Sensored speed control of brushless DC motor based salp swarm algorithm

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ABSTRACT

This article uses one of the newest and efficient meta-heuristic optimization algorithms inspired from nature called salp swarm algorithm (SSA). It imitates the exploring and foraging behavior of salps in oceans. SSA is proposed for parameters tuning of speed controller in brushless DC (BLDC) motor to achieve the best performance. The suggested work modeling and control scheme is done using MATLAB/Simulink and coding environments. In this work, a 6-step inverter is feeding a BLDC motor with a Hall sensor effect. The proposed technique is compared with other nature-inspired techniques such as cuckoo search optimizer (CSO), honey bee optimization (HBO), and flower pollination algorithm (FPA) under the same operating conditions. This comparison aims to show the superiority features of the proposed tuning technique versus other optimization strategies. The proposed tuning technique shows superior optimization features versus other bio-inspired tuning methods that are used in this work. It improves the controller performance of BLDC motor. It refining the speed response features which results in decreasing the rising time, steady-state error, peak overshoot, and settling time.

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1. INTRODUCTION

Nowadays, brushless DC motor (BLDC) motors play a vital role in various industrial, medical, military, aerospace, robotic, and automotive applications. BLDC motor characterized by, low maintenance, silent operation, more reliability, long operating life, fast dynamic response, high efficiency, preferable speed/torque characteristics, wide speed range and higher torque/weight percentage [1]–[7]. BLDC motor has three-phase stator windings and a permanent-magnet rotor. Its structure is similar to permanent magnet synchronous motor (PMSM) with a quasi-rectangular current waveform as well as a trapezoidal back electromotive force (BEMF) waveform [1], [2], [8], [9]. In this motor, an electronically current commutation arrangement is implemented due to the absence of brushes. Electronically commutation arrangement is used instead of mechanical commutation which is based on the rotor position feedback. The feedback information is supplied either based on sensor or sensorless technique [1], [3], [10]. The rotor position is a typical operation of BLDC with the help of hall sensors. This sensor is used to find the position of rotor. The rotor angular speed and position are detected using this sensor for motor speed controlling. It detects rotor transition from one sector to another sector instead of detecting accurately where the rotor is within a sector. So, Hall effect sensors provide the necessary information to specify when the motor correct phases are needed to be commutated with each sector crossing. A commutation logic circuit is used to detect the correct phases [2]. Nowadays, various types of nature-inspired optimization algorithms are used for controllers tuning. Each algorithm has its own advantages and disadvantages [11], [12]. So, it is necessary to search about the simplest, fastest, and efficiently covering the search-space algorithm.

Literature review: recently, researchers focus on controller tuning based on various meta-heuristic optimization algorithms [13]–[16]. The literature review below shows the researcher's interest in the utilization of the new nature-inspired techniques for traditional controller tuning for BLDC motor speed control schemes. Particle swarm optimization (PSO) was introduced by Portillo *et al*. [17]. PSO and bacterial foraging (BF) techniques were proposed by Ibrahim *et al.* [18]. Adaptive tabu search (ATS) and intensified current search (ICS) were introduced by Kumpanya *et al.* [19]. Bat algorithm (BA) was proposed by Premkumar and Manikandan in [20]. FireFly algorithm (FA) segmentation was proposed and compared with classical FireFly and particle swarm techniques by Jaber [21]. BA artificial bee colony (ABC) optimization method and modified genetic algorithm (MGA) were proposed by Vanchinathan and Valluvan [22]. Genetic algorithms-adaptive neuro-fuzzy inference system (GA-ANFIS) was introduced by Dasari *et al.* [23]. Flower pollination algorithm (FPA) was introduced by Potnuru *et al.* [24]. FireFly and genetic algorithms (GA) were introduced by Kommula and Kota in [2].

Problem: practically, BLDC motor drive design includes complex processes such as modeling, simulation, control scheme, and parameters tuning. Traditional controller tuning strategy is difficult, with poor robustness therefore, it cannot achieve the best controller performance with optimal accuracy under sudden disturbance and parameter variations. Proposed solution: in this work, salp swarm algorithm (SSA) is proposed to overcome the controller tuning issue. The proposed optimization technique is used for speed controller tuning to achieve optimal controller performance under various operating conditions. The results are compared with other metaheuristic tuning algorithms like cuckoo search optimizer (CSO), honey bee optimization (HBO), and flower pollination algorithm (FPA).

2. BLDC MOTOR MODELLING

In the modern control theory, the state-space equations represent a common analysis and designing control systems [25]. The mathematical model of the three-phase BLDC motor is illustrated below. The stator winding voltages are expressed as [2], [26],

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \tag{1}$$

where, v_{as}, v_{bs}, v_{cs} and i_{as}, i_{bs}, i_{cs} represent the voltages and currents of the three-phase stator windings respectively, v_{as}, v_{bs}, v_{cs} represent the back e.m.f due to the stator windings current, R_s and L represent the stator winding resistances and inductances. The stator windings self-inductances are equal as well as the mutual inductances are equal also due to the symmetry in the three-phase stator windings. This fact is illustrated in (2) and (3). BLDC motor voltage are expressed in (6).

$$L_{aa} = L_{bb} = L_{cc} = L_s \tag{2}$$

$$L_{ab} = L_{ac} = L_{ba} = L_{bc} = L_{ca} = L_{cb} = M \tag{3}$$

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \tag{4}$$

As the algebraic sum of the stator currents equal zero, so (4) can be reduced as [26],

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{\infty} \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \tag{5}$$

$$\begin{aligned} v_{as} &= R_s i_{as} + (L_s - M)\frac{di_{as}}{dt} + e_{as} \\ v_{bs} &= R_s i_{bs} + (L_s - M)\frac{di_{bs}}{dt} + e_{bs} \\ v_{cs} &= R_s i_{cs} + (L_s - M)\frac{di_{cs}}{dt} + e_{cs} \end{aligned} \tag{6}$$

The output torque (T_e) of three-phase BLDC motor is found from its output power (P_e) and the mechanical angular speed ω_m,

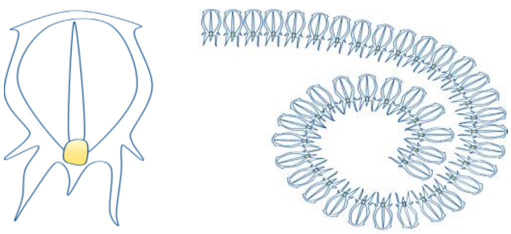
$$T_e = \frac{P_e}{\omega_m} = \frac{e_{as}i_{as}+e_{bs}i_{bs}+e_{cs}i_{cs}}{\omega_m} \text{ where } P_e = e_{as}i_{as} + e_{bs}i_{bs} + e_{cs}i_{cs} \quad (7)$$

The motor torque equation with inertia (*J*), load-torque (T_l) and friction constant (*B)* is [2].

$$T_e - T_l = J\frac{d\omega}{dt} + B\omega \quad (8)$$

3. OVERVIEW OF SALP SWARM ALGORITHM (SSA)

Salps are classified as a part of the Salpidae class. It has a diaphanous drum body [27], [28]. Its tissues are extremely comparable to a jelly fishes' tissues. Salps move forward by pumping the water through their body with a mechanism similar to propulsion. Figure 1(a) shows the shape of a salp. SSA is a novel metaheuristic algorithm proposed by Mirjalili *et al.* [27]. SSA is a new kind of nature-inspired metaheuristic algorithm. SSA imitates the salps behavior in sea [29]. It is mostly live together in groups. It is forming a salp-chain as shown in Figure 1(b). The first salp is called the leader while followers represent the followers [27]–[29]. The salp group are guided by the leader making the followers salps follow each other (and leader directly or indirectly) [28].



(a) (b)

Figure 1. Salps shape and group (a) salps body and (b) salps chain

Like other SI strategies, salps location in the n-dimensional search space. Where (n) represents the problem's variable numbers. So, all salps positions are kept in a 2-dimensional x-matrix. The food-source (F) in the search-space represents the target of swarm's [27]. The equation (9) is used to update the leader salp position,

$$x_j^1 = \begin{cases} F_j + c_1((ub_j - lb_j)c_2 + lb_j) & c_3 \geq 0 \\ F_j - c_1((ub_j - lb_j)c_2 + lb_j) & c_3 < 0 \end{cases} \quad (9)$$

where: x_j^1 is the leader salp position in the jth dimension, F_j represent food source position in the jth dimension, ub_j and $lb_j$are the upper and lower bounds of jth dimension respectively, while c_1, c_2, and $c_3$represent random numbers. From (9) it is clear that the leader position is only updated concerning the source of food. In SSA, the most important coefficient is c_1 due to its effect in balancing the exploration phase and exploitation phase:

$$c_1 = 2e^{-\left(\frac{4l}{L}\right)^2} \quad (10)$$

l is current iteration and L represent max. iteration number. The coefficients c_2 and c_3 are random uniformly generated numbers in the interval [0,1]. These coefficients indicate the step-size and specify the next position in jth-dimension. It should be towards positive infinity or negative infinity. As shown in (11) is used to update the follower's salps location. The position of ith follower salp in jth dimension is indicated by $i \geq 2$ and x_j^i [27]–[29].

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \quad (11)$$

4. DESIGNING OF BLDC MOTOR CONTROL SCHEME

BLDC motor driving principle is based on the phase-windings changing which is excited based on the position of rotor permanent magnet. The rotor position is sensing with a Hall-effect sensor. The closed-loop control system of BLDC motor is shown in Figure 2. It consists of inner and outer loops. The inner loop is responsible for extracting the back EMF (BEMF) information from the Hall-Decoder. BLDC motor is fed from the inverter which is based on Hall-sensor signals. These signals are characterized by three binary digits (HA, HB, HC) that changed every 60º (electrical degrees) synchronized with the rotor position changing as shown in Table 1. The letters A, B, and C represent the motor phases. The current commutation is based on the 6-steps inverter with either MOSFETs or IGBTs switches. The outer loop sensing the motor speed and compared it with the desired reference speed to produce the error speed which is processed by a speed controller.

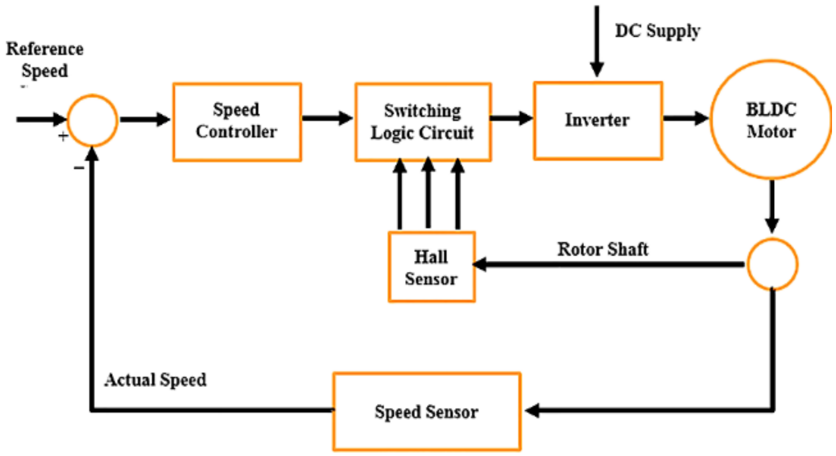


Figure 2. BLDC motor speed control system

For controlling the rotor, it is necessary to sense the rotor speed and angular position using a Hall-effect sensor. to control it. This sensor detects only the rotor transition between sectors. So, the rotor precisely information where the rotor is within a sector still missing. So, a commutation logic circuit is used to specify the correct phases to be commutated with each sector crossing. It provides the three-phase inverter switching pattern as mentioned in Table 1.

Table 1. Inverter switching pattern

H_A	H_B	H_C	EMF_A	EMF_B	EMF_C	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	-1	+1	0	0	0	1	1	0
0	1	0	-1	+1	0	0	1	1	0	0	0
0	1	1	-1	0	+1	0	1	0	0	1	0
1	0	0	+1	0	-1	1	0	0	0	0	1
1	0	1	+1	-1	0	1	0	0	1	0	0
1	1	0	0	+1	-1	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0	0	0	0

5. SIMULATION AND RESULTS DISCUSSION

The simulation work is carried out based on MATLAB/SIMULINK and the coding environment. The complete model of the motor and its complete control scheme is modeled using MATLAB/Simulink toolbox. The proposed optimization techniques are done using MATLAB/coding. The BLDC motor parameters used in this work are illustrated in Table 2.

The simulation of the BLDC motor control scheme is illustrated in Figure 3. BLDC motor is fed from a 6-steps inverter. This inverter is supplied from (500 V) constant DC source for obtaining three-phase currents that energized the motor coil pairs in turn. Hall-Decoder sensed the motor angular speed and position and convert it to BEMF. BEMF is converted to inverter triggering signals using a commutating logic circuit. The speed controller sensed the actual motor speed and comparing it with the desired speed to generate an error speed signal. This error signal is fed to the inverter which in turn controls the motor. Hall decoder and commutation logic circuit blocks are illustrated in Figures 4 and 5 respectively.

Table 2. BLDC motor parameters

Parameters	Values
Motor power rating (P)	1 kW
Motor speed (N)	3,000 RPM
No. of phases	3
Equivalent resistance (Rs)	2.875 Ω
Equivalent inductance (Ls)	8.5 mH
Inertia coefficient (J)	0.0008 kg.m^2
Friction constant (B)	0.001 N.m.s

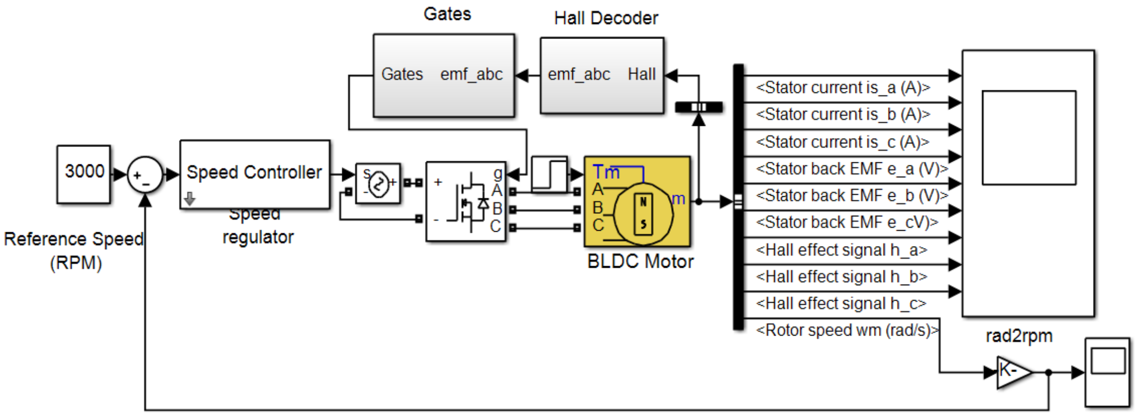
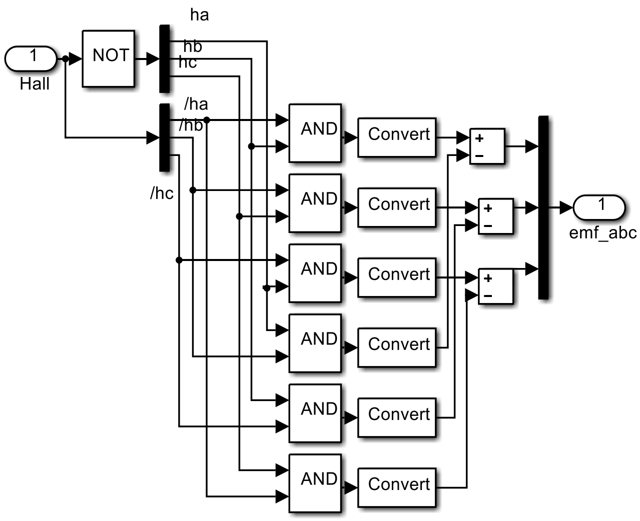


Figure 3. Simulation of BLDC motor speed control system



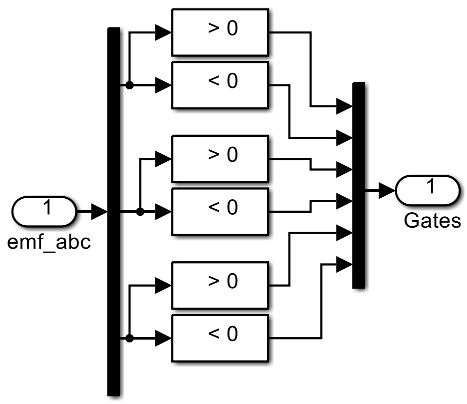


Figure 4. Hall-decoder circuit Figure 5. Commutation-logic circuit

In this work, SSA is proposed to tune the controller parameters for BLDC motor speed control purposes. The proposed tuning technique is compared with other nature-inspired algorithms like CSO, HBO, and FPA. This comparison is necessary to verify the dominance of the proposed technique. All optimization algorithms used in this work are done under the same conditions. The search-agents No. and Iteration No. are 50 and 100 respectively for all algorithms. BLDC motor stator currents, BEMF, and torque are shown in Figures 6 to Figure 8 respectively, while the hall-sensor signals are illustrated in Figure 9.

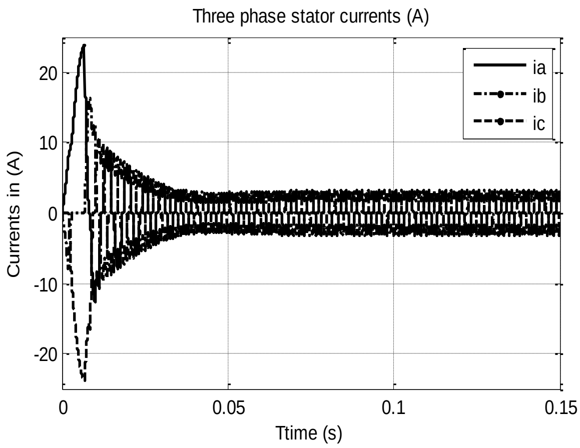


Figure 6. Motor stator currents

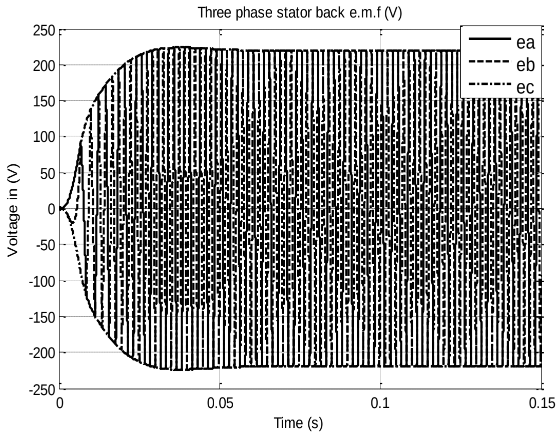


Figure 7. Motor BEMF

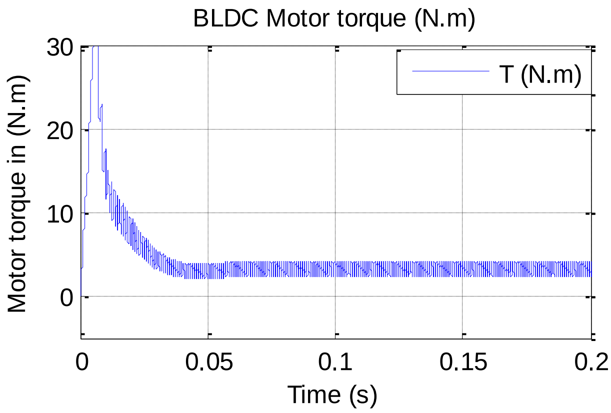


Figure 8. Motor torque

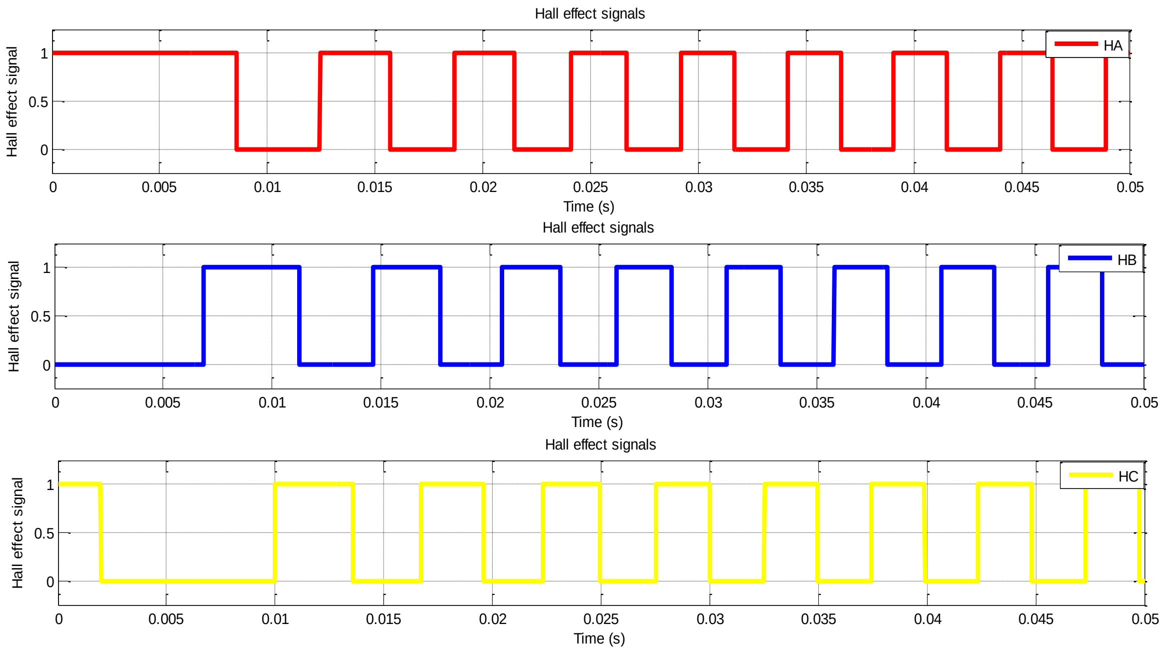


Figure 9. Hall-sensor signals

Figure 10 shows the comparison in motor speed responses based on different optimizing techniques. The motor reference speed is 3,000 rpm. It is clear that the motor performance-based SSA as a controller tuning method shows a superior improvement in transients and steady-state response. The motor response-based SSA shows good rising-time, settling-time, zero steady-state error, and no overshoot as compared with responses obtained based on other optimization algorithms. Figure 11 shows the convergence curves for all used techniques. SSA shows a fast convergence ability. It converges sharply at the 8 iterations while other techniques converge after a larger number of iterations. This fast convergence ability is due to the nature of algorithms structure which makes it have the feature of good search space exploring. It has a good balance between exploring and exploiting search phases.

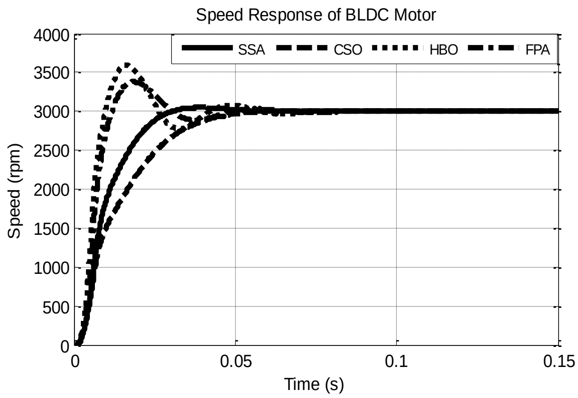


Figure 10. Motor actual speed

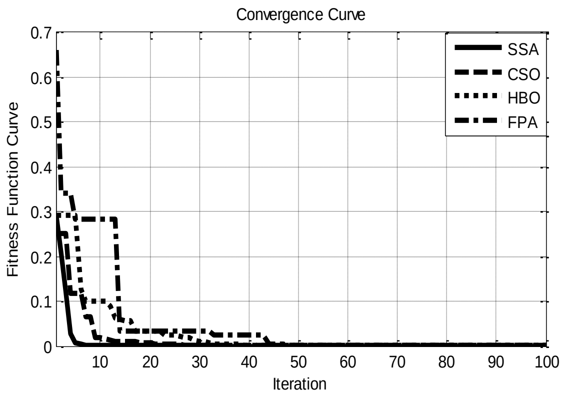


Figure 11. Convergence curve

6. CONCLUSION

Various types of nature-inspired optimization strategies are discovered recently because this field has become the scientists' focus of attention. A variety of optimization methods made us look for the best technique that is characterized by simple structure, fast convergence, lower run time, avoiding entrapping in local-optima, but the utmost significant feature is the ability of proper balance between exploration and exploitation phases. In this work, one of the newest and more efficient nature-inspired optimization techniques is proposed for BLDC motor speed controller tuning. The proposed tuning strategy is called SSA. The controller tuning process is very necessary to achieve the best motor performance for speed control purposes. A 6-step inverter is feeding the BLDC motor. The inverter switching pattern is obtained from commutation logic circuits and with the aid of a Hall sensor. The proposed optimizing technique is compared with other nature-inspired algorithms such CSO, HBO, and FPA. The proposed tuning method shows good features like good exploring and efficient ability, simple structure, fast convergence ability. BLDC motor transients and steady-state speed response is improved prominently when the controller is based on the SSA tuning technique. So, the proposed tuning technique is more suitable for various optimization fields.

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