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Design Analysis of SSD Optimized Speed Controller for BLDC Motor

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ABSTRACT- Brushless Direct Current (BLDC) motor is widely applied for both domestic and industrial applications especially in computer peripheral devices and electric vehicles. This paper introduces BLDC motor design using Social Ski Driver (SSD) optimized speed controller. Better efficiency, high power density, good reliability, less noise & maintenance, and the use of simpler control mechanisms are major benefits of the BLDC motor. Proposed work mainly focuses on torque ripple compensation with speed control at low cost. The use of a small DC link capacitor instead of a bulkier capacitor helps to reduce ripples by using Social-Ski Driver optimized controllers. However, torque reduction with reasonable speed control has not been achieved in existing works. So, the proposed work planned to design an advanced controller with the recent bio-inspired algorithm to control the PWM signal. The proposed work will be implemented in MATLAB Simulink working environment for research analysis. From the implementation result, the proposed work achieves 422 (rad/sec) speed, 0.03(Nm/A) torque constant, and 25 (MW) rated power.

Keywords: Brushless DC Motor (BLDC); Social Ski Driver (SSD); Back Emf; Torque Ripple; MATLAB Simulink; PWM Signal.

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1. INTRODUCTION

Nowadays, BLDC are a growing technology. Owing to their effective operation, high efficiency also low maintenance, and exchanging the motor with brushes in numerous applications [1]. This permits utilizing the motor in unsafe areas [2]. In this motor, the procedure of commutation is proficient spontaneously when the motor is brushless. The position sensors are used in this kind of commutation to the reach position of the rotor concerning the stator winding. A Brushless DC motor is one kind of synchronous motor. Owing to a lack of brushes, they can be worked at high speeds in dangerous atmospheric situations. Usually, the BLDC motors are classified into two types [3-5]. They are the outer rotor motor and inner rotor motor. Flux distribution is reliant on BLDC motors as well as permanent magnet synchronous motors (PMSM). The PMSM back-EMF waveform is sinusoidal. However, BLDC motors require a trapezoidal wave shape [6-8].

The BLDC motors control is characterised by sensorless control and sensor-based control. The stator winding is motivated in sensor- based control which is calculated using hall sensors. By the way of PWM- based voltage source inverter, the BLDC motors are commonly controlled [9]. To convert the AC source into the DC, the predominant control method is applied and not including automobile applications for the BLDC motor. To control the armature current, Brushless DCM uses an inverter and position decoder [10]. The BLDC uses electronic commutation rather than using a mechanical commutator as in the mechanical commutator and conventional DC motor without brushes. The simulation and modelling analysis of BLDC motor based on computing design and evaluates rationality of the control algorithm and effectively improves BLDC motor control system [11-12]. Therefore good modelling is very important and it deals with potential cost savings.

BLDC motor eliminates commutators, brushes and therefore remaining performance of BLDC motor creates an effective contender for AC drives [13-15]. Owing to the quiet operation, maintenance-free, lower electromagnetic interference (EMI), high power density, high reliability, and fast response, it has been commonly utilized in servo control and drive systems [16-17]. The motor covering of distributed stator winding and permanent magnet rotors are wound such that electromotive force is trapezoidal [18]. They have low inertia and higher speed torque features, which improves their dynamic presentation when related to DC motor. Brushless motors overwhelmed the limits of brushed DC motors [19-20].

This paper proposes design analysis of SSD optimized speed controller for BLDC motor. It's commonly applied for both domestic and industrial application particularly in computer peripheral devices and electric vehicles. High power density, less noise, good reliability, better efficiency and maintenance and use of simpler control mechanisms are main advantages of BLDC motor. Smooth driver designs for motor operation under different speed is very difficult task. Trapezoidal type back EMF with constant torque will be present at ideal condition of BLDC motors. Physical structure of motor and its design

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parameters are main reason for torque ripple availability at output torque side. Control and motor driver section is associated with generated ripple.

Contribution of the research work is given below:

- To design the BLDC motor with current sensor, current to voltage converter, ideal voltage gain, analog to digital converter and pulse width modulation controller.
- PWM controller is designed in the BLDC motor to control the speed. This causes a reduction in torque ripple with proper speed control through the generation of PWM optimized PWM signal.
- Social Ski Driver optimization algorithm is used in the PWM controller for optimizing the parameter, thus will get efficient output.

This paper is organized as follows, *Section 2* gives a literature review and *Section 3* explains the proposed methodology which includes converter, BLDC, current sensor, Analog to digital converter, Pulse width modulation and SSD optimized PWM controller. The *Section 4* includes the result and comparison process and the following *Section 5* covers the conclusion part.

2. RELATED WORK

Some of the recent related works are given as follows:
In Maharajan et al., [21], the spider-based controller used for torque ripple reduction and speed control of BLDC motor have been developed by Matlab implementation. From result analysis, the performance of PI, fuzzy logic, PID, and anti-windup PI were investigated. Performance comparison utilized settling time and peak overshoot with various loading conditions. When comparing with traditional controllers, fuzzy and fuzzy-PI provide the best performance than others. The benefits of the anti-windup controllers were listed as cost-effective, reliable, and applicable for fuel pumps.

Vehicle emission contributions were more in the present world and EV (electric vehicles) had a great impact in mitigation of pollution and fuel efficiency improvement. Available converters and highly efficient electric motors play a vital role in electric vehicle construction. In Avanish Kumar and Thakura [22], speed control of BLDC motor with or without distractions was labeled. The controller design of the proposed work concentrates on overshoot minimization. The development of a three-phase inverter was specially simulated for speed control in a three-phase Brushless DC motor design.

Devendra Potnuru et al., [23] had proposed a naturally inspired algorithm for speed controlling of BLDC motor. Flower pollination algorithms had followed the presented approach to tune PID controller operation by assuming integral square error as fitness value. This work had been specially developed for speed control purposes. The performance comparison showed that this flower pollination algorithm outputs better than existing schemes like PSO, firefly, and ALO optimization procedures. This technique was suitable for static PID gains but given more enactment associated with predictable approaches.
Amirthalingam Ramya et al., [24] focused on the fuzzy logic-based controller to obtain the superior dynamic performance beneath parameter uncertainties and non-linearities. In the proposed controller, parameter variations of the motor were tuned by the membership function parameters. The benefits of the controller was enlightened for the servo response and regularity of the steady-state suggested controller. The results were compared with predictable approaches to indicate the faster time response and better tracking ability.

Potnuru et al., [25] focused BLDC motor drive under steady-state and transient conditions. The speed response was enhanced by the grasshopper optimization algorithm. For reducing the integral square error, the gain of PID was optimally tuned and formulate by an objective function. The gain of PID was obtained by the grasshopper optimization algorithm for closed-loop speed control of the BLDC motor. The detected speed control performance was better under steady-state and transient conditions.

In BLDC motor, a modified genetic algorithm (MGA) based fractional order PID controller was designed by Vanchinathan et al. [26] to achieve the speed control. The algorithm was used for solving nonlinearity issues like motor misalignment, power fluctuation and sudden load disturbance. Based on varying set speed condition and load condition, the MGA-optimized fractional order PID controller was recommended for sensor less BLDC motor speed control.

BLDC motor with voltage source inverter was implemented and comparative analysis of speed performance was carried out by Kommula and Pardhu [27]. The adaptive ANFIS based speed controller was effectively evaluated for controlling the torque and speed. The characteristics of torque and speed of two level inverter were compared to various operating condition. Torque ripple was eliminated by AANFIS based speed controller.

Motivation: Generally, BLDC machines attracts many of the industrialists due to their special characteristics such as better output, stabilized performance and high torque to current ratio. Low starting torque, high speed and high cost are the main disadvantages which present in the BLDC drive. Moreover, BLDC have low inertia and higher speed torque features, which improves their dynamic presentation when related to DC motor. Brushless motors overwhelmed the limits of brushed DC motors. Thus, the aim of the present work is to develop novel optimization based controller in BLDC motor for overcoming those issues.

3. PROPOSED METHODOLOGY

Proposed work mainly focuses on torque ripple compensation with speed control at low cost. Use of small DC-link capacitor instead of bulkier capacitor used to reduce ripples with help of Social Ski-Driver (SSD) Optimized controllers. Generally, pulsating DC supply is provided to stator field windings of BLDC motor. In three-phase BLDC, two phases will be active and another one will be off at a particular instant. The PWM signal generated from the control circuit is used to regulate the two active switches at a particular instant. The proposed SSD controller normally operates in two modes like speed and current control. Controlling operation performed by producing suitable switching sequence through SSD optimization process. Mainly speed and rotor position are considered to generate the optimized switching sequence from the controller. Sensor signals exhibit rotor position and A/D converted current outputs are forward to control SSD controller. Back EMF calculated at controller which is compared with incoming voltage. Next, the controller optimizes the switching operation based on the resultant difference obtained through comparison. This optimized switching pulse sends to DC switches to enables the charging and discharging process of a small DC-link capacitor. *Figure 1* shows the block diagram of the proposed work. This causes a reduction in torque ripple with proper speed control through the generation of PWM optimized PWM signal.

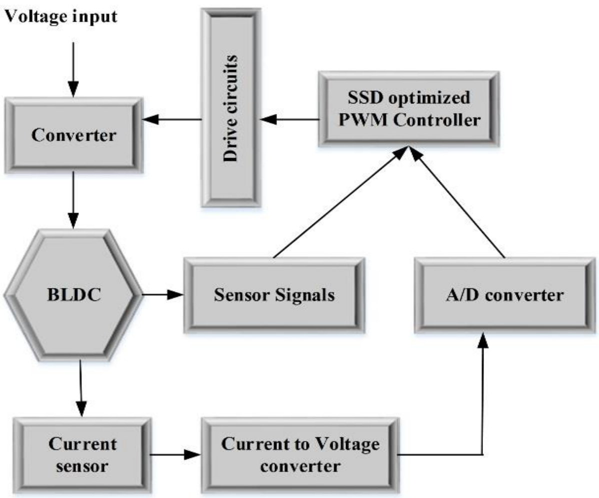

Figure 1: Block Diagram of Proposed Work

3.1 Converter
The converter is an electronic device and it is used for converting the voltage from alternating current (AC) to direct current (DC). That DC is the input of a BLDC. The converters are classified into six types. There are diode rectifiers, static switches, AC to AC converter, DC to AC converter, AC to DC converter, and DC to DC converter. The proposed work uses AC to DC converter. The common applications of the converter are lighting control, soft starting induction motors, AC voltage controller, domestic and, industrial heating.

3.2 BLDC
BLDC are higher to brushed DC motors in several methods, such as the capability to work at better heat dissipation, high speeds, and high efficiency. These days, BLDC are commonly used in many home and industrial application. For instance electrical vehicles and computer peripheral devices. BLDC is the one kind of synchronous motor. The induced current change in the inductor or coil is opposed by the electromotive force and that force is called back emf.

The Direct current is given to the stator field windings of BLDC motor. Assuming three pole pairs which are represented by R, S, and T. The Direct Current pulses are passes through the pair R at that time the pole R_1 magnetizes at south and R_2 magnetizes at North Pole. Formerly, the current have supplied to pole pair R is turned off and the pulsated DC passes via pole pair R and pole pair T. Three phase motor driver using six step inverter motor driver then the revolving field is generated over the stator coil pairs. In 3ϕ BLDC, 2 phases will be active and another one will be off at particular instant. PWM signal generation from control circuit used to regulate the two active switches at particular instant. Speed and torque control modes are capable to control the controller circuit. The BLDC motor switching algorithms are shown in *Table 1*. In 'on' state switch provides a freewheeling route to off state switch period of inductive current. The outputs of hall sensor are represented by h_L, h_M and h_N.

$$\vartheta_r = ri_r + (l-m)\frac{dI_r}{dt} + E_r \quad (1)$$

$$\vartheta_s = ri_s + (l-m)\frac{dI_s}{dt} + E_S \quad (2)$$

$$\vartheta_t = ri_t + (l-m)\frac{dI_t}{dt} + E_t \quad (3)$$

Here, the stator phase voltage is represented as $\vartheta_r, \vartheta_s and \vartheta_t$. The i_r, i_s, i_t denotes the stator phase current and E_r, E_s, E_t denotes the phase back-EMF. Then 'm' is the mutual inductance and 'l' is the self-inductance. The phase resistance is represented as 'r' also the time instant is denoted as 't'. The below expression can represent the motion equation.

$$\frac{ds_m}{dt} = \left(\frac{p}{2j}\right)(\tau_E - \tau_l - fs_e) \quad (4)$$

$$\frac{d\phi}{dt} = s_e \quad (5)$$

Where, electromagnetic torque τ_E and load torque is τ_l (Nm). The rotor speed in mechanical is represented as s_m and the rotor speed in electrical is represented as s_e. Then friction coefficient is f (Nms/rad) and the moment of inertia is j(kgm^2). Speed of mechanical and electrical motor is interrelated as,

$$ps = \frac{d\varphi_R}{dt} \quad (6)$$

The number of pole pair is represented as 'p'.

Table 1: BLDC Motor Switching Algorithm

Stage	Output of hall sensor			On state switch	Controlled switch
	h_L	h_M	h_N		
1	1	0	0	R_1	T_2
2	1	1	0	T_2	S_1
3	0	1	0	S_1	R_2
4	0	1	1	R_2	T_1
5	0	0	1	T_1	S_2
6	1	0	1	S_2	R_1

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3.3 Current Sensor

The current sensor is an electronic device that identifies the current in a system or a cable. The current sensing methods are classified into two types and, they are direct current sensing and indirect current sensing. The current sensor measurement is required for several applications such as household fields, industrial and automotive. The direct current sensing method is based on ohm's law and it ixs used for <100A load currents. Differential amplifiers are used in the voltage over the shunt restrained for instance operational amplifier, shunt amplifier, and difference amplifier. The indirect current sensing method is based on the ampere's law and it is used for 100A-1000A load currents. The major advantages of the current sensor are low cost, electrical isolation, measures AC only, and no power supply.

3.4 Current to Voltage Converter

In this method the input current is converted into a voltage. The current to voltage converter is used for various application such as measurement of photodiode current, photo resistor *Figure 2.*

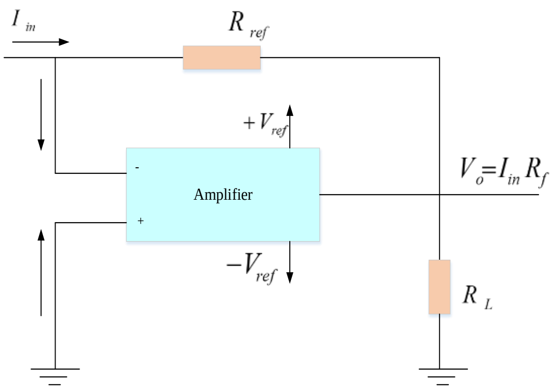

Figure 2: Current to Voltage Converter

Ideal Voltage Gain

$$\frac{v_0}{v_{in}} = \frac{-R_f}{R_1} \quad (7)$$

$$v_0 = -\left[\frac{v_{in}}{R_1}\right] R_f \quad (8)$$

$$v_1 = 0 and v_1 = v_2$$

$$I_{in} = \frac{v_{in}}{R_1} \quad (9)$$

$$v_0 = -I_{in} R_f \quad (10)$$

Where, v_{in} is the input voltage and v_{out} is the output voltage, Feedback resistor is represented as R_f and I_{in} is the input current. Sensor signal is used to convert the displacement into electrical signal. That electrical and digital signals are the input of SSD optimized PWM controller. Sensor signals exhibits rotor position and A/D converter current outputs are forward to control SSD controller.

3.5Analog to Digital Converter

Analog to digital converter is used to convert the analog signal into digital form. That analog signal is used in various applications such as data transmission, data computing, and information processing and control systems. While the digital signals are represented as binary forms i.e., 0 and 1. The '1' denotes the ON state, as well as '0', which represents the OFF state. *Figure 3* indicates the schematic diagram of the analog to digital converter. Generally, transducers are similarly used to convert the input analog signal into the form of current or voltages. In our proposed work the input analog variables are in the form of voltages. The Analog to digital converter process includes two steps: (i) sampling and holding, (ii) Quantizing and encoding. Finally, the analogue signal is converted into digital form.

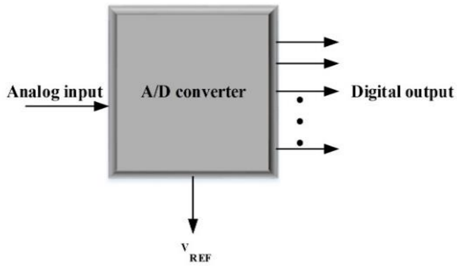

Figure 3: Analog to Digital Converter

3.6 Pulse Width Modulation Controller

It is a method of converting the average power from the electrical signal into discrete parts. There is a switch placed in between the supply and load for controlling the load at a fast rate. The PWM switching frequency must be high enough not to affect the load, i.e. the wanted waveform of the load must be as smooth as possible.

3.7 SSD Optimized PWM Controller

Social Ski Driver (SSD) optimized controllers generally work in two modes like current and speed control. The controlling process is achieved by producing a suitable switching sequence through the SSD optimization method. Mostly rotor position and speed are considered to produce the optimized switching sequence from the controller. Pulse width controller is used to generate the analog signal utilizing a digital source.

$$z_i = \frac{w_{max} + w_{min}}{2} \quad (11)$$

Where w_{max} represent the high value and w_{min} denotes the low value, z_i is the mean value.

Where,

$$w_{max} = \frac{1}{t}\int_0^{\tau} w_{max}\, dt \quad (12)$$

$$w_{min} = \frac{1}{t}\int_{\tau}^{t} w_{min}\, dt \quad (13)$$

The average value of the waveform is given by,

$$\overline{X} = \frac{1}{t}\int_0^t s(t)dt \tag{14}$$

Where s (t) is the pulse wave, $w_{\max}$ represent the high value and $w_{\min}$ denotes the low value, $\overline{X}$ denotes the average value of the waveform and't' denotes the period, τ is the duty cycle. The average value of the waveform is given by,

$$\overline{X} = \frac{1}{t}\left[\int_0^{\tau} w_{\max}\,dt + \int_t^{\tau} w_{\min}\,dt\right] \tag{15}$$

The i^{th} agent is the best solution given by,

$$p_i = \max\left[w_i^{t+1}\right] \tag{16}$$

The pulse waveform locations are upgraded by adding velocity v_i is following,

$$w_i^{t+1} = w_i^t + v_i^t \tag{17}$$

Where,

$$v_i^{t+1} = \begin{cases} C\sin(r_1)(p_i^t - w_i^t) + \sin(r_1)(z_i^t - w_i^t) & if \quad r_2 \le 0.5 \\ C\cos(r_1)(p_i^t - w_i^t) + \cos(r_1)(z_i^t - w_i^t) & if \quad r_2 > 0.5 \end{cases} \tag{18}$$

Where v_i represents the velocity of w_i, z_i denotes the mean value of the whole population, $r_1 and r_2$ are [0, 1] range of generated random numbers, p_i represents the i^{th} agent best solution and C denotes the control parameter. The control parameter calculated by using below form,

$$C^{t+1} = \beta C^t \tag{19}$$

Where t denotes the present iteration and $0 < \beta < 1$ is used to decrease the control parameter value. Therefore, C=0 and t= $t_{\max}$ and $t_{\max}$ is the maximum number of iterations. Drive circuit is used to control the speed of the motor and its supply the voltage. That voltage is given to the converter block.

3.8 SSD Algorithm

1. Initialize the pulse waveform s(t)
2. **While** ending conditions are not met do
3. **For all** pulse **do**
4. Estimate the $W_{\max}$ and W_{mim} values
5. Calculate the mean value (Z ^{i})
6. Find the average pulse waveform
7. Pulse waveform locations are upgraded by adding velocity as indicated in eq. no. 16
8. **end for**
9. **Completion while**
10. Return to the greatest result value

4. RESULT AND DISCUSSION

The MATLAB/SIMULINK tool is used for the simulation and synthesis of the proposed work. The proposed work including a Brushless DC motor and social ski- driver optimized speed controller. Here we using some existing methods such as spider based controller algorithm, grass hopper optimization algorithm and flower pollination algorithm for evaluating our proposed work.

Table 2 displays the comparison of simulation parameters with proposed and existing algorithm. Parameters like speed, torque constant and rated power is compared with existing methods namely spider-based controller algorithm [21], grass hopper optimization algorithm [25] then flower pollination algorithm [23]. Compared with existing methods, the proposed work gives better performance. The proposed design analysis of SSD optimized speed controller for BLDC motor achieves 422 (rad/sec) speed, 0.03(Nm/A) torque constant, and 25 (MW) rated power.

Table 2: Comparison of Simulation Parameters with Proposed and Existing Algorithm

Parameters	Spider based controller algorithm	Grass hopper optimizatio n algorithm	Flower pollination algorithm	Social-Ski Driver optimized algorithm [Proposed]
Resistance (Ω)	3	1.535	1.5	0.05
Inductance	15(mH)	3.285(mH)	6.1(mH)	$5e^{-3}$ (mH)
Rotor inertia	0.0024 (kgm^2)	0.00018 (kgm^2)	8.2614 $(e^{-5}kgm^2)$	$23.16^{*}10^{-4}$ (kgm^2)
Speed (rad/se)	420	390	380	430
Number of poles	5	4	6	3
Torque constant (Nm/A)	0.8	0.49	0.2148	0.03
Rated power	250(W)	380(W)	1500(W)	25MW

The speed of BLDC motor is controlled in our SSD optimized proposed work. Compared to other existing technology, the speed of this work is 422 rad/sec and the value of torque constant (Nm/A) is 0.03. High value of output power is produced in our proposed work. Also, the toque constant value is very low compared to other methods.

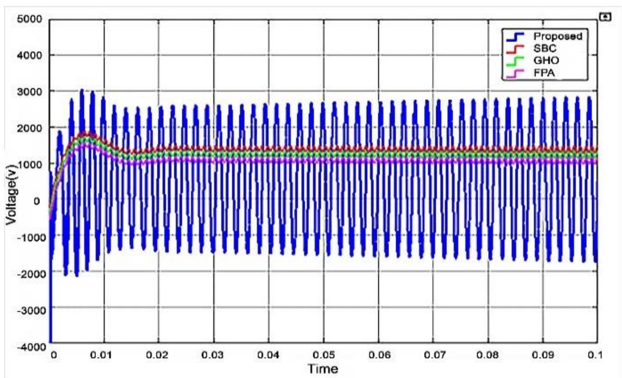

Figure 4: Comparison Analysis of Voltage

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Comparison analysis of voltage is shown in *Figure 4*. In the starting time the voltage is high range and then it decreases to a particular value. The proposed voltage value is in 2900v, then the values of existing methods such as SBC, GHO and FPA are 1200v, 1100v and 100v respectively.

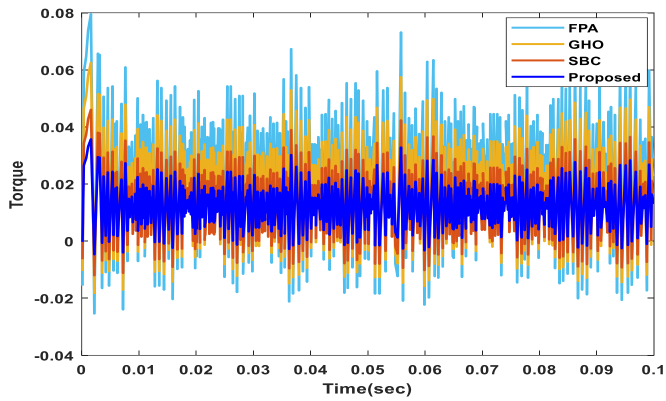

Figure 5: Comparison Analysis of Torque

Comparison analysis of torque is shown in *figure 5*. At the starting time of the motor reaches a maximum value of torque. In our proposed work we are mainly focused on torque ripple compensation. This compensation is useful for manufacturing low-cost BLDC motor. Low value of torque constant is attained from this proposed technique.

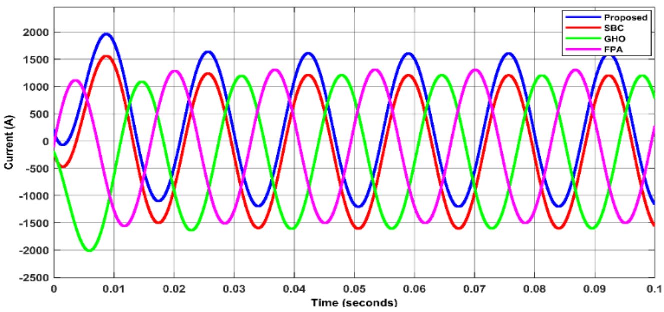

Figure 6: Comparison Analysis of Current

Figure 6 shows the comparison analysis of current. Compared to other existing technologies high variations are produced in our proposed work. The electric current in one phase is zero at a time and the back EMF goes through the phase the electromagnetic torque ripple is observed. Current is always directly proportional to torque.

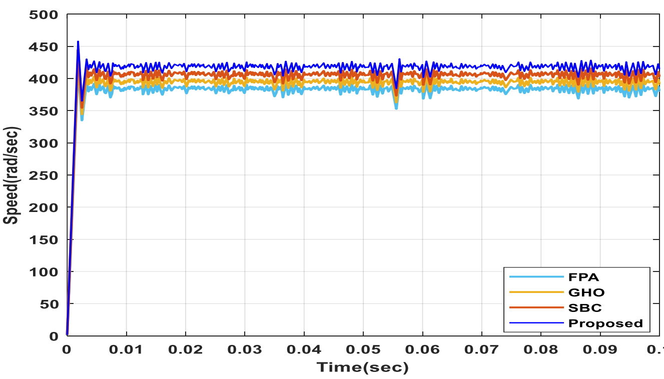

Figure 7: Speed Waveform of Proposed Work

The spider-based controller algorithm, grass hopper optimization algorithm, flower pollination, and SSD optimized controller methods showed the speed to be 420 rad/sec, 390 rad/sec, 380 rad/sec and 430 rad/sec respectively. The proposed speed waveform can be clearly seen from *Figure 7*. Here we can control the speed by using our proposed work.

5. CONCLUSION

Design exploration of SSD optimized speed controller for BLDC motor has been proposed. This work mainly focuses on torque ripple compensation with speed control at low cost. The use of a small DC-link capacitor instead of a bulkier capacitor helps to reduce ripples using Social Ski –driver (SSD) optimized controllers. The proposed work will be implemented in MATLAB Simulink platform and resultant performances like phase current, torque ripple, speed control capability will be taken. The power value of the proposed scheme is extremely high (25 MW), speed is low (422 rad/sec), low torque constant (0.03 Nm/A). Similarly, the results are compared with the various existing method and display the execution of the suggested process which is better than the existing method. However, some faults are occurred in the BLDC motor, thus will reduce the efficiency of the BLDC motor. So, in the future, we will develop a novel controller based algorithm to identify and detect the faults which present in BLDC motor.

Conflict of Interest

Authors declare that they have no conflict of interest.

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