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Salp swarm algorithm based optimal speed control for electric vehicles

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ABSTRACT

The paper is all about the implementation of a novel bio-inspired meta-heuristic salp swarm algorithm (SSA) for speed control of brushless DC (BLDC) motor drive that is run in sensorless control mode. The angular speed of the motor is evaluated using an extended kalman filter, in which the dynamics of the motor are nonlinear. The error in speeds between actual and estimated is fed to the PID controller. To achieve the good transient operation of the motor drive, the parameters of the PID are tuned with the SSA. The optimum PID gains are determined by the minimization of integral square error and then final optimum gains are validated on the laboratory testbed. The proposed method is also tested in various cases to check the performance of the drive. The experiments are also performed at low speeds to know the superiority of the proposed method.

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1. INTRODUCTION

Electric vehicles are popular means of transportation in the present day. Because of reasons like high efficiency, zero carbon emissions, maintenance-free, fast torque production, cost-effectiveness; the market growth of electric vehicles has surged in recent years. The major components in an electric vehicle are the electric motor, battery, power electronic converter, speed controller and transmission unit. More recently electric vehicle sales across the world are increasing. In India, government is also promoting electric vehicles by giving incentives for manufacturers as well as the customers' who are buying the EVs.

The brushless DC (BLDC) motor is emerging in different fields such as electric vehicles, industrial and commercial applications due to their excellent characteristics viz, good control flexibility, noise-free operation, wide speed range and good speed regulation [1]. There are two types in the category of BLDC motors. One is a permanent magnet synchronous motor (PMSM) (motor with distributed stator winding and the other motor is BLDC with concentrated stator winding [2]. The BLDC motor is more popular because of its low cost and better control flexibility as compared to its counterpart. The motor runs in self-control mode which means that the stator winding will be given a power supply from the rotor angular position information. Therefore, we could run the motor more than the synchronous speed. In closed-loop speed control of this drive, rotor position and speed sensors are essential [3]. Figure 1 shows an electric vehicle employing a BLDC motor. The speed of the vehicle is regulated by controlling the BLDC motor [4]. The position of the rotor is sensed using the hall sensor and is fed back to the controller which controls a three-phase IGBT inverter. To improve the drive performance and avoid the cost of the hall sensors, sensorless speed control is proposed in the literature [5]-[8]. The speed can be estimated using observers like extended Kalman filter (EKF), cubature Kalman filter. More recently many researchers worked on sensorless speed regulation of BLDC motor [9]–[12], and some of them used BLDC motor drive control in real-time applications [13], [14].

The PID based speed controller is extensively used in industrial applications whereas in Ziegler-Nichols method is used for tuning suitable PID gains. Many researchers proposed the metaheuristic optimization approaches for getting PID gains offline and obtaining better performance in real-time using these fixed gains at various operating conditions of the motor drives [15]–[17]. Further, the speed regulation of the BLDC motor drive using optimization methods is also proposed recently [18]–[21].

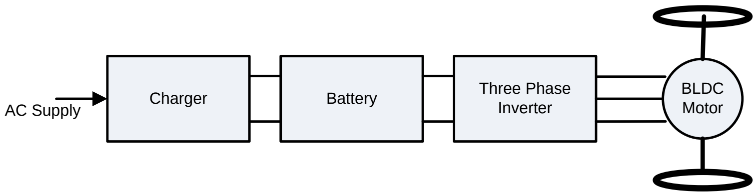


Figure 1. Schematic diagram of an electric vehicle using BLDC motor

This paper proposed an optimal sensorless speed control of BLDC motor using salp swarm optimization which is a bio-inspired heuristic optimization algorithm. It is nothing but imitating the behavior of salp swarms in deep oceans in search of food. An objective function using an integral square error is formulated to improve the operating speed profile of the electric vehicle. The speed of the BLDC motor is estimated using an EKF. Initially, extensive simulations have been performed on BLDC motor for speed control using salp swarm optimization and later the optimal PID gains are used for hardware implementation in off-line. The rest of the paper is organized as follows. BLDC motor drive and sensorless speed control using EKF are discussed in section 2. The description of salp swarm optimization is presented in section 3. Simulation results are provided in section 4. Hardware implementation and description is given in section 5, following that the conclusions are given in section 6.

2. PROPOSED BLDC MOTOR DRIVE AND ITS DYNAMICS

The laboratory prototype for the proposed motor drive scheme for real-time implementation is shown in Figure 2. Implementation of the drive consists of different subsystems, such as inverter, speed controller (PID controller), and hysteresis current control. The control of the motor drive is based on the reference current value generated by the speed controller [22]–[24]. The angular speed of the BLDC motor is estimated using EKF and is given to the controller as shown in Figure 3. The dynamics of the BLDC motor are given in (1)-(6). The BLDC motor has been modelled by considering stator phase currents (i_a, i_b, i_c), rotor speed (ω_m), and rotor angular position (θ_r) as state variables of the drive system.

$$\frac{di_a}{dt} = \frac{1}{L-M}\left[v_a - R_s i_a - k_p \omega_m e_a(\theta_r)\right] \quad (1)$$

$$\frac{di_b}{dt} = \frac{1}{L-M}\left[v_b - R_s i_b - k_p \omega_m e_b(\theta_r)\right] \quad (2)$$

$$\frac{di_c}{dt} = \frac{1}{L-M}\left[v_c - R_s i_c - k_p \omega_m e_c(\theta_r)\right] \quad (3)$$

$$\frac{d\omega_m}{dt} = \frac{-B}{J}(\omega_m) - \frac{1}{J}(T_e - T_l) \quad (4)$$

$$\frac{d\theta_r}{dt} = \frac{P}{2}[\omega_m] \quad (5)$$

The electromagnetic torque value of the motor is, $P = T_e \omega_m$ (6)

In the above equations, L and M are self and mutual inductances of stator winding respectively. Where R_s is stator resistance per phase and ω_m is rotor speed in rad/sec. The factor $k_p\omega_m e_a(\theta_r)$, is contributing induced EMF in phase–A and this is mostly speed dependent. Here, k_p (=2NlrB$_{max}$) is called EMF or voltage constant, wherein B_{max} is maximum flux density, N is the number of turns, l is length and r is internal radius of one phase of winding. Moreover, it is considered that $E = k_p\omega_m$ is the peak value of the trapezoidal electromotive force and the actual value of EMF will vary depending on the rotor position. Where, J is the moment of Inertia, B is the viscous friction coefficient of the motor, T_e is electromagnetic torque produced in the motor and T_l is the load torque required for a given load. Figure 4 shows the Back-EMF values with respect to the rotor angular position. One can observe that it is in between $0 < \theta_r < \pi / 6$ for phase-A. This is similar for other two phases.

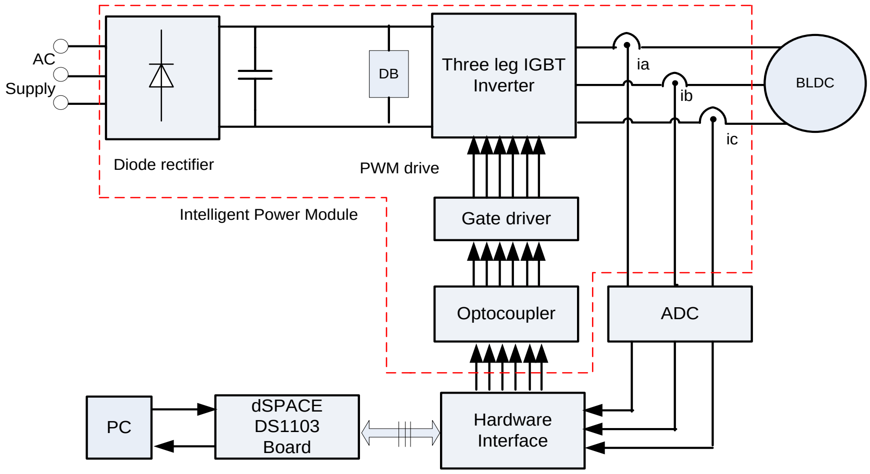


Figure 2. Drive schematic for laboratory execution

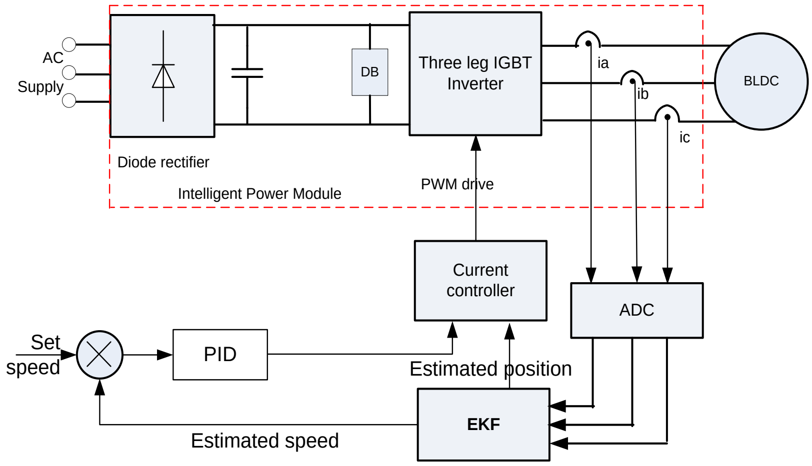


Figure 3. Sensorless speed control using EKF

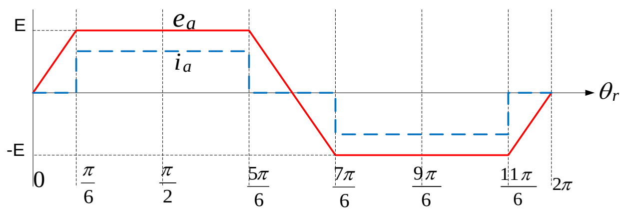


Figure 4. Back-EMF waveform and current excitation for phase-A with rotor-position

To minimize the cost of the electric vehicle, the hall sensors which are used for position measurement are eliminated. The motor's angular speed is estimated using the current measurements. The procedure for state estimation using EKF algorithm is given below. It includes the initialization of states, state covariance matrix, and P_0; and prediction of state vector and state covariance using (7), (8) respectively.

$$\hat{x}_k^- = \mathbb{F}_k(\hat{x}_{k-1}) \tag{7}$$

$$P_k^- = F_{k-1} P_{k-1}^+ F_{k-1}^T + Q_e \tag{8}$$

Update the covariance matrix using (9).

$$P_k^+ = [I - K_k\, H_k\, P_k^-] \tag{9}$$

Calculate the Kalman gain and update the states using (10) and (11).

$$K_k = P_k^- H_k^T [H_k P_k^- + R]^{-1} \tag{10}$$

$$\hat{x}_k^+ = \hat{x}_k^- + K_k[y_k - \mathbb{S}_k(\hat{x}_k^-)] \tag{11}$$

Where, $F_{k-1} = \frac{\partial \mathbb{F}_{k-1}}{\partial x}$ and $H_k = \frac{\partial \mathbb{S}_k}{\partial x}$. However, the real challenge of closed-loop speed control is tuning of PID gains. Hence the PID gains are selected optimally at the best fitness function.

3. OPTIMAL SPEED CONTROL USING SALP SWARM ALGORITHM

SSA optimization is a bio-inspired heuristic algorithm inspired by the salp swarms. Salps live in deep oceans and the salp swarm behavior is modelled for solving the optimization problems [25]. The salps are grouped to form chains where a group of followers follows the leader. The leader position is updated based on the food location. The drive scheme with SSA is shown in Figure 5 to obtain the optimum PID gains.

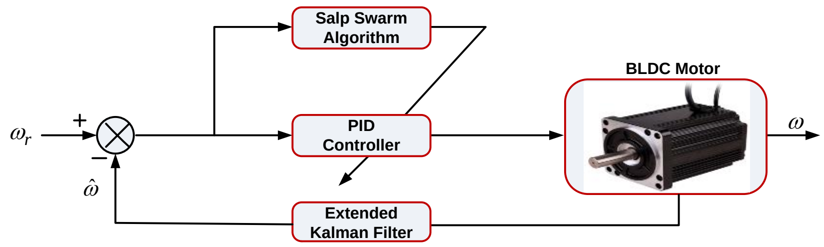


Figure 5. Drive scheme with SSA

Salp Swarm Algorithm [25]

Initialization:
The following parameters are initialized for the proposed method.
Maximum iteration max= 100; Population of salps N = 30;
Upper bound ub= [200 20 0.2]; Lower bound lb= [20 0.2 0.002];
dimension of the problem d = 3 and current iteration i = 0;
If i<max
Calculate the fitness of the swarm:
Integral square error of the speed is considered an objective function for tuning the PID controller gains.

$$Objective\ function\ \mathbb{F} = min\left(\int_0^{t_s} (\omega_r - \omega)^2 dt\right) \tag{12}$$

Where, ω is the actual speed and ω_r is the reference speed
Calculate the fitness of each salp using (12).
Select the leader:
Select the salp with best fitness as the leader L.
Update the parameter α_1 as given by (13).

$$\alpha_1 = 2e^{-\left(\frac{i}{max}()\right)} \tag{13}$$

(Update the position of Leader:
for each salp j=1:30
if (j==1)
The position of the Leader ζ_k^1 *is updated using (14):*

$$\zeta_k^1 = \begin{cases} P_k + \alpha_1\big((ub_k - lb_k)\alpha_2 + lb_k\big) & \alpha_3 > 0.5 \\ P_k - \alpha_1\big((ub_k - lb_k)\alpha_2 + lb_k\big) & \alpha_3 < 0.5 \end{cases} \tag{14}$$

where P_k *is the position of the food in the kth dimension and* α_2 *,* α_3 *are constants which are randomly generated in [0 1].*
else
Update the follower's position:
The position of the follower ζ_k^i *is updated using (15):*

$$\zeta_k^i = \frac{\zeta_k^i + \zeta_k^{i-1}}{2} \tag{15}$$

end
end
Return the Leader L

Final PID gains obtained for speed controller are *Kp* = 163.4896; *Ki* = 9.2613; and *Kd* = 0.0500 and the convergence of the objective function is as shown in Figure 6. It is observed that the speed of the convergence of the proposed algorithm is superior to the PSO algorithm as shown in Figure 6. The algorithm implementation flow is shown in Figure 7.

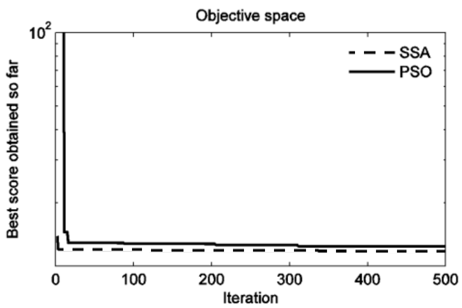


Figure 6. Convergence curve of SSA in speed control of BLDC motor

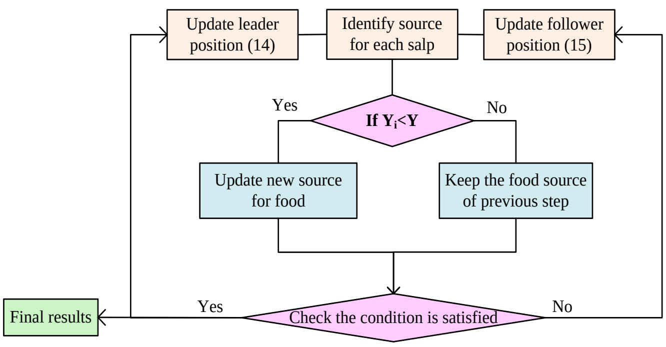


Figure 7. SSA implementation flowchart

4. SIMULATION RESULTS

The proposed control idea of the BLDC motor with EKF is first simulated in MATLAB/Simulink. The PID gains obtained after tuning with SSA are loaded in to the controller. Now the performance of the motor is evaluated for various test cases with various reference speeds and loading conditions. One can see that the motor reached to given reference speed smoothly. Figure 8, Figure 9, and Figure 10 shows that the actual speed of the motor tracks the given staircase, ramp, and triangular commands respectively. Also, a good transient and steady-state behavior is observed with the proposed algorithm.

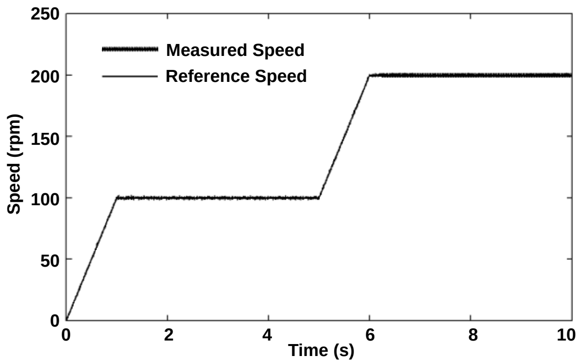


Figure 8. Speed control with SSA for staircase input

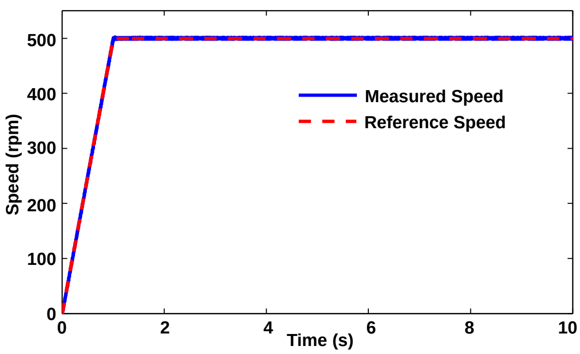


Figure 9. Speed control with the SSA for ramp input

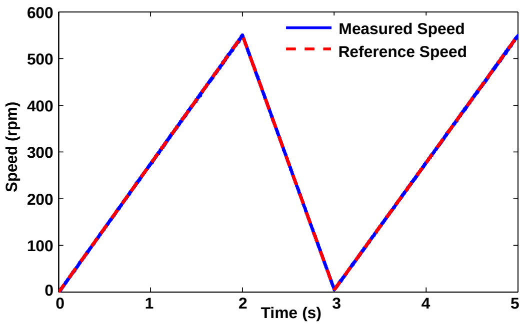


Figure 10. Speed control with the SSA for triangular input

5. HARDWARE IMPLEMENTATION AND RESULTS

The effectiveness of the proposed work has been tested using hardware implementation after the extensive simulations on MATLAB/Simulink environment. Hardware execution of the proposed work consists of a BLDC motor with mechanical load arrangement, a dSPACE DS1103 R&D controller board, voltage source inverter, Hall Effect sensors for voltage and current measurements. The prototype of the block diagram given in Figure 3 is developed as shown in Figure 11 for experimentation. One can read [3], [11] for more details of the modelling and hardware implementation. The BLDC model parameters are given in Table 1.

Figure 11. Hardware implementation testbed

Table 1. BLDC motor parameters

Parameter	Value
Resistance (R_L)	1.5Ω (line – line)
No. of Poles (P)	6
Power	1.5 hp
Moment of Inertia (J)	8.2614 e^{-5} kg.m^2
Inductance (L-M)	6.1 mH (line-line)

The transient and steady-state behavior of the drive with the proposed slap swarm algorithm is validated with various reference speeds, as described follows.

– Case1-Low-speed of 30 rpm: Experiments are conducted on closed-loop speed control for 30 rpm step reference and its performance depicted in Figure 12. The motor tracks the reference speed within 1 sec. The noise and speed oscillations are due to higher cogging torque at low speed and as well as non-sinusoidal EMF of the motor. Figure 13 shows the rotor angular position at 30 rpm and it shows 0 to 2π (0 to 6.28 rad).
– Case2-High-speed of 2000 rpm and 3000 rpm: Experiments are conducted on 2000 rpm. Figure 14 (a) gives the behaviour of the closed-loop speed control for 2000 rpm and its zoomed view is shown in Figure 14 (b). From this, one can notice that the motor tracks the given set speed so closely. The steady-state speed error is negligibly low. Similarly, one more experiment is conducted at a higher speed of 3000 rpm. Figure 15 (a) shows the speed control of the BLDC motor drive at 3000 rpm and its zoomed view is shown in Figure 15 (b). From these experiments, the superiority of the closed-loop speed control by means of the PIDs obtained from the SSA can be recognized.

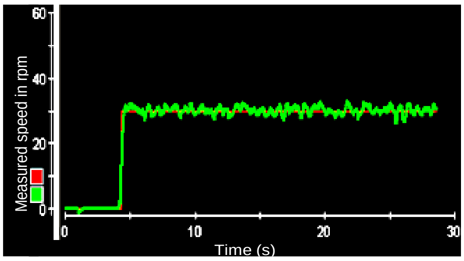


Figure 12. Speed control with 30 rpm step reference

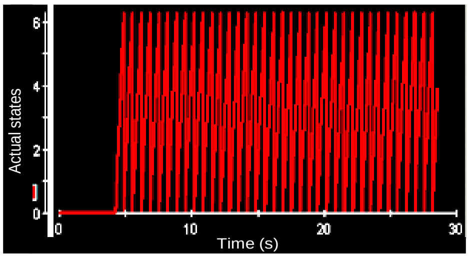
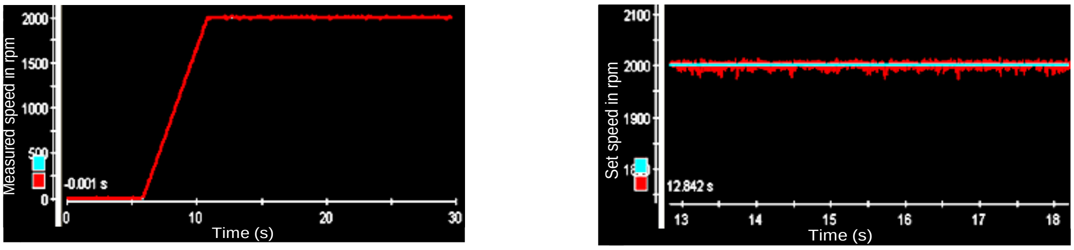
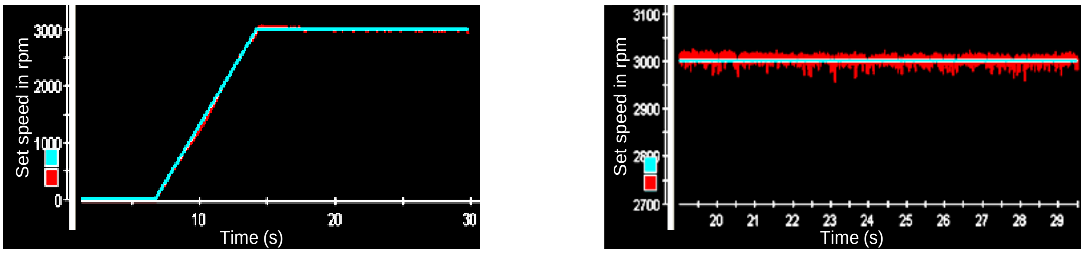


Figure 13. Rotor positions at 30 rpm



(a) (b)

Figure 14. Closed-loop speed control with the ramp reference speed 2000 rpm (a) actual response and (b) zoomed view



(a) (b)

Figure 15. Closed-loop speed control with the ramp reference speed 3000 rpm (a) actual response and (b) zoomed view

6. CONCLUSION

Thus, this paper successfully implemented the bio-inspired metaheuristic salp swarm algorithm (SSA) for closed-loop speed control of the Brushless DC (BLDC) motor drive. The effectiveness of the drive operation is shown for both lower and higher step reference speeds. The extensive simulation results show that the proposed SSA can be used offline for practical implementation of BLDC motor drive's speed control. This is further supported and justified by the experimental validation results achieved presented.

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