International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 14, No. 1, March 2023, pp. 283~293
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i1.pp283-293

Design of optimal PI controller for torque ripple minimization of SVPWM-DTC of BLDC motor

Mallempati Sunil Kumar[1], Gopisetti Satheesh[2], Sujatha Peddakotla[3]
[1]Department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University Anantapur, Ananthapuramu, India
[2]Department of Electrical and Electronics Engineering, G Pulla Reddy Engineering College, Kurnool, Affiliated to Jawaharlal Nehru Technological University Anantapur, Ananthapuramu, India
[3]Department of Electrical and Electronics Engineering, JNTUA College of Engineering, Ananthapuramu, Constituent college of Jawaharlal Nehru Technological University Anantapur, Ananthapuramu, India

Article Info

Article history:

Received Sep 25, 2022
Revised Nov 17, 2022
Accepted Nov 30, 2022

Keywords:

Brushless direct current motor
Conventional direct torque control
Direct torque control
JAYA
Particle swarm optimization
Space vector pulse width modulation

ABSTRACT

Conventional direct torque control (CDTC) for brushless DC motor (BLDCM) using proportional integral (PI) controller suffers from torque ripple minimization and speed regulation issues. A novel method in fusion with space vector pulse width modulation (SVPWM) with DTC using optimal PI controller is developed to minimize these issues. In this method, SVPWM replaces switching table and hysteresis controllers in CDTC. To get better performance in steady state, conventional PI controllers are preferred in SVPWM-DTC for BLDCM. However, uncertainty arises due to PI controller tuning as well as load variations. In such a case, optimal PI controller tuned properly can minimize these uncertainties. Here, JAYA algorithm is used to tune controller gain parameters. Simulations of proposed PI controller of SVPWM-DTC for BLDCM are carried away in Simulink. To appreciate the performance of proposed optimal controller of SVPWM-DTC for BLDCM, the simulation results are compared with Conventional PI controller and particle swarm optimization (PSO) technique based tuned PI controller. This proposed technique reduces the toque ripple by 63.1% when compared to conventional PI and 58.5% when compared to PSO-PI controller. It also improves the settling time by 43.9% when compared to conventional PI and 46.79% when compared to PSO-PI controller.

Corresponding Author:

Mallempati Sunil Kumar
Department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University Anantapur, Ananthapuramu, India
Email: sunilmallempati@gmail.com

1. INTRODUCTION

Now-a-days, brushless direct current motors (BLDCM) are extensively used in aeronautics, family machinery and vehicle equipment due to their high reliability and smooth regulation of speed over wide range [1], [2]. In view of construction, BLDC motors provide the advantage of size, simple control as well as operation. The Brushless direct current motor has a permanent magnet rotor and stator with three phase windings. The performance of a Brushless direct current motor depends on the rotor position, which in turn is identified by Hall Effect sensors. But ripples are present in commutation torque and motor torque, which is the main limitation of BLDC motor confining its use to limited applications [3]. Hence, torque ripple minimization has become an emerging research topic.

A numerous speed and torque controlling techniques are introduced to reduce ripple in speed and torque for smooth response of BLDCM. Kumar *et al*. [4], a hysteresis current controller (HCC) is used in BLDC motor control. Even, this controller suffers from high torque ripple. A direct torque control method is introduced to regulate the torque of BLDC motor [5]–[10]. It allows good performance with hysteresis control scheme. But this too has high torque ripple and variable switching frequency. In order to avoid these drawbacks a SVPWM-DTC technique is applied to improve the torque and speed performance of BLDC motor [11].

Generally, PI controller is preferred for BLDC motor control due to its simplicity. But its performance is uncertain under load and speed variations. Hence, fuzzy logic and neural network (NN) strategy techniques have been introduced as control strategies to tune conventional PI [12]. When training NNs, the required data is supplied offline from a standard PI controller, leading to inaccurate dynamic response. Fuzzy logic control offers better transient response but framing logical rules and selecting membership functions take longer to execute.

In [13], [14] PI controller is tuned based on optimization algorithms in order to get fast response under load and speed variations. Optimization algorithms like particle swarm optimization PSO [15]–[18], bacterial foraging BF [19], [20], differential evolution DE [21], teaching learning-based optimization TLBO [22], cuckoo search [23], nonlinear sine cosine algorithm [24], deep reinforcement learning with shallow controllers [25], a piecewise affine PI controller [26] and tuning inspired by Ziegler and Nichols [27], [28] were introduced to tune the controller to regulate the torque and speed of BLDC drive. In PSO, the random variables in velocity equation yields to the optimal value. To overcome these pitfalls, a modified controller is needed with improved features to solve the ripple problem of BLDC drive. In this paper, PI controller tuned with JAYA algorithm is employed for controlling the SVPWM-DTC of BLDC to have better response in torque and speed.

2. CALCULATION OF FLUX LINKAGES AND ELECTROMAGNETIC TORQUE OF BLDC MOTOR

The phase currents (I_α,I_β) and voltages (V_α,V_β) are used for flux linkage calculations (Ψ_α,Ψ_β) by (1) and (2).

$$\Psi_\alpha = \frac{1}{L_\alpha}(V_\alpha - i_\alpha r_a) \tag{1}$$

$$\Psi_\beta = \frac{1}{L_\beta}\left(V_\beta - i_\beta r_a\right) \tag{2}$$

The electromagnetic torque is expressed as shown in (3).

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \tag{3}$$

The back EMF is expressed as shown in (4).

$$e_p = k\omega_m \tag{4}$$

The electric rotor position (θ_{re}) is given by (5).

$$\theta_{re} = tan^{-1}\left(\frac{\Psi_{s\beta} - L_s i_{s\beta}}{\Psi_{s\alpha} - L_s i_{s\alpha}}\right) \tag{5}$$

3. SVPWM–DTC OF BLDC MOTOR WITH OPTIMAL PI CONTROLLER

In DTC method [6], bang-bang controllers are used to have speed control. However, it fails to meet the required torque and flux at the same instant, leading to dramatic variations in flux linkage and torque. These effects produce ripples in torque and current. Hence, in SVPWM-DTC approach [11], the bang-bang controller is replaced to minimize the above said drawbacks. Here, the inverter pulses are supplied by using SVPWM algorithm.

In order to have dynamic and smooth control of Brushless direct current motor, even with parameter variations and external load changes, the typical PI controller is to be tuned properly. The PI controllers are tuned by using the trial-and-error method (which is a primitive solution) in control of closed loop BLDC. To eradicate this time-consuming process, the optimization algorithms, based on various nature-inspired phenomenon are proposed in Figure 1 [5].

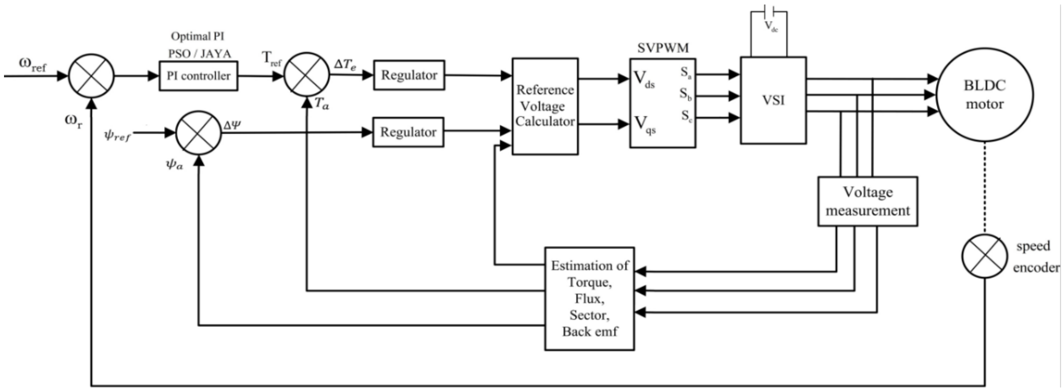


Figure 1. Block diagram of SVPWM-DTC of BLDCM with proposed optimal PI controller

3.1. SVPWM–DTC of BLDCM with optimal PI controller tuned using Jaya algorithm

JAYA optimization as shown in Figure 2 solves the problems which are unconstrained as well as constrained. The basic theme of this algorithm is that for any optimization problem, the solution must be the best. JAYA optimization technique needs only control parameters which are common but not specific-algorithm control parameters [29], [30]. Every algorithm has its own ability to find best solution for a particular problem.

$$X^1_{j,k,i} = X_{j,k,i} + r1_{j,i}\left(X_{j,best,i} - \left|X_{j,k,i}\right|\right) - r2_{j,i}\left(X_{j,worst,i} - \left|X_{j,k,i}\right|\right) \quad (6)$$

Here, $X_{j,best,i}$ = Best solution of the variable (j) in the (i^{th})iteration, $X_{j,worst,i}$ = Worst solution obtained for variable (j) in (i^{th}) iteration, $X^1_{j,k,i}$ = Candidate value of $X_{j,k,i}$is determined up to present iteration, $r1_{j,i}$&$r2_{j,i}$ = Two numbers taken in random in the range of [0, 1](j^{th}) variable in (i^{th}) iteration, $r1_{j,i}\left(X_{j,best,i} - \left|X_{j,k,i}\right|\right)$ is used to identify the difference between best and obtained solutions, $-r2_{j,i}\left(X_{j,worst,i} - \left|X_{j,k,i}\right|\right)$ is used to find the difference between worst and obtained solutions. If the obtained solution is better than existing one $X^1_{j,k,i}$ is accepted as (6). All the function values which are accepted are recorded and used as the inputs for next iteration.

3.2. Speed controller

By using speed sensor, the original speed of BLDC is obtained. The error in speed is determined by comparing with reference. Later, error in speed is fed to the speed controller to regulate the speed and to generate the reference electromagnetic torque signals [31]–[34]. Here, improvements in the PI controller depends on the values of gain parameters k_P and k_i. Hence, based on different loading conditions these two gain parameters are to be modified. Initially, the output of PI controller is given by (7).

$$T_{ref} = k_P e_s(t) + k_i \int e_s\,(t)dt \quad (7)$$

Here, the reference torque value for every iteration, $T^*{}_{ref}$is calculated with modified parameters k'_p and k'_iusing JAYA optimized controller from (8).

$$T^*{}_{ref} = k'_p e_s(t) + k'_i \int e_s\,(t)dt \quad (8)$$

Where $e_s(t) = \omega_{ref} - \omega_r$ (9)

3.3. Torque controller

The torque error is observed from the difference between reference and actual torque values. Here, the optimal torque error value for every iteration, $\Delta T_e$is calculated with modified parameters k''_p and k''_i using JAYA optimized controller from (10).

$$\Delta T_e = k''_p e_t(t) + k''_i \int e_t\,(t)dt \quad (10)$$

Where $e_t(t) = T_{ref} - T_a$ (11)

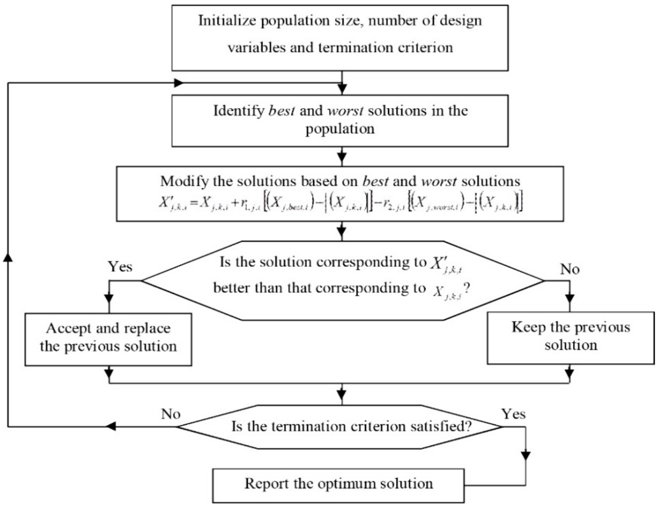


Figure 2. Step-by-step implementation of JAYA algorithm

3.4. Flux controller

The flux error is observed from the difference between reference and actual flux values. Here, the optimal flux error value for every iteration, $\Delta\Psi$is calculated with modified parameters k_p''' and k_i''' using JAYA optimized controller from (12).

$$\Delta\Psi = k_p'''e_\psi(t) + k_i''' \int e_\psi\,(t)dt \tag{12}$$

Where $e_\psi(t) = \psi_{ref} - \psi_a$ (13)

3.5. Objective function for proposed method

The objective function of proposed method is minimization of integral square error of speed and torque. It is given by (14).

$$\mathrm{F} = \min\,[\int_0^T w_1|e_s(t)|^2 + \int_0^T w_2|e_t(t)|^2] \tag{14}$$

Where w_1 and w_2 are the weights which takes the values belongs to (0 1), such that $w_1 + w_2 = 1$,$e_s(t)$ is speed error as given in (9) and $e_t(t)$ is torque error as given in (11). With constraints

$$k_{p,min}<k_p<k_{p,max} \tag{15}$$

$$k_{i,min}<k_i<k_{i,max} \tag{16}$$

Optimal k_p and k_i values are selected by using JAYA algorithm in order to minimize the objective function shown in (14) to reduce ripples in torque and speed of BLDCM. The procedure of proposed algorithm is described as follows:

Step 1: Initialize the algorithm parameters like population size, maximum iterations, range of gain parameters k_p and k_i
Step 2: Generate population of k_p and k_i
Step 3: Calculate the fitness as mentioned in (14)
Step 4: Identify the best and worst solution in the population
Step 5: Generate new population of k_p and k_i using jaya algorithm as per (6)
Step 6: Find the fitness of new population as per (14), if fitness of new population is less than the fitness of old population, update the old population with new population otherwise keep the previous population.
Step 7: If maximum iteration criteria is met, select the global best population as optimal k_p and k_i values.

At the end of all iterations, with optimal k_p and k_i values the torque controller, flux controller and rotor position are estimated from which reference voltage vector is controlled. By using SVPWM technique the required pulses for VSI are generated.

4. SIMULATION ANALYSIS

Here, SVPWM-DTC of Brushless direct current motor with Conventional PI and optimal PI controllers are illustrated using Simulink/MATLAB. The motor parameters used for simulation are considered as $R_s = 2.87\ \ \Omega, J = 0.00008, \lambda = 0.175, B = 0.001, L_s = 8.5\text{e-}3$ mH, back emf constant = 0.018 [V/rpm], speed = 1200 rpm, torque = 1.5 NM and poles = 4. Case 1: The performance analysis of SVPWM-DTC of brushless direct current motor with conventional PI controller is simulated and the results are portrayed in Figures 3 to 6. Here, the motor is rotated at 1200 rpm with load torque of 10 N-m applied at 0.4 sec, released at 0.7 sec.

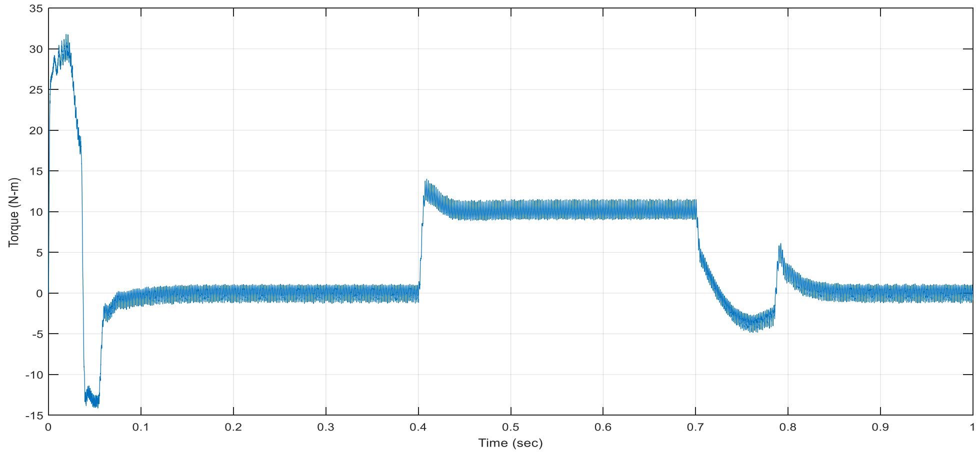


Figure 3. Torque waveform of SVPWM-DTC of BLDCM tuned with PI controller

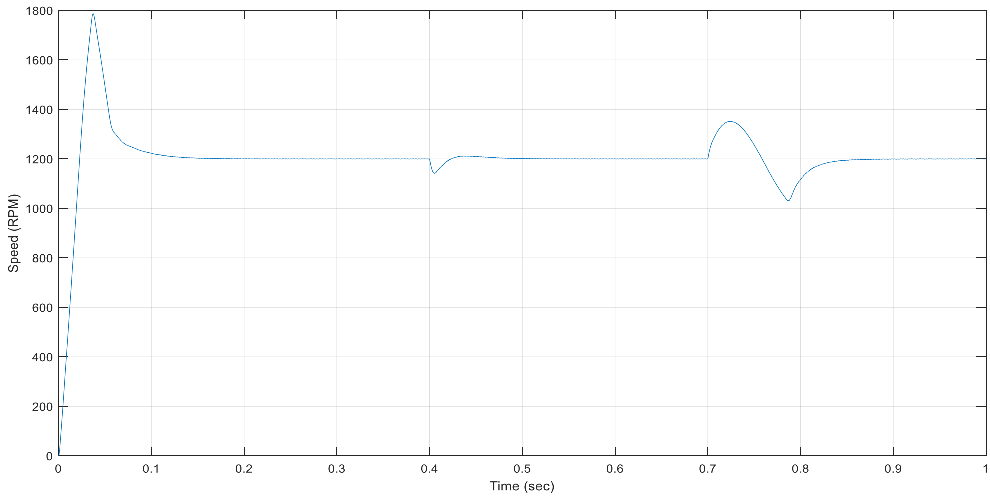


Figure 4. Speed waveform of SVPWM- DTC of BLDCM tuned with PI controller

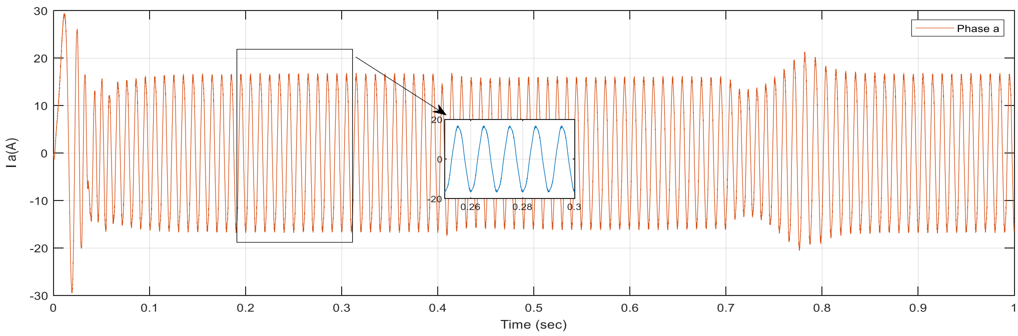


Figure 5. Stator phase ‘a’ current waveform of SVPWM- DTC of BLDCM tuned with PI controller

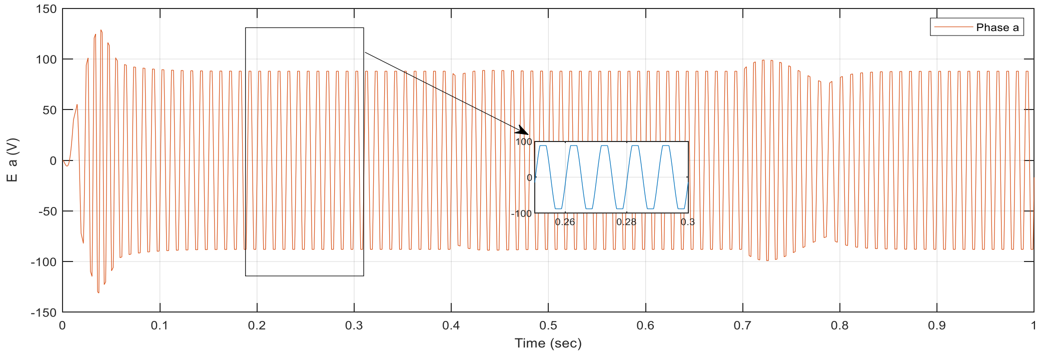


Figure 6. Back EMF waveform phase ‘a’ of SVPWM- DTC of BLDCM tuned with PI controller

Case 2: The performance analysis of SVPWM-DTC of BLDCM with optimal PI controller is simulated and the results are depicted in Figure 7 to Figure 10 for PSO and for JAYA. Figure 7(a), Figure 8(a), Figure 9(a) and Figure 10(a) depicts the torque, speed, stator phase ‘a’ current and back EMF of phase ‘a’ wave forms of SVPWM- DTC of BLDCM with PSO-PI controller. Figure 7(b), Figure 8(b), Figure 9(b) and Figure 10(b) depicts the torque, speed, stator phase ‘a’ current and back EMF of phase ‘a’ wave forms of SVPWM-DTC of BLDCM with JAYA-PI controller. Here, the motor is rotated at 1200 rpm with load torque of 10 N-m applied at 0.4 sec, released at 0.7 sec.

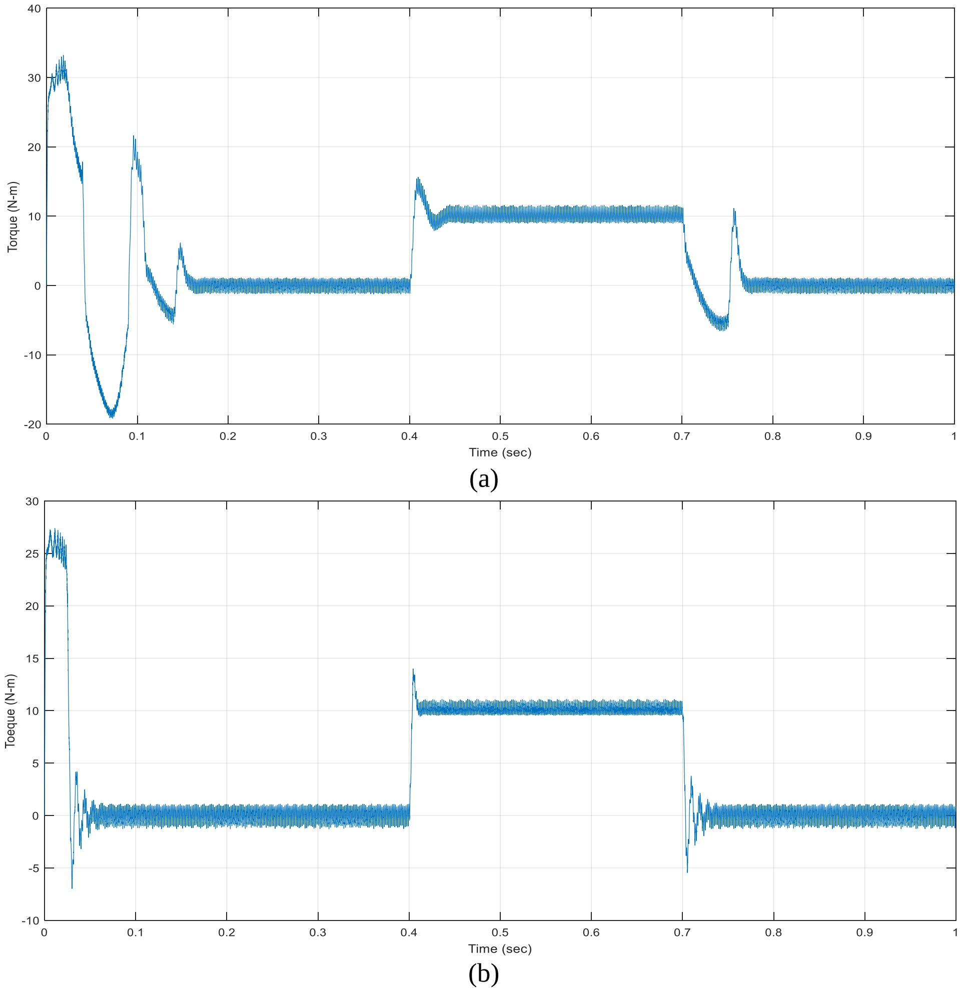
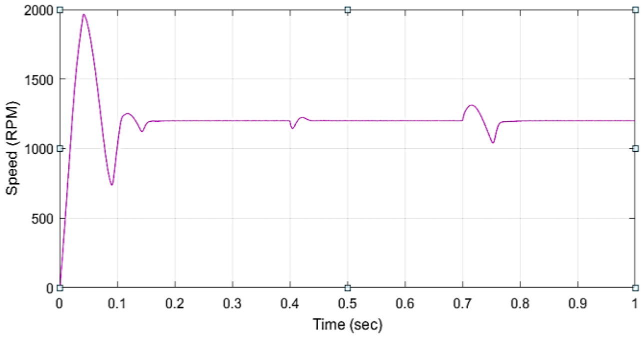
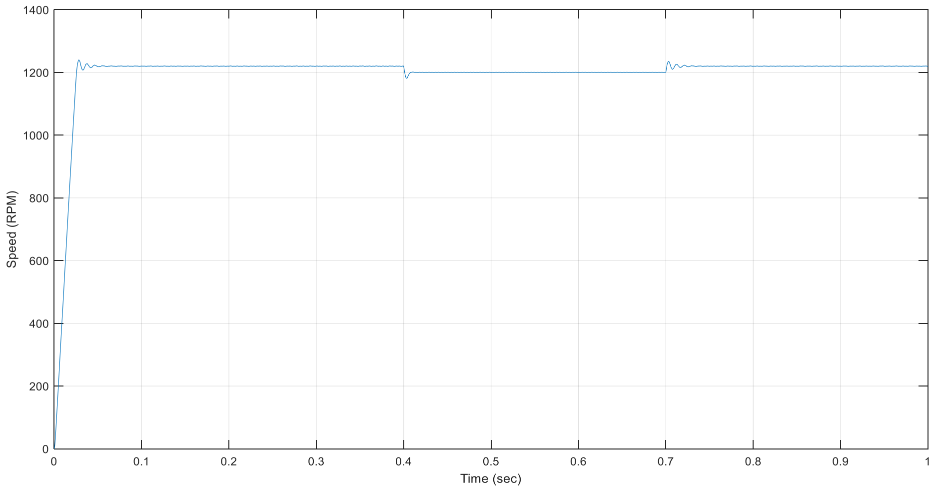


Figure 7. Torque waveform of SVPWM- DTC of BLDCM with (a) PSO-PI controller and (b) JAYA-PI controller

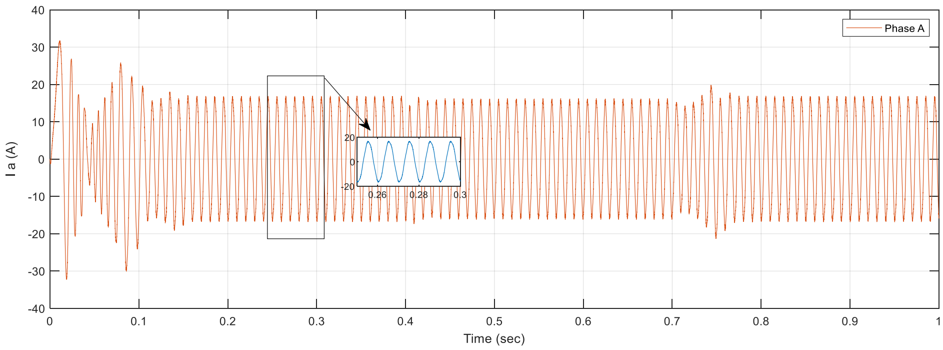


(a)

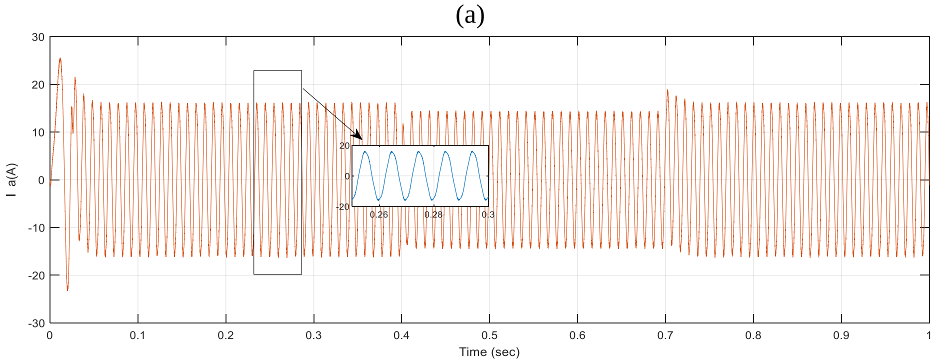


(b)

Figure 8. Speed waveform of SVPWM- DTC of BLDCM with (a) PSO-PI controller and (b) JAYA-PI controller

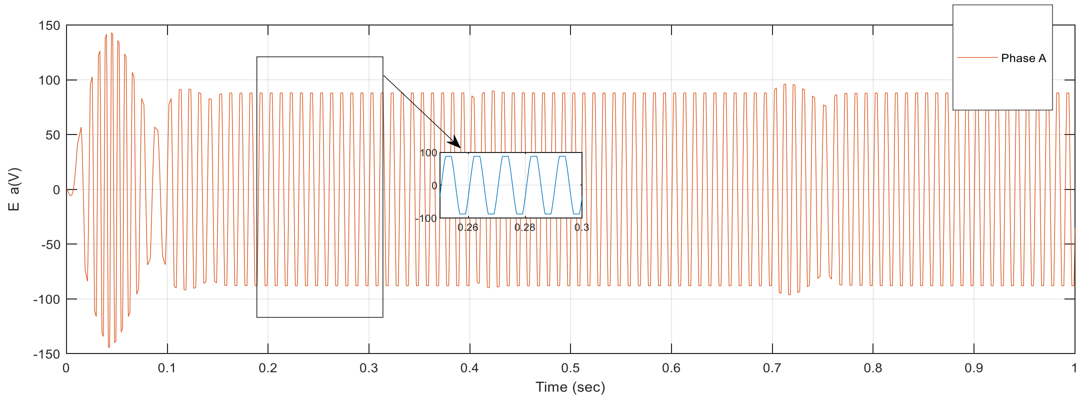


(a)

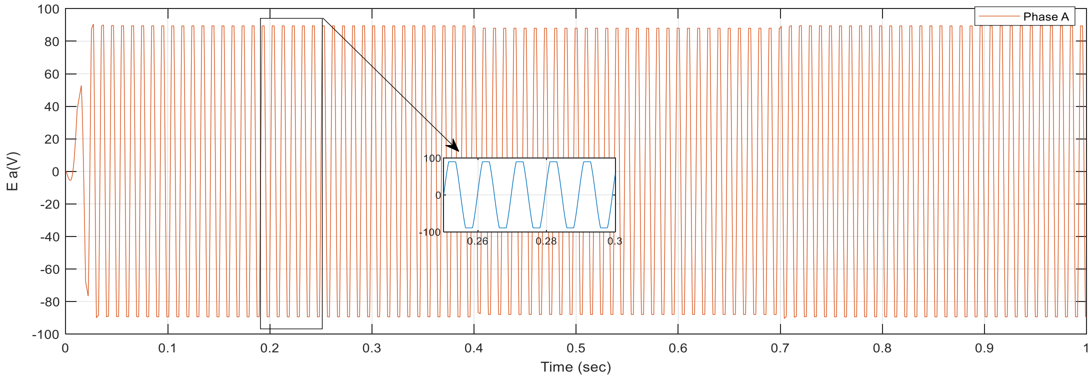


(b)

Figure 9. Stator Phase 'a' current waveform of SVPWM- DTC of BLDCM with (a) PSO-PI controller and (b) JAYA-PI controller



(a)



(b)

Figure 10. Back EMF waveform phase ‘a’ of SVPWM- DTC of BLDCM with (a) PSO-PI controller and (b) JAYA-PI controller

Case 3: In the performance analysis, the SVPWM-DTC based BLDCM parameters like torque and speed variation are compared. From Figures 11 to 13 analyses the performance of proposed controller with various existing controllers. Torque ripple (%), speed (rpm) and time domain specification’s viz. rise time (t_r), settling time (t_s), overshoot, Peak value (speed in rpm) and Peak time (t_p) for various controllers are presented in the Table 1. Algorithm parameters like population, number of iteration and number of variables are shown in Table 2. Convergence characteristics of optimal PI controller tuned using PSO & JAYA algorithms are presented in Figure 14.

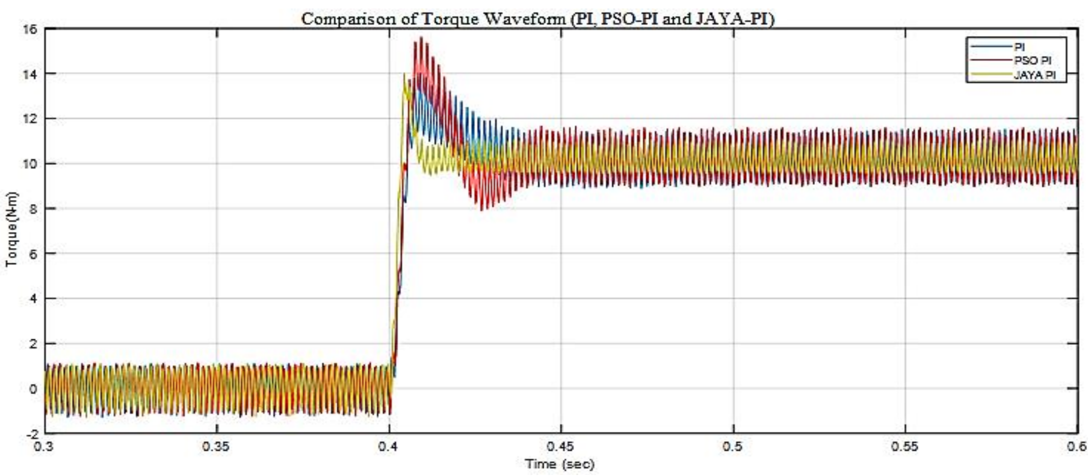


Figure 11. Torque waveform of SVPWM-DTC of BLDCM with PI, PSO-PI and JAYA-PI, load torque of 10N-m applied at t = 0.4 sec

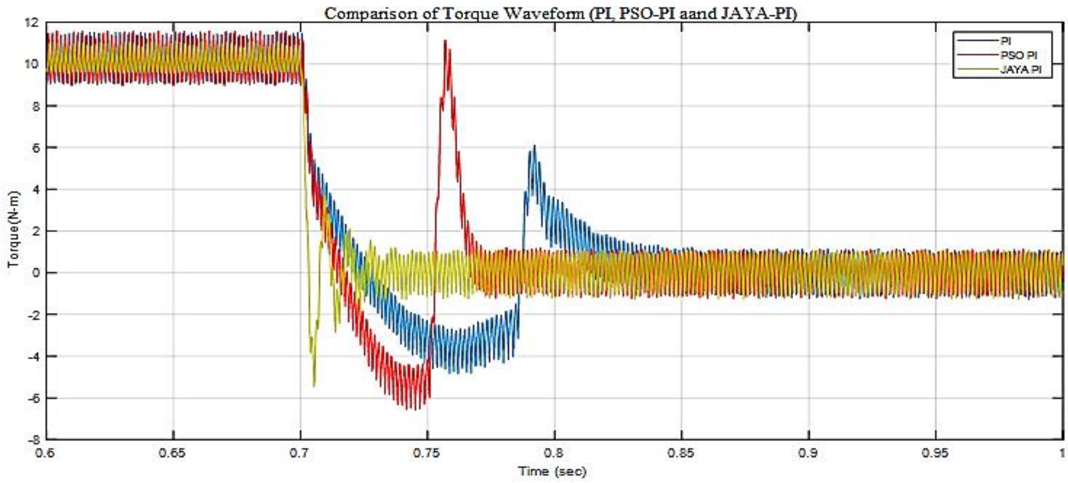


Figure 12. Torque waveform of SVPWM- DTC of BLDCM with PI, PSO-PI and JAYA-PI, load torque of 10N-m released at t = 0.7 sec

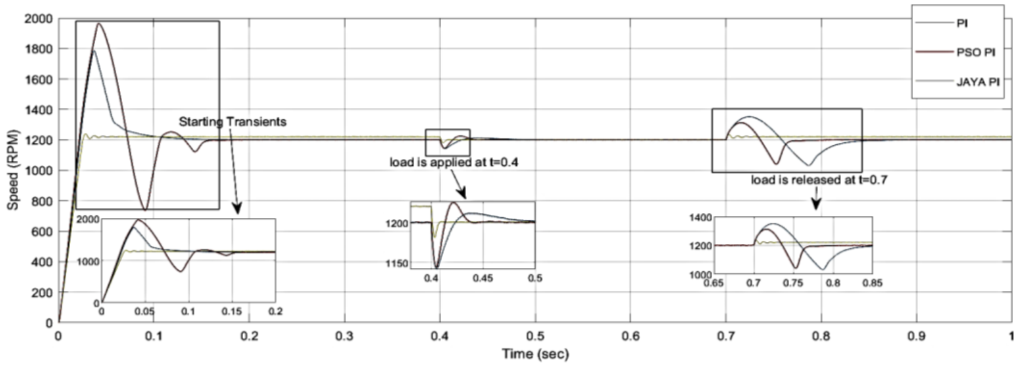


Figure 13. Speed waveform of SVPWM- DTC of BLDCM with conventional PI, PSO-PI and JAYA-PI, load torque of 10 N-m applied at t=0.4 sec, released at t=0.7 sec

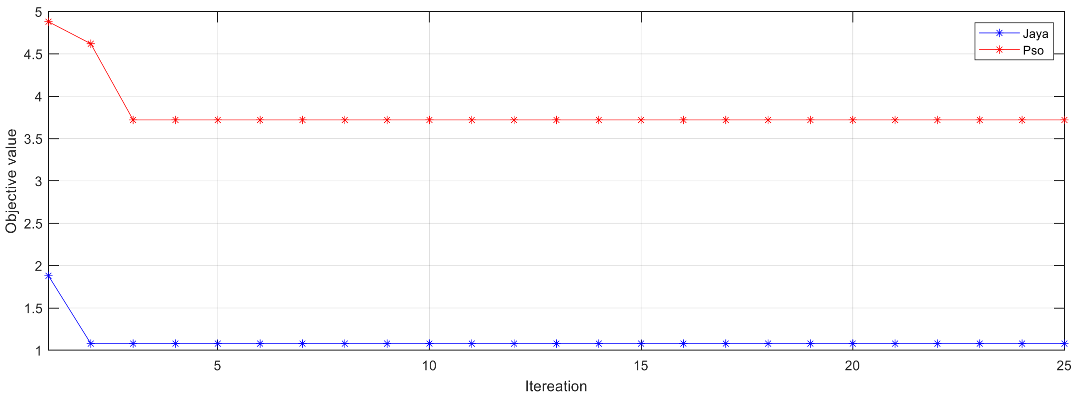


Figure 14. Convergence characteristics of optimal PI controller tuned using PSO & JAYA algorithms

Table 1. Performance analysis of proposed method with existing methods

Comparison parameters	PI	PSO-PI	Proposed method (PI tuned using JAYA)
Rise time (t_r in sec)	0.0175	0.0168	0.0200
Settling time (t_s in sec)	0.8208	0.7636	0.4063
Overshoot (percentage)	48.893	23.792	1.6182
Peak (speed in rpm)	1786.6	1980.3	1231.04
Peak time (t_p in sec)	0.0373	0.0422	0.0283
Torque ripple (%)=(Tmax –Tmin)/Tavg×100	25.2	23.1	9.7

Table 2. Algorithm parameters

Specifications	Values
Population	20
Iterations	25
No. of variables	2

5. CONCLUSION

In this paper, JAYA algorithm based optimal PI controller for SVPWM-DTC BLDCM drive has been proposed. It minimizes the integral square error of speed as well as torque ripple by controlling the gain parameters of PI controller. The proposed method improves the control parameters of speed and toque by controlling the switching sequence of VSI fed BLDCM. The proposed PI controller is implemented with the help of MATLAB/Simulink to validate its performance. The simulation results show that JAYA-PI based SVPWM-DTC BLDCM out performance the existing techniques like PSO-PI, PI in terms of speed, torque ripple and time domain specifications. This technique reduces the toque ripple by 63.1% when compared to conventional PI and 58.5% when compared to PSO-PI controller. It also improves the settling time by 43.9% when compared to conventional PI and 46.79% when compared to PSO-PI controller. As a future scope the performance of proposed technique can be enhanced by using hybrid optimization algorithms.

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BIOGRAPHIES OF AUTHORS

Mallempati Sunil Kumar is currently pursuing his Ph.D. in EEE Department from JNTU Ananthapur, A.P., India. He obtained his B.Tech (Electrical and Electronics Engineering) from JNTUH, Hyderabad, India in 2008 and M.Tech (Power Electronics) from JNTUK, Kakinada, A.P., India in 2012. He is currently associated with DVR& Dr. HS MIC College of Technology as Asst. Prof. in EEE department. He has life membership of ISTE. His area of research lies in designing of controllers for motor drives, optimization techniques. He can be contacted at email: sunilmallempati@gmail.com.

Gopisetti Satheesh is currently working as Associate Professor in GPREC, Kurnool. He has a total of 19 years of experience in teaching and published 32 international research papers. His area of research are non-conventional energy sources, power semi-conductor drives, power electronic converters, multi-level inverters. He can be contacted at email: gsatish.eee@gmail.com.

Sujatha Peddakotla is currently working as Principal of JNTUA CEA and Professor in EEE Department. She has more than 23 years of teaching experience. Up to now 48 international research papers were published by her. Her research covers renewable energy sources, power systems and control systems. She can be contacted at email: psujatha1993@gmail.com.