to failure of machine components and noise aspects.[2] Many researchers have reported sensorless commutation process for better performance and robust control of BLDC motor drives. The sensorless BLDC motor drives can produce effective speed and position control without shaft mounted position sensor to the closed loop feedback system.[3,4] The sensorless BLDC motor drive gives better optimal rotor speed control and precision of the desired speed control with the help of Fractional-order Proportional Integral Derivative (FOPID) controller.

Fractional-Order Calculus (FOC) and Mathematics are constituted since many centuries ago which established from the traditional calculus of integer order system.[5] Liouville prepared a very first study on FOC in 1832 and Grunwald proceeded on the fractional-order system in 1867. Riemann matured the theoretical analysis and development of fractional-order integration system in the year 1892. The fractional-order system scientifically agrees to the fundamental concept and real-time model phenomenon more than the accurate conventional integer order system.[6,7] The flexible structure of FOPID controller was developed by Podlubny which has the extension of the traditional concept of PID controller.[8] The FOPID controller is suitable for Process Control System, Distributed Control System (DCS) or Supervisory Control and Data Acquisition (SCADA) and also in special electric machine speed control applications. Vinagre had a detailed study on frequency and time domain analysis using optimization technique for generating optimal five-degree parameter values of the FOPID controller.[9] The Bat Algorithm (BA) is a metaheuristic optimization algorithm which combines heuristics and mathematical programs to perform a particular task.[10,11] The BA generates optimal parameter, i.e., K_p, K_i, K_d, λ and μ for tuning controller which can change the numerical values based on iteration methods which can provide better optimal solutions that vary from small exploration to improved exploitation.[12] The BA feasible solution is produced with the help of fine-tuning loudness, changeable frequencies and Echolocation pulse emission rates. The precision of user requirement speed control depends on the BA feasible solution which is exceptionally effortlessness and adaptability to FOPID controller.[13] It a proficient algorithm than other algorithms for example, Modified Genetic Algorithm (MGA) and Artificial Bee Colony (ABC) for speed control applications.

The remaining of this paper is formed under five sections: In Sec. 2, preliminaries of sensorless BLDC motor with FOPID controller, i.e., basic functional blocks and working principle are explained in detail. In Sec. 3 includes the conventional speed control methodologies and materials of ABC and MGA for optimal tuning of FOPID controller. The proposed work of FOPID controller with BA for optimal tuning of five degrees of freedom parameter for achieving quick settling time and the minimization of steady state error is explained in Sec. 4. Section 5 contains the simulation results by the software named Matrix Laboratory and the discussion on the results produced by the FOPID-based BA. Finally, Sec. 6 presents the comparison of the results.

2. Preliminaries

Many industries need to control the speed of BLDC motors by sensorless techniques for various applications. The conventional speed control strategies, i.e., speed controller, PI controller, PID controller, Neuro-PID controller, Fuzzy PID controller, provide a less precise and ineffective performance so the improved speed controllers are designed for these sensorless BLDC motor drive from classical PID controller to the superior FOPID controller with metaheuristic optimization techniques. The BLDC motor-based speed control system consists of the power converter, electrical parameter measurements, speed estimation, FOPID controller and metaheuristic optimization algorithms. The rotor speed is proportional to motor current and terminal voltage which is changed by using power semiconductor devices with the Pulse Width Modulation (PWM) techniques.[14]

2.1. *Sensorless BLDC motor drive*

The BLDC motors have destitute performance because of the complex electric wiring arrangements and expensive rotor position sensors. To overcome these drawbacks, the inventor recommends the use of sensorless drive systems for improved transient and steady state characteristics performance.[15] The sensorless drive is operated on the trapezoidal shape back electromagnetic force (EMF) induced by movement of a permanent magnet rotor. It reduces the occurrence of variations caused by discrete sensors. The speed of sensorless BLDC motor, flux and torque are estimated by using input parameters, such as the terminal voltage and current under fluctuation load setting.[16] The basic functional block of a sensorless drive of BLDC motor is shown in Fig. 1.

2.2. *Fractional-order PID controller*

The FOPID controller is a closed loop with feedback signal system which is commonly used for process control and motor speed control systems. The FOPID controller for speed control regulation in sensorless BLDC motor using optimization

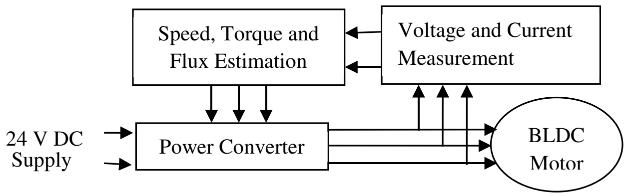

Fig. 1. Functional blocks of a sensorless BLDC motor drive.

technique has extra two degrees of freedom for the enhanced adjustment of the dynamic characteristic behavior of fractional-order controller which is in closed loop feedback system. It has five degrees of freedom parameters such as proportional gain (K_p), integral gain (K_i), derivative gain (K_d), integral order (λ) and derivative order (μ). The optimal design of FOPID controllers involves the five parameters K_p, K_i, K_d and fractional-orders λ, μ. The basic structure of FOPID controller is shown in Fig. 2. The error detector is continually compared with the desired set point $W(s)$ and measured process variable $Y(s)$, as a result, it determines the difference of the value $E(s)$ produced. The purpose of FOPID controller is to provide a great adaptability and frequency response as well as excellent performance. It has been fine-tuned with the help of ABC and MGA optimization techniques for improving transient response and minimization of a steady state error.

The transfer function of FOPID is given below:

$$G_c(s) = \frac{U(s)}{E(s)} = K_P + K_I S^{-\lambda} + K_D S^{\mu}, \quad (\lambda, \mu > 0)\,. \tag{1}$$

The equation for the FOPID controller in the time domain is

$$U(t) = K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^{\mu} e(t)\,. \tag{2}$$

Unit step responses of closed loop speed control system with FOPID controller is given by

$$\sum_{k=0}^{n} a_k D^{\beta k} y(t) + K_P y(t) + K_I D^{-\lambda} y(t) + K_D D^{\mu} y(t)$$
$$= K_P w(t) + K_I D^{-\lambda} w(t) + D^{\mu} w(t)\,. \tag{3}$$

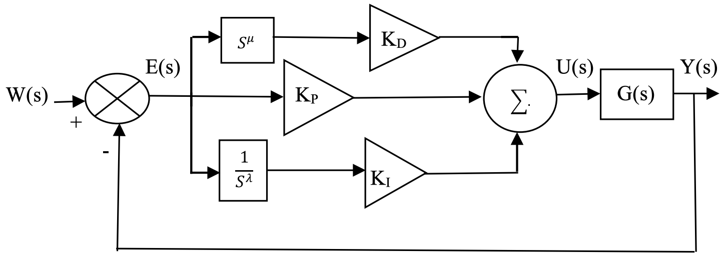

Fig. 2. Basic structure of FOPID controller.

From Eq. (3), the following expression for the transfer function of the considered closed loop system is obtained as

$$G_{\text{closed}}(s) = \frac{K_P S^{\lambda} + K_I + K_D S^{\mu+\lambda}}{\sum_{k=0}^{n} a_k S^{\beta} k + \lambda + K_P S^{\lambda} + K_I + K_D S^{\mu+\lambda}} \,. \tag{4}$$

The unit step response $G_{\text{closed}}(t)$ is then obtained by the Laplace inversion of Eq. (4).

2.3. *Speed control of sensorless BLDC motor drive based on FOPID controller*

The power converter is a static gadget that converts the settled DC supply voltage to variable AC voltage produced by triggering the pulse edge to the power switching devices. The switching action, i.e., switch ON or switch OFF is determined by the estimated rotor position for controlling the direction of the rotation, speed and the torque of the motor. In sensorless technique, voltage and current values are measured and the actual rotor speed is estimated. Figure 3 shows the overall block diagram of the speed control of sensorless BLDC motor. The error detector receives the actual speed (ω_{rm}), i.e., estimated speed by the sensorless techniques and the manually set reference speed 1,500 rpm (ω_r). Let assumption of rotor angle position θ_{rm} lags behind the actual rotor angle position θ_r. The BLDC motor model is used to the stator streams that is done in a reference outlined at an expected rotor speed. It suggests that the reference casings are α and β not d- and q-axes which are the standard rotor reference outlines. Assumed position or model speed[2] is as follows:

$$\theta_r = \int \omega_r \mathrm{dt} \,, \tag{5}$$

$$\theta_{rm} = \int \omega_{rm} \mathrm{dt} \,, \tag{6}$$

$$\delta\theta = \theta_r - \theta_{rm} = \int (\omega_r - \omega_{rm}) \mathrm{dt} \,. \tag{7}$$

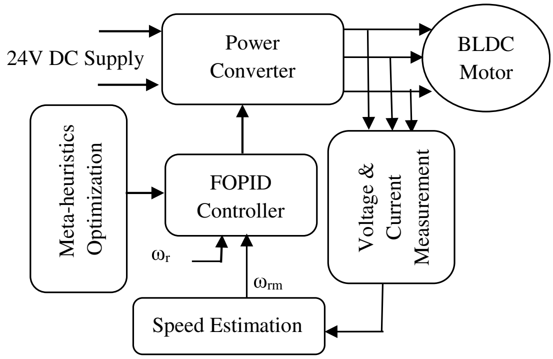

Fig. 3. Overall block diagram of speed control of sensorless BLDC motor.

The error current results in

$$\delta i_\alpha(kT) = -\frac{\lambda_{af}}{Lq}\mathrm{T}(-\omega_{rm} + \omega_r)\,, \tag{8}$$

$$\delta i_\beta(kT) = \omega_r \frac{\lambda af}{L_d}\delta\theta\,. \tag{9}$$

The actual rotor speed is obtained as

$$\omega_r = \frac{-L_q}{\lambda af}\,\frac{1}{T}\,\delta i_\alpha(kT) + \omega_{rm}\,. \tag{10}$$

The error in estimated rotor angle position is

$$\delta\theta = \frac{L_d}{\lambda_{af}}\,\frac{1}{T}\,\frac{\delta i_\beta}{\omega_r}(kT)\,. \tag{11}$$

The BLDC motor rotor speed in the error rotor angle position equation is given as

$$\delta\theta = \frac{\left(\frac{L_d}{T\lambda_{af}}\right)\delta i_\beta(kT)}{\left(\omega_{rm} - \frac{L_q}{T\lambda_{af}}\delta i_\alpha(kT)\right)}\,, \tag{12}$$

where $\delta\theta$, ω_{rm} and ω_r are for the sampling time of kT.

Then, the rotor position is

$$\theta_r = \theta_{rm} + \delta\theta\,. \tag{13}$$

The estimation of θ_{rm} in the sampling time of feeding into the FOPID controller depends on stator current command. The error detector generates different value, i.e., the error value to feed the FOPID controller. The FOPID controller generates five optimal degrees of freedom parameters which are K_p, K_i, K_d and λ, μ with the help of metaheuristic optimization. Finally, these are enhanced to control the speed of the sensorless BLDC motor which will be achieved by varying the triggering pulse and analysis of the step response of time domain systems. The next section illustrates the methodology of the metaheuristic optimization algorithm for tuning FOPID controller for speed control of BLDC motor.

3. Methods and Materials

In the last two decades, metaheuristic optimization algorithms were developed for solving complex problems and finding optimal values but a few intelligent optimization algorithm such as Artificial Immune Systems, Ant Colony Optimization, Bacteria Forage Techniques were unable to find better optimal value, although it has been shown that these are good optimization methods to find better optimal values. In this section, the metaheuristic optimization used in FOPID controller, that is

ABC and MGA, to obtain the fractional-order controller optimal tuning parameter for precise speed control of sensorless BLDC motor is briefly described.

3.1. *Formulation of the objective function for tuning of FOPID controller*

The FOPID controller parameter is tuned in an optimal fashion such that drive gives optimal performance for tuning of controller based on objective function. It is expressed as follows:

$$J = \sqrt{\sum_{i=0}^{T} \frac{(\omega(t)_{\mathrm{ref}_i} - \omega(t)_{\mathrm{act}_i})^2}{T}}, \tag{14}$$

where $\omega(t)_{\mathrm{ref}i}$ is the reference speed in rpm $\omega(t)_{\mathrm{act}i}$ actual speed in rpm at each sample, time (T) is the total simulation time for the optimization. The range of tuning parameter of the FOPID controller, i.e., K_p, K_i, K_d, λ and μ, is same as used in Table 1 for MGA, ABC and BA.

An objective function (J) is used to obtain the tuning parameters of the FOPID controller under various operating conditions of the BLDC motor drive. The best controller is represented as an overall speed control system that minimizes the objective function (J). It is expressed in Eq. (14). The objective function used for BA-based FOPID controller tuning to ensure good transient and steady state characteristics is under changing motor reference speed.

3.2. *Modified genetic algorithm (MGA)*

The MGA is an efficient optimization technique for the speed control of sensorless BLDC motor using FOPID controller.[17,18] The MGA is a local search optimization technique that manipulates the MATLAB coding representation of an FOPID controller parameter set to local search of near optimal parameter values through cooperation and competition among the potential solutions. The MGA determines the optimal tuning of the five degrees of freedom parameters K_p, K_i, K_d and fractional-order λ, μ of the FOPID controller. As indicated by control objectives, the five parameters of an FOPID controller are required to be outlined in these settings.

$$\text{Fitness function } F_g = J_{\max} + J_{\min} - J_g\,, \tag{15}$$

where $J_{\max}$ and $J_{\min}$ are the largest and the smallest values of J, respectively, observed and J_g is the value of the criterion for the current population.

Table 1. Typical ranges of the optimized parameters.

Tuning parameter/Range	K_p	K_i	K_d	λ	μ
Minimum	1	1	1	0.1	0.1
Maximum	100	600	700	0.9	0.9

The pseudo-code to initialize the genetic algorithm in FOPID controller is given below:

Step 1. Initialize iteration values [Chrom = abs(10*(rand(sol,len)-.5));].
Step 2. Calculation of the fitness for the population pool – [[Fit(i,1)] = fitness_calc(G);].
Step 3. Selection operation — short ascending order, save best fitness, best half solution based on fitness [Best_Weight = Chrom(ind(1):);] Fitness calculation values K_p, K_i, K_d and $\lambda = 0.9969$; $\mu = 0.9884$; compute the steady state error and overshoot [F = sum (beta+sys_overshoot*alpha*rand);].
Step 4. Crossover operation — Calculate how many gens used for crossover, [cross_crom = Crossover (New Chrom, Crossover_points);].
Step 5. Mutation — Calculate how many gens used for mutate, Combine best half solution & Mutation output [mut_crom = Mutation (cross_crom, Mutation_points);].

The step response analysis of sensorless BLDC motor drives using FOPID controller is based on genetic algorithm with the help of MATLAB toolbox. The important time domain transient and steady state characteristics of FOPID–MGA controller for these speed control scheme at no load condition values are thus: rise time: 0.351 s, settling time: 0.840 s, settling min: 1,446 rpm, settling max: 1,486 rpm, overshoot: 0%, undershoot: 0%, peak: 1,486 rpm, peak time: 0.641 s and steady state error is 14 rpm. Table 2 shows the MGA parameters for speed control of sensorless BLDC motor.

3.3. *Artificial bee colony (ABC)*

The ABC is modeled on the behavior of original bees for an optimal solution to solve multiple problems.[19] The ABC has three kinds of group of bees presented, that is, employed bees, onlooker bees and scout bees for attaining their objectives.[20] The ABC optimization algorithm is to generate the optimal tuning parameter values for FOPID controller in sensorless BLDC motor speed control application.[21]

The pseudo-code to initialize the ABC in FOPID controller is given below:

Step 1. Initialize the artificial bee food source positions — Population size 10, Length of bee 3, No of iteration 10 — initialize the error detector values, estimated speed and reference speed [bee = abs(10*(rand(pop_size, L)-.5))].

Table 2. Parameters of MGA.

S. No.	Genetic algorithm parameter	Values
1	Lower bound [λ, μ]	[0.1, 0.1]
2	Upper bound [λ, μ]	[0.9, 0.9]
3	Population size	100
4	Crossover function	0.01
5	Mutation function	0.03
6	No of iteration	10

Step 2. All employed bee finding another sustenance source in her nourishment source site with achievement of the improved food source — fitness call function — Measured voltage and current of BLDC motor [Em = [bee(ind(1),:) Fit(ind(1))].

Step 3. Each onlooker bee picks the nourishment source in view of the high caliber of her sustenance source optimal solution, generates a new food source in the chosen food source site with achievement of the improved food source — Tuning the optimal values [$Qi = 0.5$ (Onlooker = [bee(ind(1),:) Fit(ind(1))])].

Step 4. Observing the sustenance source to be deserted and assign the employed bee as scout bee for finding fresh sustenance sources — determine the optimal values K_p, K_i, K_d and λ, μ [best_out = abs(10*(rand(2, length(pi_ann_in))-.5))].

Step 5. Remember the excellent food source established so far — Best optimal values K_d, K_p, K_i and λ, μ [best_weight = best(1:end-1))].

Step 6. Repeat steps 2–5 until the ending criterion.

The FOPID controller optimal parameters are K_p, K_i, K_d and λ, μ and represent a number of food sources. They generated a fresh food source as per the equation $v_{ij} = x_{ij} + \varphi_{ij}(x_{ij} + x_k)$, where φ_{ij} is an evenly circulated real random number within the range of speed in rpm [1,000, 1,500], k is the optimal solution select from the ABC $k =$ int (rand $*$ optimal five degree of freedom parameter $+ 1$) and D is the dimension of optimal problems in FOPID controller five degree parameters K_p, K_i, K_d and λ, μ where $D = 5$. Later, it generates v_i fresh optimal solution which is contrasted with x_i optimal solution.

This method is used for controlling speed of sensorless BLDC motor with FOPID controller based on ABC optimization algorithm. The important time domain transient and steady state characteristic of FOPID–ABC controller for these speed control schemes at no load condition values are rise time: 0.270 s, settling time: 0.631 s, settling min: 1,460 rpm, settling max: 1,490 rpm, overshoot: 0%, undershoot: 0%, peak: 1,490 rpm, peak time: 0.420 s and steady state error 10 rpm. The ABC-based FOPID controller is deprived steady state error under different load condition. For better improvements, the proposed BA is based on FOPID controller for minimizing settling time and steady state error.

4. Proposed BA-Based FOPID Controller

The proposed FOPID controller based on the bat-inspired algorithm is a metaheuristic optimization algorithm which was developed by Yang in 2010.[22] This BA is based on the echolocation behavior of microbats with changing emission pulse rates and loudness pulse rate. It is an efficient optimized algorithm which has three major features for better performance. They are frequency tuning, automatic zooming and parameter control.[23] The parameter control brings about several metaheuristic optimization algorithms with constant parameters using pre-tuned algorithm, i.e., dependent parameter. The five degree of freedom optimal parameter values are K_p, K_i, K_d, λ and μ, which are generated by using BA that uses fine tuning of FOPID controller for sensorless BLDC motor speed control application.[24]

4.1. *Tuning of optimal parameters of FOPID controller using BA*

Several metaheuristic algorithms used fixed FOPID controller parameters such as K_p, K_i, K_d, λ and μ. In the iteration proceed method, a value is generated with BA which gives a variation in result while comparing with the MGA and ABC optimization techniques. This proposed BA is a global search optimized algorithm.

The pseudo-code to initialize the BA in FOPID controller is as follows:

Objective function $(J) = f(n) = (n1)$
Assigned bat population Ni and Vi for $i = 1 \ldots n$ ($n = 5$ population size)
Describe the pulse frequency Fi ($F_{\min} = 1$; $F_{\max} = 2$)
Assigned pulse rate Ri and loudness Li ($R = 1$; and $L = 1$)
While ($t <$ Max. Num. of iteration) — total number of function evaluations
produce fresh optimal solutions by varying frequency and renew velocities Vi & locations.
Frequency F = zeros $(n, 1)$; and Velocities Vi = zeros (n, d);
  if(rand $> ri$) − if inp $< 1{,}000$
choose better solution Sol $= 1 + (90 - 1)$*rand$(d, n)'$;
  end if
produce a best solution by floating at random- $S(i, :) =$ best $+ 0.001$*rand $n(1, d)$;
  if (rand $< Ai$ & $f(xi) < f(xo)$) − (Fnew $<=$ Fitness(i)) & (rand $< A$),
Satisfied fresh solutions
Increase Ri and reduce Li
  end if
Rank the bats with determine the current best $Xo -$ best $= Si$ and $F_{\min} = F_{\text{fresh}}$
end while
post process results and apparition

The steps for BA-based FOPID controller are given below:

Step 1. Assigned objective function J for BA optimization with $S = (S1$ to $St)$, where t is the number of optimal tuning value and $d = 5$, $S1 = K_p$, $S2 = K_i$, $S3 = K_d$, S4 $= \mu$, S5 $= \lambda$.

Step 2. Assigned to population Ni and early velocity Vi for $(i = 1, 2, 3, 4, \ldots, n)$, where N is the number of populations.

Step 3. Decide pulse rate frequency Fi at Si. Assigned pulse rates Pi, Max. no of iterations with loudness factor Li.

Step 4. The fresh bat population is produced by varying the position xi and the velocity Vi for each optimal solution in the population (Determine the optimal values K_p, K_i, K_d, and λ, μ.):

$$f_i = f_{\min} + (f_{\max} - f_{\min})\gamma\,, \tag{16}$$

$$L_i^t = L_i^{t-1} + (S_i^{t-1} - S_b)f_i\,, \tag{17}$$

$$S_i^t = S_i^{t-1} + L_i^t\,, \tag{18}$$

where γ is a random vector drawn from a uniform distribution and frequency range $f_{\min} = 1\,\text{KHz}$, $f_{\max} = 90\,\text{KHz}$. S_b is a good value for every process.

Step 5. The new population is assessed by ascertaining the J values for every solution and better optimal solution x chosen from the population.

Step 6. The applied searching techniques, i.e., iteration methods for finding the optimal solution at every process (Finding best optimal values K_p, K_i, K_d and λ, μ):

$$G\text{best} = [g\text{best}_1, g\text{best}_2, \ldots, g\text{best}_n]\,.$$

Step 7. The new optimal solution is created in any respect and acknowledged with some proximity contingent upon parameter Ai, the pulse emission rate increments and diminishing loudness and estimation values of Ai and ri are improved (optimal values are updated K_p, K_i, K_d and λ, μ).

Step 8. The new population is assessed and the best optimal solution is preferred.

This method is used for speed control of sensorless BLDC motor with BA–FOPID controller. Table 3 shows the BA parameter of FOPID controller. The important time domain transient and steady state characteristics of FOPID–BA controller for these speed control schemes under no load condition values are rise time: 0.021 s, settling time: 0.082 s, settling min: 1,470, settling max: 1,496 rpm, overshoot: 0%, peak: 1,496 rpm, peak time: 0.042 s and steady state error 4 rpm.

Table 3. Parameter of BA with FOPID controller.

S. No.	BA parameter	Values
1	Population size (Xi)	10
2	No of dimension	3
3	Number of iteration	10
4	Loudness (A)	90
5	Pulse emission rate (R)	[1, 10]
6	Changing Frequency $Q_{\min}$ & $Q_{\max}$	1–90 KHz
8	Echolocation	8–10 ms

5. Results and Discussion

This segment demonstrates the unit step response of speed control of sensorless BLDC motor using FOPID controller based on MGA, ABC and proposed BA. The simulation output is performed on the speed control scheme in different optimization techniques for analyzing time domain step response characteristics by Matrix Laboratory. Figure 4 shows the stator current and Fig. 5 shows the back EMF of sensorless BLDC motor by various optimization techniques.

In order to measure the unit step response of the FOPID controller under various operating conditions, a comparative study has been made using MGA, ABC and BA

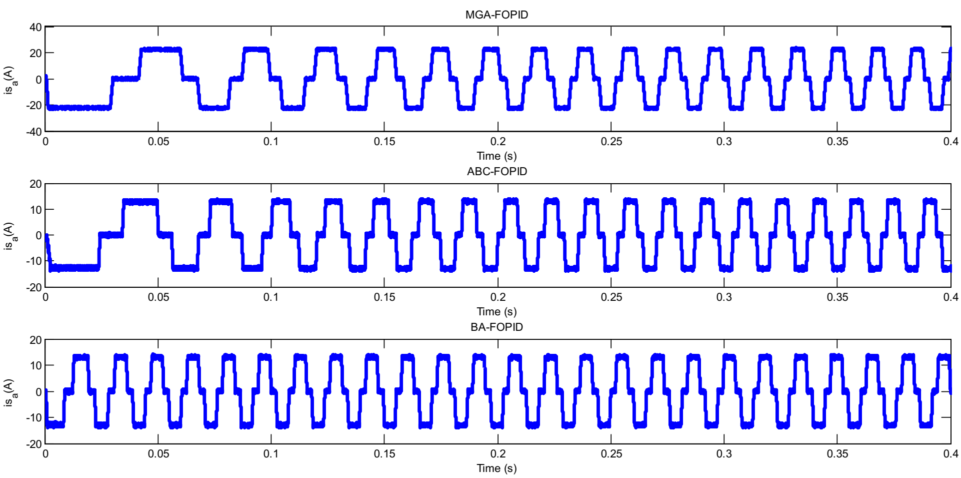

Fig. 4. Stator current of sensorless BLDC motor with FOPID controller using MGA, ABC and BA.

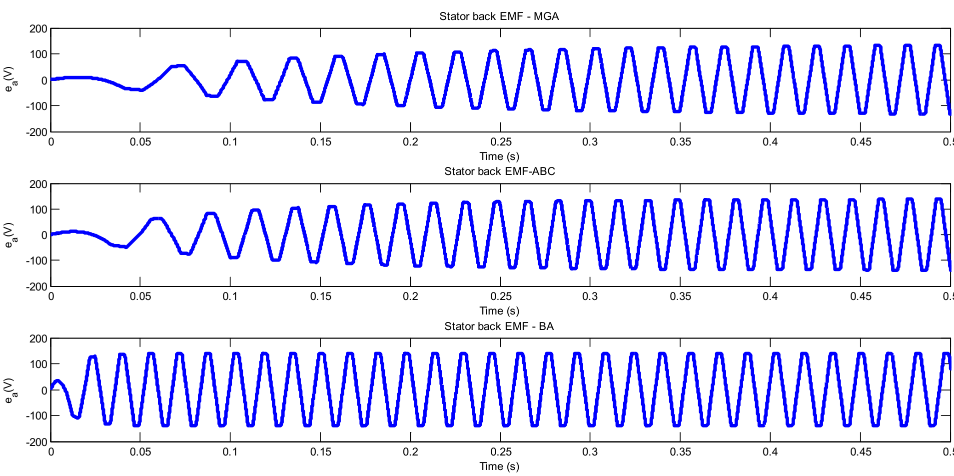

Fig. 5. Stator back EMF of sensorless BLDC motor with FOPID controller using MGA, ABC and BA.

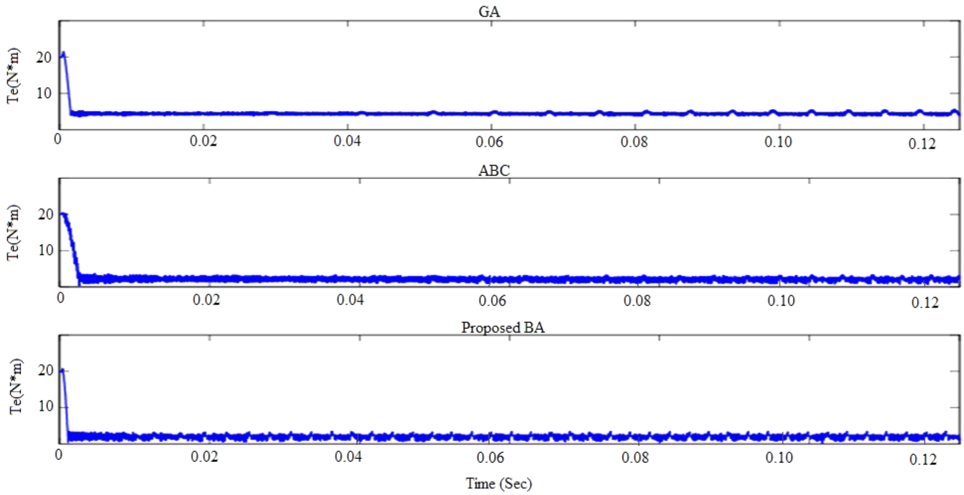

Fig. 6. Effect of torque variation using MGA, ABC and proposed BA.

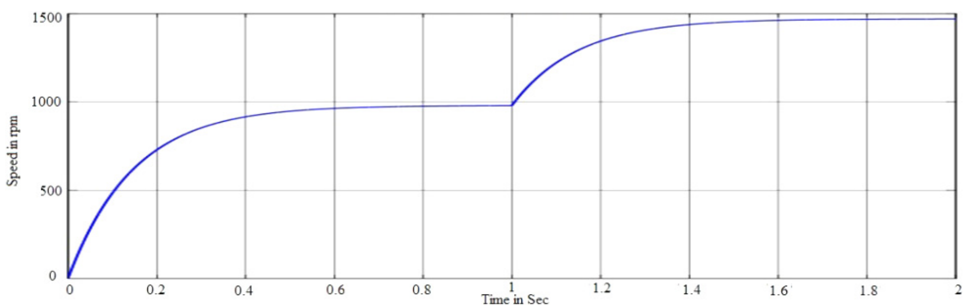

Fig. 7. Evolution of rotor speed of sensorless BLDC motor with FOPID controller using BA.

for regulating the speed of the BLDC motor. Figure 6 shows the effect of torque variation using Metaheuristic optimization and Fig. 7 shows the performance of rotor speed of sensorless BLDC motor with FOPID controller using BA.

An FOPID controller comparative study has been made to analyze unit step response characteristics using BA over conventional ABC and MGA for speed regulation of the motor. At first, the machine keeps running at a speed of 1,000 rpm under 1.18 Nm under load condition. The reference speed is changed from 1,000 to 1,500 rpm for step response. Suddenly, the machine speed will reach 1,500 rpm and unit step time domain performance parameters such a peak overshoot, peak time, settling time and steady state error are measured. Figure 8 shows the performance of stator back EMF and Fig. 9 shows the performance of electromagnetic torque of BA–FOPID controller.

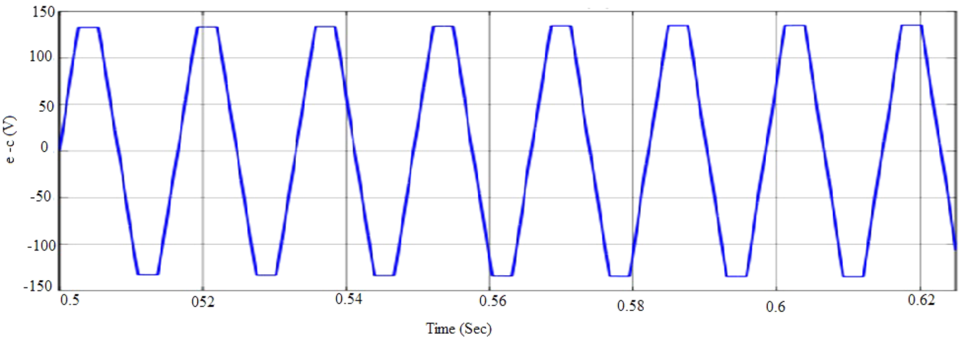

Fig. 8. Evolution of stator back EMF of sensorless BLDC motor using Proposed BA.

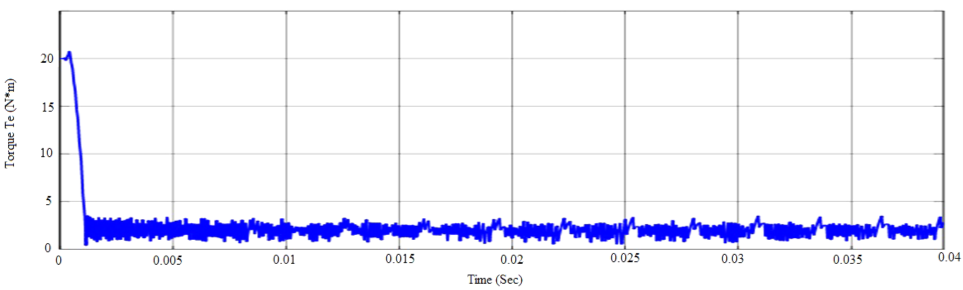

Fig. 9. Evolution of electromagnetic torque with FOPID controller using BA.

Under 50% load condition, the unit step reaction utilizing FOPID–MGA controller gives an overshoot of 0%, peak time 0.392 s, settling time: 0.635 s, steady state error: 15 rpm and unit step response by using FOPID–ABC gives an overshoot: 0%, peak time: 0.325 s, settling time: 0.466 s and steady state error: 11 rpm. Both the conventional optimization techniques are undesirable. To minimize these time domain characteristics parameters, the proposed FOPID–BA controller gives an overshoot: 0%, Peak time: 0.029 s, settling time: 0.065 s and steady state error: 6 rpm which can give the better optimal solution. Table 4 shows the optimal parameter values of FOPID controller obtained using MGA, ABC and BA. The Unit Step response and control execution parameters for FOPID–BA compared to FOPID–MGA,

Table 4. Optimal parameter values of FOPID controller obtained using MGA, ABC and BA.

Parameters/algorithm	Proportional gain (K_p)	Integral gain (K_i)	Derivative gain (K_d)	Integral order (λ)	Derivative order (μ)
MGA	10	7	5	0.94	0.46
ABC	10	9	4	0.96	0.36
BA	6	5	3	0.95	0.13

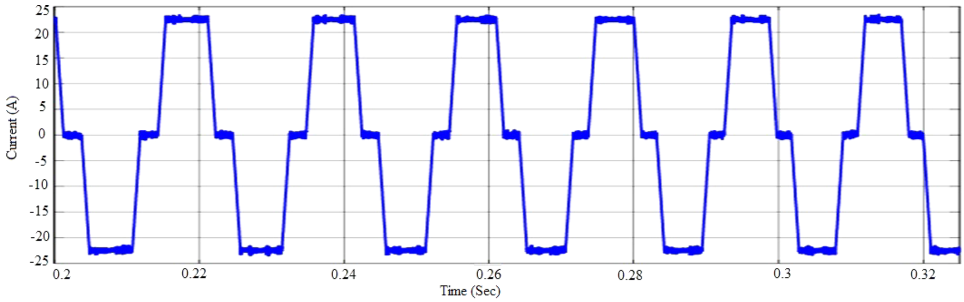

Fig. 10. Evolution of stator current of sensorless BLDC motor.

FOPID–ABC. The derivative order μ and integral order λ are infraction, i.e., divisions can be under 1. Figure 10 shows the performance of stator current of sensorless BLDC motor.

The steady state error analysis of step response characteristics for speed control of sensorless BLDC motor is used. The error detector reference speed is 1,500 rpm, the proposed FOPID-BA desired rotor speed 1,496 rpm, FOPID-ABC technique desired rotor speed is 1,490 rpm and for the FOPID–MGA, the desired rotor speed is 1,486 rpm. The problem under discussion could be solved using the proposed BA which gives a significant amount of improvement of steady state error in the step response characteristics. Figure 11 shows the step responses of speed control of sensorless BLDC motor under load condition.

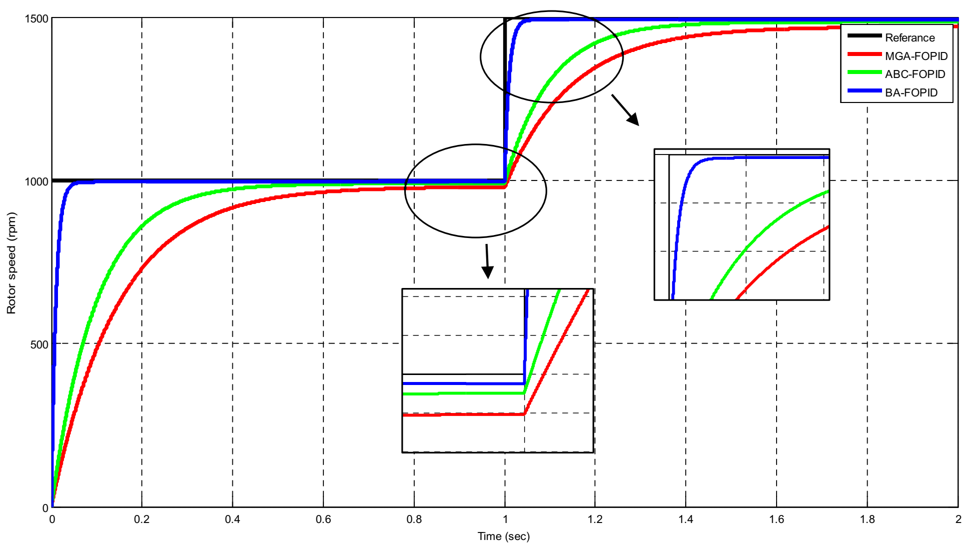

Fig. 11. Unit step response of the sensorless BLDC motor with FOPID controller under load condition.

Table 5. Comparison of time domain response of FOPID controller using MGA, ABC and BA under no load condition.

Techniques \ Time response	Settling time (s)	Rise time (s)	Peak time (s)	Steady state error E_{ss} (%)	Steady state error (rpm)	Settling values (rpm) Min.	Settling values (rpm) Max.	Peak values (rpm)
MGA	0.840	0.351	0.641	0.94	14	1,446	1,486	1,486
ABC	0.631	0.270	0.420	0.67	10	1,460	1,490	1,490
BA	0.082	0.021	0.042	0.26	4	1,470	1,496	1,496

Table 5 shows the comparison of time domain response of FOPID controller using MGA, ABC and BA at no load condition. Under no load operating condition, BA based FOPID controller has minimized settling time and steady state error. The outcomes attain from the matrix laboratory simulation obviously demonstrate the exceptional enhancements on time domain characteristic performance measures and demonstrated that the sudden load disturbance or set point variation is substantially more successful with the utilization of the proposed BA-based FOPID controller. Figure 12 shows the step response of the sensorless BLDC motor with FOPID controller under no load condition.

Table 6 shows the comparison of time domain response of FOPID controller using modified GA, ABC and BA at 50% load condition. Under 50% load condition,

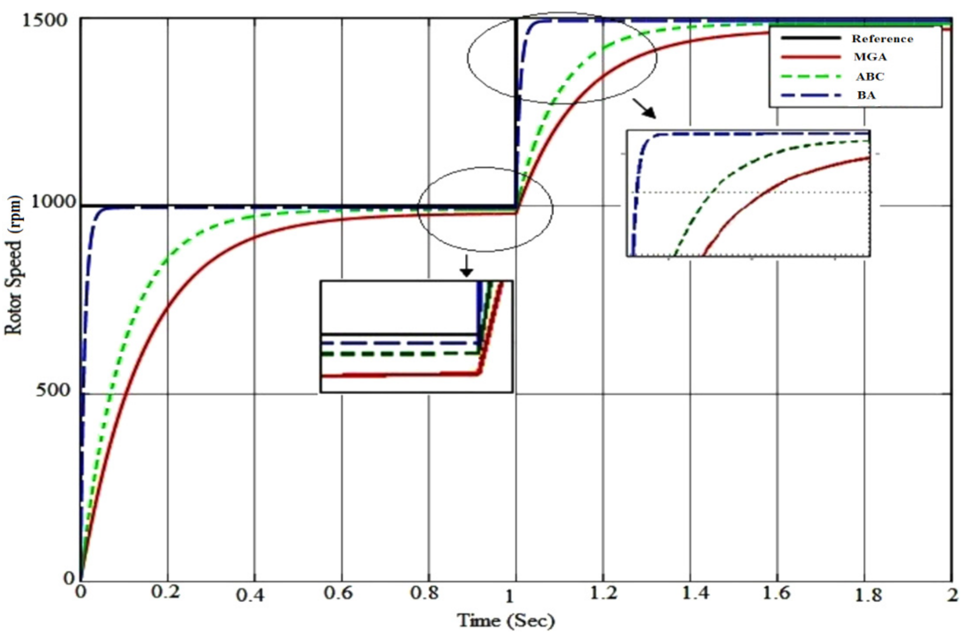

Fig. 12. Unit step response of the sensorless BLDC motor with FOPID controller under no load condition.

Table 6. Comparison of time domain response of FOPID controller using MGA, ABC and BA under 50 % load condition.

Techniques \ Time response	Settling time (s)	Rise time (s)	Peak time (s)	Steady state error E_{ss} (%)	Steady state error (rpm)	Settling values (rpm) Min.	Settling values (rpm) Max.	Peak values (rpm)
MGA	0.635	0.251	0.392	1.01	15	1,442	1,485	1,485
ABC	0.466	0.201	0.325	0.73	11	1,454	1,489	1,489
BA	0.065	0.015	0.029	0.40	6	1,462	1,494	1,494

Table 7. Comparison of time domain response of FOPID controller using MGA, ABC and BA under 100 % load condition.

Techniques \ Time response	Settling time (s)	Rise time (s)	Peak time (s)	Steady state error E_{ss} (%)	Steady state error (rpm)	Settling values (rpm) Min.	Settling values (rpm) Max.	Peak values (rpm)
MGA	0.602	0.367	0.463	1.01	15	1,423	1,485	1,485
ABC	0.468	0.335	0.401	0.81	12	1,436	1,488	1,488
BA	0.032	0.010	0.018	0.60	9	1,443	1,491	1,491

BA-based FOPID controller gives as overshoot 0 s, settling time 0.065 s, peak time 0.029 s and steady state error 6 rpm. Table 7 shows the comparison of time domain response of FOPID controller using modified GA, ABC and BA at 100% load condition. Under 100% load condition, BA-based FOPID controller gives as overshoot 0 s, settling time 0.032 s, peak time 0.018 s and steady state error 9 rpm, To approve the operation of the proposed controller under no load, 50% load, 100% load conditions, the test acknowledgment for the sensorless speed control of brushless DC motor has been tested. From the after effects of the matrix laboratory–Simulink simulation, it is made clear that the proposed BA-based FOPID controller is able to minimize the steady state error and improve transient characteristics occurring due to load variations and set speed variations for speed control application.

6. Conclusion

An optimal tuning of FOPID controller using MGA, ABC and BA are presented. The FOPID controller based sensorless speed control of BLDC motor is simulated using Matlab/Simulink model to confirm the validity and enhanced performance of proposed controller under no load, 50% load and 100% load condition. The MATLAB simulation based on speed step response characteristics for the sensorless BLDC motor drives for no load, 50% load and 100% load condition are obtained by MGA, ABC and proposed BA robust scheme. It is inferred that under no load condition, the steady state error of the proposed BA method is about 60% lesser than the ABC method and 71% lesser than the MGA method. Also, the settling time for proposed method is about 7 times lesser than the ABC and 10 times lesser the MGA. Under 50% load condition, the steady state error of the proposed BA method is about 45% lesser than the ABC method and 60% lesser than the MGA method. Also, the settling time for proposed BA method is about 7 times lesser than ABC and 9 times lesser than the MGA. Under 100% load condition, the steady state error of the proposed BA method is about 25% lesser than the ABC method and 40% lesser than the MGA method. Also, the settling time for proposed BA method is about 14 times lesser than the ABC and 18 times lesser than the MGA. In addition, the performance of proposed BA-based FOPID controller was analyzed and compared with MGA and ABC based on FOPID controller. From the above results, it is concluded that the BA based FOPID controller has enhanced performance and good controllability than MGA and ABC based FOPID controllers in terms of minimization of steady state and transient time domain characteristics such as rise time, peak time, settling time and steady state error under various operating conditions.

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