Reduction of Cogging Torque by Adapting Bifurcated Stator Slots and Minimization of Harmonics and Torque Ripple in Brushless DC Motor

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ABSTRACT

This paper proposes an improved methodology to minimize the cogging torque, harmonics and torque ripples in Brushless DC (BLDC) motor. The cogging torque is reduced by designing the BLDC motor with bifurcated active surface area using Finite Element Analysis (FEA). The harmonics and torque ripple is minimized using PI and Fuzzy controllers. These controllers are analyzed to bring out an optimal solution. The effectiveness and flexibility of the individual techniques of proposed control method is verified through simulations [Matlab Simulink]. The experimental result is shown only for fuzzy control because fuzzy is better comparing the performance of PI controllers.

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1. INTRODUCTION

Brushless DC Motors (BLDCM) is widely used in automated industrial applications like Computer Numerical Control (CNC) machinery, aerospace applications and in the field of robotics. The main problem that occurs in Brushless DC Motors (BLDCM) is Cogging torque and Torque ripples. Cogging torque is caused due to the interaction between the permanent magnet and stator slot of the machine. The cogging torque is mitigated by bifurcated active surface area. Cogging torque can be determined analytically as well as by Finite element methods. The dynamics of this motor should be smooth for many industrial and automated applications and free from unwanted interference. But due to high speed switching circuits used in the commutation circuits, the BLDC motor current contains harmonics component and this causes high electromagnetic interference problems. Normally torque ripple in BLDC motor is caused by two factors viz. 1) motor design and 2) Power inverter supply. The proposed work is based on current control method which utilizes PI controller and fuzzy logic controller in sensored Brushless DC motor. The Hall Effect sensor is used here to detect the position of the rotor. Various techniques have been adopted to reduce cogging torque such as magnet pole design, skewing, and dummy slots [1] and [6]. The CAD of radial flux surface mounted magnets is easy to fabricate and was applied successfully [2]-[5]. Asymmetric magnets and shifting angles were applied experimentally to reduce harmonics of cogging torque [3].The different kind of methods carried out to minimize the cogging torque in BLDC motor is presented in previous research [7]. The harmonics and torque ripple was reduced with voltage control method using LC filter [8]. The torque ripple is minimized using pwm switching scheme presented in paper [9]-[11]. Torque ripple is minimized using neuro-fuzzy controller in [12]-[14]. This paper [15] describes a new approach to analyze the stator internal fault of a brushless dc motor. This paper presents an approach for minimizing torque ripple in

Brushless dc motor due to phase commutation using fuzzy control. It uses double closed loop with current hysteresis and speed fuzzy control.

2. COGGING TORQUE REDUCTION BY BIFURCATED ACTIVE SURFACE AREA

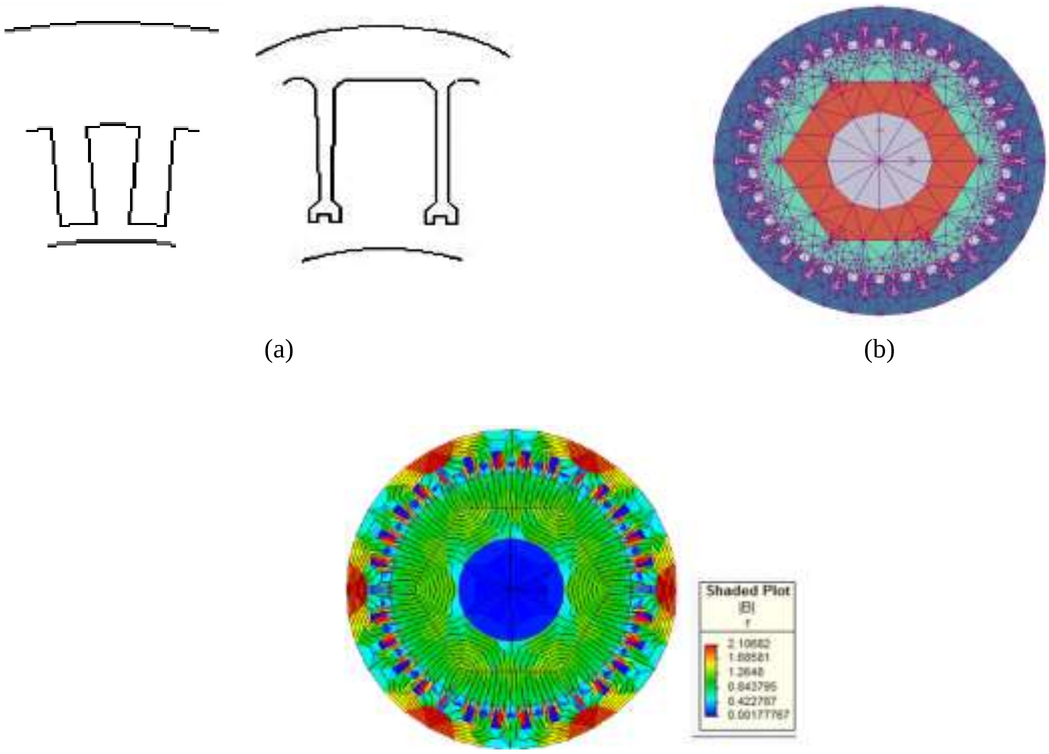
The cogging torque of a motor has been considered as the summation of the interactions of each edge of the rotor PMs with the stator slots [1]. Hence, the result of cogging torque can be reduced obviously to the study of these interactions. The cogging torque can be expressed as

$$\mathrm{Tcog} = \sum_{k=1}^{\infty} Tck \ \cos kQ\Theta \tag{1}$$

where $T_{ck}$is the amplitude of the k^{th} harmonic component of the cogging torque, Q is the number of slots and k is the order of cogging harmonics. The 30-slots, 6-poles BLDC motor with certain dimensions [18] is considered as the specified motor for which the cogging torque is determined analytically. But, for some special designs the cogging torque can be determined by FE method only. In the present work the cogging torque is determined analytically and by FEA for the specified motor. The tooth shape, mesh distribution and flux density distribution of the motor for the bifurcated active surface area is shown in Figure 1. The cogging torque for the specified machine is determined analytically using Matlab. The analytical expression for the cogging torque is given below [7].

$$T_c = -\frac{g' L_i}{\mu_0} \frac{D_{1in}}{2} A_T \frac{B_{mg}}{k_c} \sum_{k=1,2,3..}^{\infty} \varsigma_k \sin(k \frac{\pi}{t_1} c_t) \sin(\frac{2k\pi}{t_1} X) \tag{2}$$

The cogging torque for the specified motor [2] and [7] is determined analytically and by FEA analysis and both results are found to be very close to each other as shown in Figure 2. The FEA software tool MagNet 6.11 is used for simulation.The pre and post processing calculation has carried out by the three phase excitation by 120 degree square wave inverter.The cogging torque comparison of the existing and proposed method of stator slots are shown in Table 1.



(a) (b)

(c)

Figure 1. Bifurcated model of BLDC motor (a) design view of conventional and bifurcated stator slot, (b) mesh analysis and (c) flux density distribution- tangential

Table 1. Comparison of Cogging Torque

Type of slot	Cogging Torque Nm
Conventional stator slot	2.2
Bifurcated stator slot	0.43

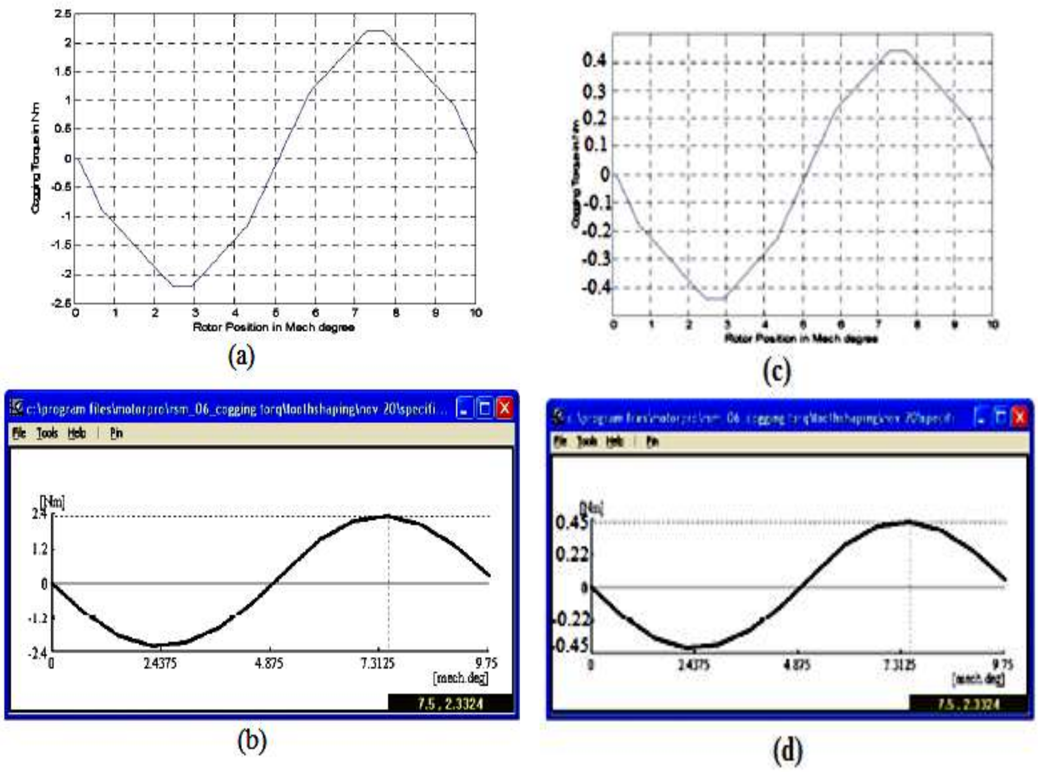


Figure 2. Cogging torque result for normal stator slot (a) analytical and (b) FEA analysis. Cogging torque result for bifurcated stator slot (c) Analytical and (d) FEA analysis

3. PROPOSED CONTROL SYSTEM

The overall block diagram of the planned system is shown in Figure 3 to minimize harmonics and torque ripple. The operation of the system is as follows: the armature current is sensed through current sensors and converted into voltage signals. These signals are then rectified and a dc component, with the value of the ceiling of the current I_{dc} is obtained as shown in Figure 4. This dc signal is compared with desired reference signal I_{ref}, and from this comparison the error signal I_{err} is obtained. This error signal is passed through a controller (PI or fuzzy) to generate the PWM pulses as shown in Figure 4 for all the switches of the three phase inverter, which are sequentially activated by the shaft position sensor.

3.1. PI Controller

The proportional–integral (PI) controller employed, contains a feedback signal derived from the armature current. The current controller block along with PI controller is shown in Figure 4. The gain of the PI controller will be initialized using a well known conventional method, but the gain depends on the BLDC motor estimated model at rated operating conditions. The output of this PI controller comprises the modulation index MI, and depending on its value, the gate-firing angles for the inverter switch (1-6) is decided.

3.2. Fuzzy Controller

Fuzzy logic control has been found to be excellent in dealing with imprecise and non-linear system. Fuzzy logic control is easy to implement and it does not need any mathematical model of the control system. This is achieved by converting the linguistic control strategy of human experience and knowledge into an automatic control strategy. Initially a Fuzzy logic controller is developed using Matlab Fuzzy logic toolbox and then inserted in Simulink model. The current controller block with fuzzy controller is shown in Figure 5. Here the input and output for the fuzzy logic control system are error (e), change in error (ce) and current value. For these input and output values seven membership functions are created. The most important parameters of Fuzzy logic are scaling factors. The input scaling factors affect the FLC sensitivity while the output scaling factors affect the system stability. The rules are written in fuzzy editor block in matlab tool using the following rule base Table 2.

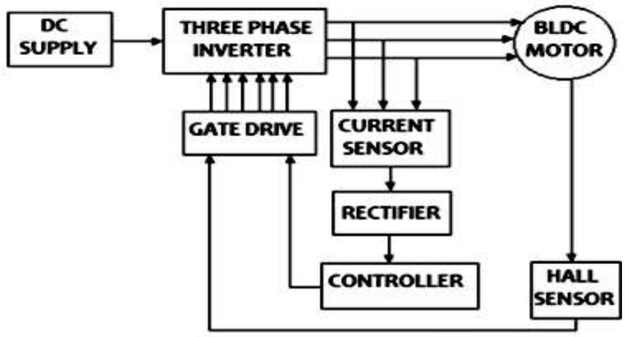


Figure 3. Basic block diagram

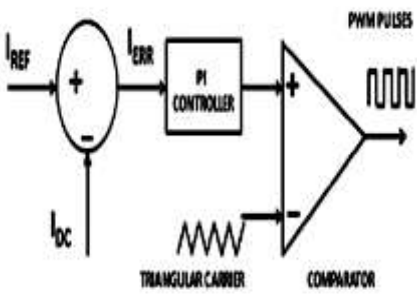


Figure 4. Current controller block with PI controller

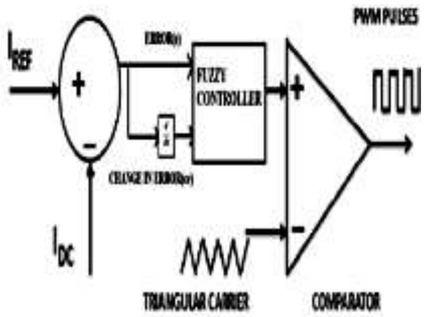


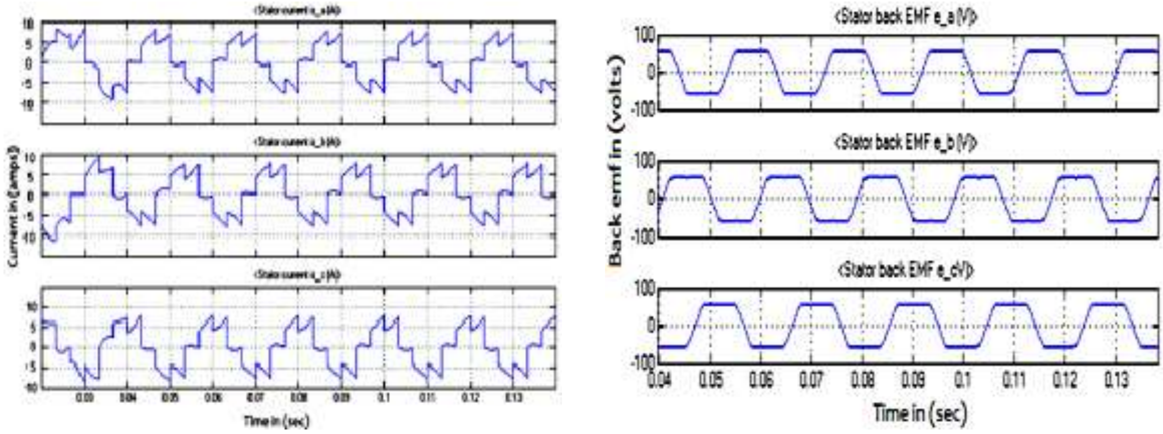
Figure 5. Current controller block with fuzzy controller

Table 2. Fuzzy Rule Base

CE\E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

4. SIMULATION RESULTS

The phase current waveform and back emf waveform with PI controller is shown in Figure 6. The phase current for PI controller is 10A for speed of 4000 rpm and the torque ripple output is shown in Figure 7. The Toque ripple waveform for the BLDC motor with PI controller is shown in Figure 8. The phase current waveform and back emf waveform with Fuzzy controller is shown in Figure 8. It has been found that the outputs of the BLDC motor with Fuzzy controller are excellent when compared with PI controller outputs. The phase current for PI controller is 7A for speed of 4000 rpm. The Toque ripple waveform for the BLDC motor with Fuzzy controller is shown Figure 9.



(a) (b)

Figure 6. (a) Phase current and (b) Stator back EMF of BLDC motor with PI controller.

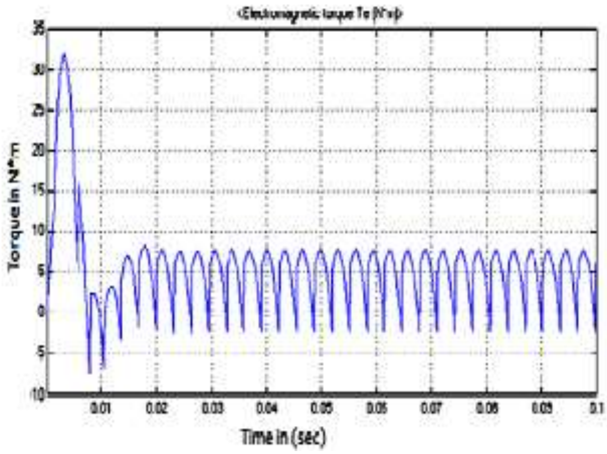
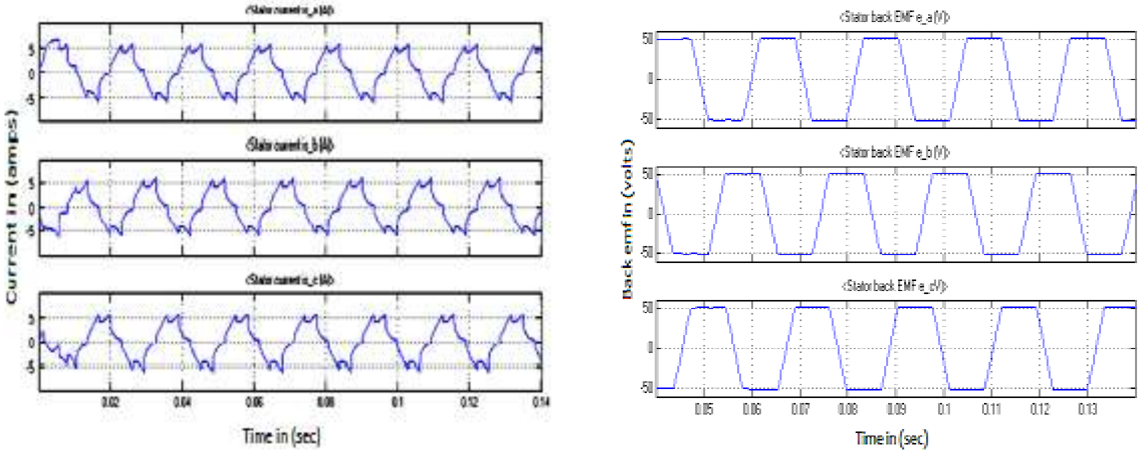


Figure 7. Torque ripple waveform of BLDC motor with PI controller



(a) (b)

Figure 8. (a) Phase current and (b) Stator back EMF of BLDC with Fuzzy controller

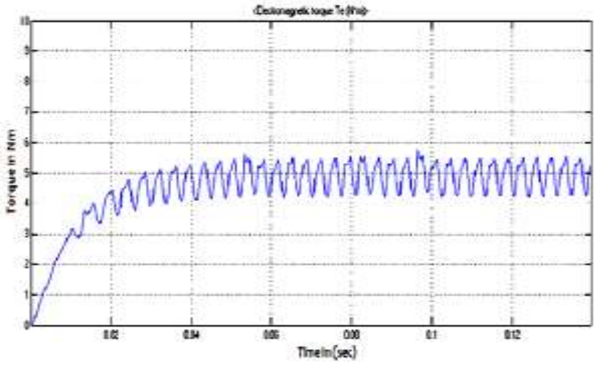
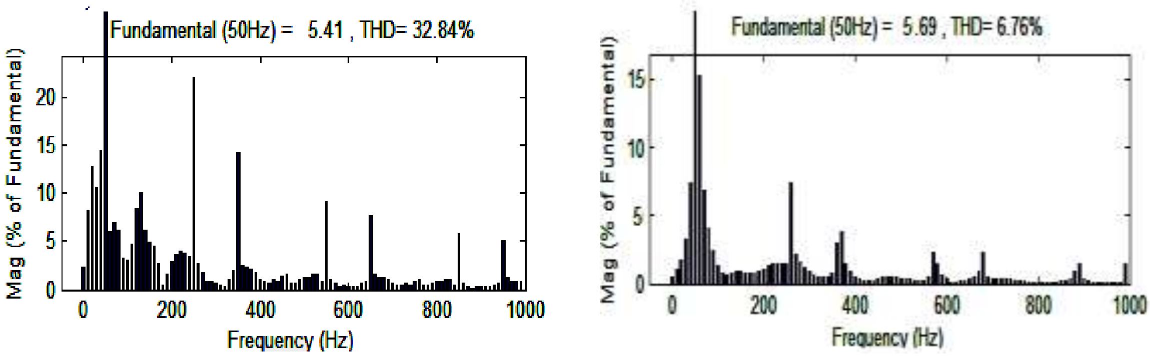


Figure 9. Torque ripple waveform of BLDC motor with Fuzzy controller

4.1. THD and Torque Ripple Calculation

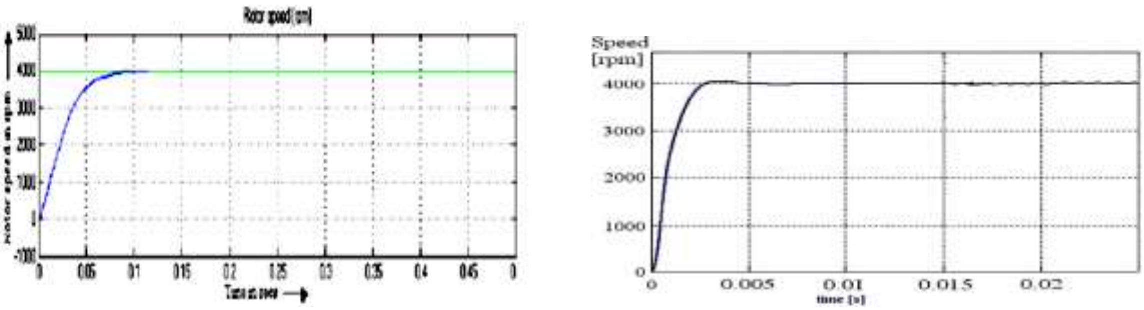
Torque ripple is defined as periodic increase and decrease in output torque. The formula for finding the torque ripple is the percentage of the difference between the maximum torque and the minimum torque compared to the average torque. The Figures10 (a) and (b) shows the FFT analysis of the Phase current with PI controller and fuzzy controller. Reduction in THD results in the smoothness in armature current, which improves the commutation effect of the BLDC motor. The performance comparison of PI and fuzzy controller is shown in Table 3.



(a) (b)

Figure 10. THD waveform for phase current for (a) PI controller and (b) Fuzzy controller

Figure 11 shows the speed response of the PI and fuzzy controller. The speed response for PI controller is not settling and in fuzzy controller the speed range is up to 4000 rpm.



(a) (b)

Figure 11. Speed response of BLDC motor using (a) PI controller and (b) Fuzzy controller

4.2. Experimental Results

The experimental result is shown only for fuzzy control because fuzzy is better comparing the simulation results of PI controllers. Fuzzy logic is developed in TMS320C6713 to control the Brushless DC motor. The motor capacity is 1HP. The position of the BLDC motor is detected by the Hall Effect sensor. The operation of motor is very quiet and smooth, both simulation and experimental set-up have provided a good dynamic performance of the fuzzy logic controller system. The speed of the BLDC motor is detected by Hall-sensor IC's accurately instead of the usual, expensive and complicated encoder system. Figure 12 shows the experimental result for phase current Waveforms of the BLDC motor via a digital oscilloscope with synchronization of spectrum analyzer, when the rotor speed is 4000 rpm. The phase difference between Ia, Ib and Ic is approximately 120 degree and the value of the current magnitude for Ia, Ia and Ic is about 7A. The experimental speed response of BLDC motor at 4000rpm is shown in Figure 13. These results of phase current and speed justify that the experimental and simulation result are very close to each other. Hence it is proven that the torque ripple and harmonics also get minimized the current is getting controlled.

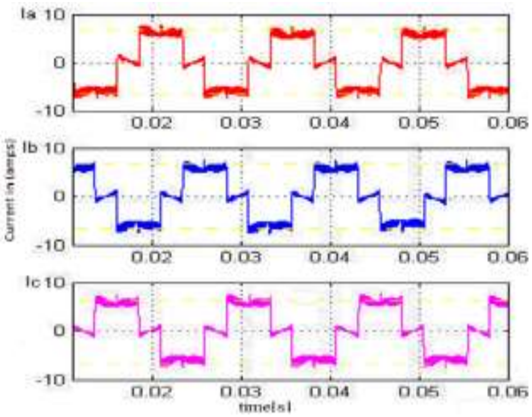


Figure 12. Phase current waveform based on speed at 4000 rpm

Table 3. Performance comparison of Controller

Type of Controller	Percentage Amount of Torque ripple reduced
PI	83.3%
Fuzzy	29.7%

Figure 13. Experimental Speed Response of BLDC motor running at 4000 rpm

5. CONCLUSION

This paper has proposed minimization of cogging torque using Bifurcated model, the harmonics and torque ripples that have been reduced using different type of controllers with the current controlled method. The armature current, back-emf and cogging torque are discussed. The harmonics content of the phase current for a BLDC motor is analyzed and the amount of torque ripples and the THD is also calculated. The result paired with Matlab/simulink is a good simulation tool for modeling and analyzing PI and fuzzy logic controlled brushless DC motor drives. Besides, the results of fuzzy controller are very good agreement compare to PI controller. From the comparison of both results it is evident that the harmonics components at the switching frequency, multiples of switching frequency and also the torque ripples are greatly reduced in fuzzy controller. The experimental results are very closely matching with the simulated results in Fuzzy controller.

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