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SPEED CONTROL OF BRUSHLESS DC MOTOR BY USING FUZZY LOGIC PI CONTROLLER

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ABSTRACT

This paper presents the fuzzy, PI controller for speed control of BLDC motor. The controller uses three fuzzy logic controllers and three PI controllers. The output of the PI controllers is summed and is given as the input to the current controller. The current controller uses P controller. The mathematical modeling of BLDC motor is also presented. The BLDC motor is fed from the inverter where the rotor position and current controller is the input. The fuzzy logic control is learned continuously and gradually becomes the main effective control. The Simulink software was used to simulate the proposed scheme. The results are obtained for variable load torque.

Keywords: brushless DC motors, speed control, PI controllers, P controllers, fuzzy logic controller.

1. INTRODUCTION

Since 1980's new design concept of permanent magnet brushless motors has been developed. The Permanent magnet brushless motors are categorized into two types based upon the back EMF waveform, brushless AC (BLAC) and brushless DC (BLDC) motors [1]. BLDC motor has trapezoidal back EMF and quasi-rectangular current waveform. BLDC motors are rapidly becoming popular in industries such as Appliances, HVAC industry, medical, electric traction, automotive, aircrafts, military equipment, hard disk drive, industrial automation equipment and instrumentation because of their high efficiency, high power factor, silent operation, compact, reliability and low maintenance [2].

To replace the function of commutators and brushes, the BLDC motor requires an inverter and a position sensor that detects rotor position for proper commutation of current. The rotation of the BLDC motor is based on the feedback of rotor position which is obtained from the hall sensors. BLDC motor usually uses three hall sensors for determining the commutation sequence. In BLDC motor the power losses are in the stator where heat can be easily transferred through the frame or cooling systems are used in large machines. BLDC motors have many advantages over DC motors and induction motors. Some of the advantages are better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation; higher speed ranges [3].

Up to now, over 80% of the controllers are PI (Proportional and integral) controllers because they are facile and easy to understand [4]. The speed controllers are the conventional PI controllers and current controllers are the P controllers to achieve high performance drive. Fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI or controllers and have better noise rejection capabilities.

In this paper, fuzzy logic controller (FLC) is used for the control of the speed of the BLDC motor. We propose the fuzzy logic PI controller based BLDC motor drive. It is not only easy to understand but also more robust. We use three fuzzy logic PI controllers at the same time. The speed of the BLDC motor is given as the input to the fuzzy logic PI controller. The paper is organized as follows: Section 2 explains about construction and operating principle of BLDC motor, Section 3 elaborates the modeling of BLDC motor, Section 4 presents the speed and current controller, Section 5 introduces the fuzzy logic PI controller. The simulation results are presented in detail in Section 6 and Section 7 concludes the paper.

2. CONSTRUCTION AND OPERATING PRINCIPLE

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the "slip" that is normally seen in induction motors. BLDC motor is constructed with a permanent magnet rotor and wire wound stator poles.

Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as shown in Figure-1. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles.

VOL. 6, NO. 9, SEPTEMBER 2011 ISSN 1819-6608
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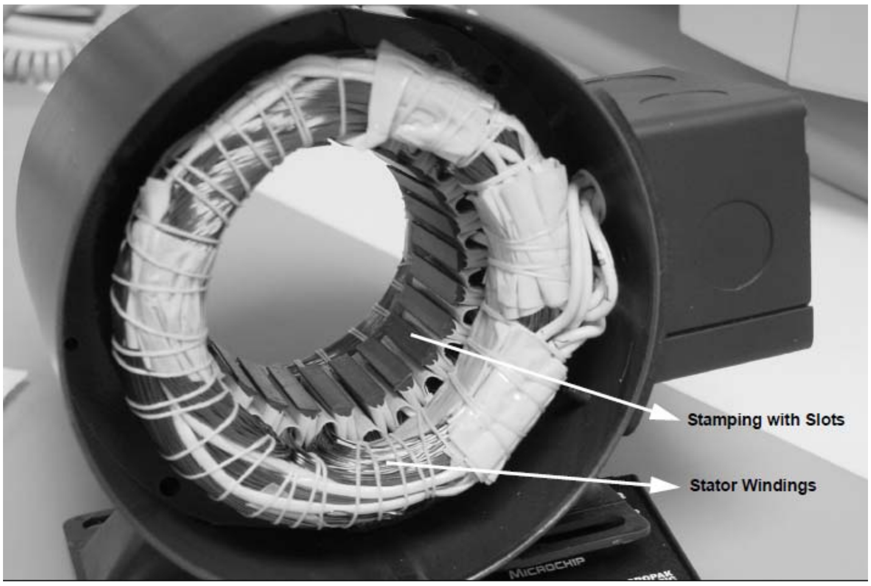

Figure-1. Stator of a BLDC motor.

Rotor

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are used to make permanent magnets. Now a day, rare earth alloy magnets are gaining popularity.

Hall sensors

The commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall Effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor as shown in Figure. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

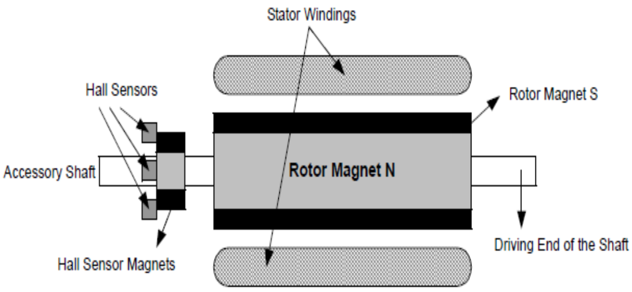

Figure-2. Rotor and hall sensors of BLDC motor.

Theory of operation

Each commutation sequence has one of the windings energized to positive power the second winding is negative and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field [3].

Commutation sequence

Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. It takes six steps to complete an electrical cycle. In Synchronous, with every 60 electrical degrees, the phase current switching should be updated. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical cycle is completed. So, the number of electrical cycles/rotations equals the rotor pole pairs. A 3-phase bridge inverter is used to control the BLDC motor. There are six switches and these switches should be switched based on the Hall sensor inputs. The Pulse width modulation techniques are used to switch ON or OFF the switches. To vary the speed, these signals should be Pulse Width Modulated (PWM) at a much higher frequency than the motor frequency. The PWM frequency should be at least 10 times that of the maximum frequency of the motor. When the duty cycle of PWM is varied within the sequences, the average voltage supplied to the stator reduces, thus reducing the speed. Another advantage of having PWM is that, if the DC bus voltage is much higher than the motor rated voltage, the motor can be controlled by limiting the percentage of

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PWM duty cycle corresponding to that of the motor rated voltage. This adds flexibility to the controller to hook up motors with different rated voltages and match the average voltage output by the controller, to the motor rated voltage, by controlling the PWM duty cycle. The speed and torque of the motor depend on the strength of the magnetic field generated by the energized windings of the motor, which depend on the current through them. Therefore adjusting the rotor voltage (and current) will change the motor speed.

Hall Sensor code	Phase #	Active drive	
101	1	Q1 (PWM1)	Q6 (PWM6)
100	2	Q1 (PWM1)	Q5 (PWM5)
110	3	Q3 (PWM3)	Q5 (PWM5)
010	4	Q3 (PWM3)	Q4 (PWM4)
011	5	Q2 (PWM2)	Q4 (PWM4)
001	6	Q2 (PWM2)	Q6 (PWM6)

Figure-3. Commutation sequence.

3. MODELLING OF BLDC MOTOR

The flux distribution in BLDC motor is trapezoidal and therefore the d-q rotor reference frames model is not applicable. Given the non-sinusoidal flux distribution, it is prudent to derive a model of the PMBDCM in phase variables. The derivation of this model is based on the assumptions that the induced currents in the rotor due to stator harmonic fields are neglected and iron and stray losses are also neglected. The motor is considered to have three phases even though for any number of phases the derivation procedure is valid. Modeling of the BLDC motor is done using classical modeling equations and hence the motor model is highly flexible. These equations are described based on the dynamic equivalent circuit of BLDC motor.

For modeling and simulation purpose assumptions made are the common star connection of stator windings, three phase balanced system and uniform air gap. The mutual inductance between the stator phase windings are negligible when compared to the self inductance and so neglected in designing the model [5]. Modeling equations involves,

Dynamic model equation of motion of the motor,

$$W_m = (T_e - T_l) / Js + B \quad (1)$$

T_e = electromagnetic torque, T_l = load torque,
J = moment of inertia, B = friction constant
Rotor displacement can be found out as,

$$\Theta_r = (P/2)\, W_m / s \quad (2)$$

P = Number of poles
Back EMF will be of the form,

$$E_{as} = k_b\, f_{as}(\Theta_r)\, W_m \quad (3)$$

$$E_{bs} = k_b\, f_{bs}(\Theta_r)\, W_m \quad (4)$$

$$E_{cs} = k_b\, f_{cs}(\Theta_r)\, W_m \quad (5)$$

K_b = back EMF constant
Stator phase currents are estimated as,

$$i_a = (V_{as} - E_{as}) / (R+Ls) \quad (6)$$

$$i_b = (V_{bs} - E_{bs}) / (R+Ls) \quad (7)$$

$$i_c = (V_{cs} - E_{cs}) / (R+Ls) \quad (8)$$

R = resistance per phase, L = inductance per phase
Electromagnetic torque developed,

$$T_e = (E_{as}\, i_{as} + E_{bs}\, i_{bs} + E_{cs}\, i_{cs}) / W_m \quad (9)$$

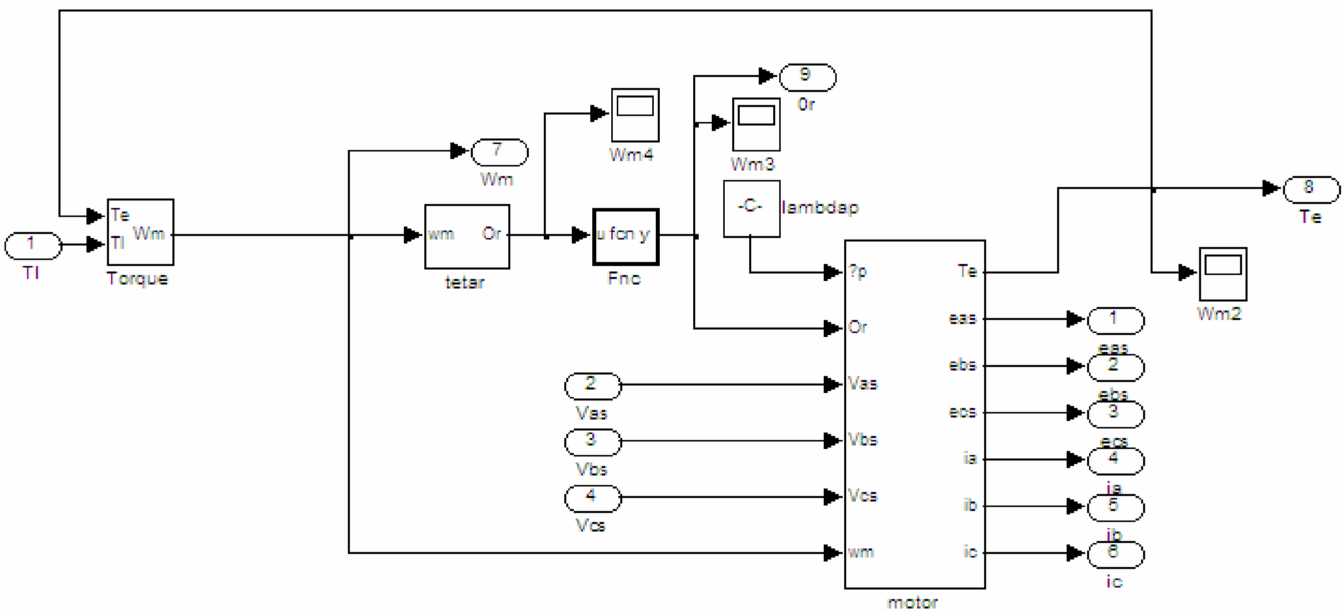

Figure-4. BLDC motor Simulink model.

VOL. 6, NO. 9, SEPTEMBER 2011 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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4. CONTROLLERS

Speed controller

The speed of the motor is taken and compared with the reference speed using summer. The resulting error is estimated as,

$w_e = w_r - w_r^*$

The resulting error is given to the PI controller. The transfer function of the PI controller has the following form [6].

$G_s(s) = K_p\,(1+1/T_i s)$ (10)

where $T_i = K_p/K_i$ known as the integral time constants.

K_p and K_i are the proportional and integral gains, respectively.

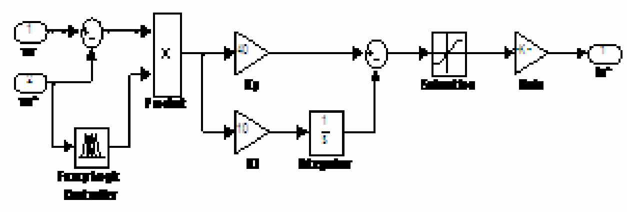

Figure-5. Speed controller sub block.

Current controller

The output of the speed controller is reference torque and the reference current is derived from the torque. The 3-phase reference currents can be obtained from,

$i_a = I_p * f_a(\Theta_r)$ (11)

$i_b = I_p * f_b(\Theta_r)$ (12)

$i_c = I_p * f_c(\Theta_r)$ (13)

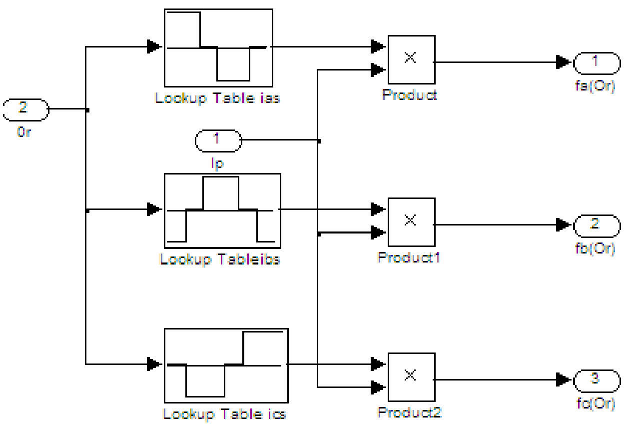

Figure-6. Current loop.

The reference currents are compared with the actual stator currents and the resulting error is is given as the input to the P controller. The transfer function of the P controller has the following form,

$G_c(s) = K_p$ (14)

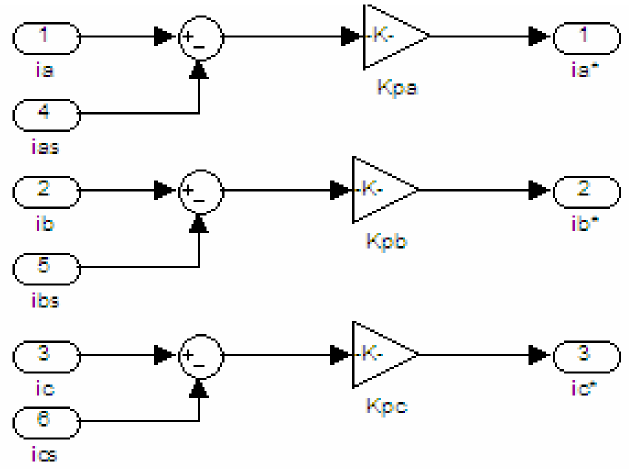

Figure-6. Current controller sub block.

5. FUZZY LOGIC PI CONTROLLER FOR BLDC MOTOR

In the past decade, fuzzy logic techniques have gained much interest in the application of control system. They have a real time basis as a human type operator, which makes decision on its own basis. We present the controller which includes three dual inputs but single rule for the fuzzy logic and three PI controllers in different sampling time, as shown below [4].

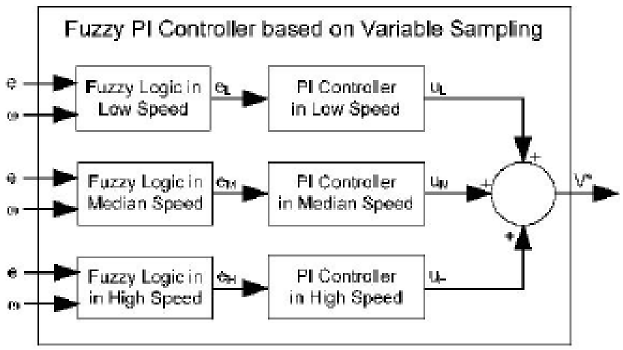

Figure-7. Fuzzy logic PI controller.

The fuzzifying, control rule and defuzzification are based on the rotor speed. The major work of the fuzzy logic is scaling speed error for PI controller.

Fuzzifying

The three fuzzy logic are based on rotor speed, and the speed is defined on the universe of discourse 0 to 3000 rpm. The input membership functions of the fuzzy sets are trapezoidal and triangular exception.

$$y_L(\omega) = \begin{cases} 1, & \text{for} \quad \omega < 500 \\ \dfrac{1500-\omega}{1000}, & \text{for} \quad 500 \le \omega \le 1500 \\ 0, & \text{for} \quad \omega > 1500 \end{cases} \qquad (15)$$

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$$y_M(\omega)=\begin{cases}0, & \text{for} \quad \omega<500\\ \dfrac{\omega-500}{1000} & \text{for} \quad 500\le\omega\le1500\\ \dfrac{2500-\omega}{1000} & \text{for} \quad 1500\le\omega\le2500\\ 0, & \text{for} \quad \omega>25000\end{cases} \tag{16}$$

$$y_H(\omega)=\begin{cases}0, & \text{for} \quad \omega<1500\\ \dfrac{\omega-1500}{1000}, & \text{for} \quad 1500\le\omega\le2500\\ 1, & \text{for} \quad \omega>2500\end{cases} \tag{17}$$

y_L, y_M and y_H are the membership degree of the fuzzy logic in low speed, in median speed and in high speed. Ω is the rotor speed.

Fuzzy control rule

The if-then rules of the fuzzy logic can be expressed as the following:

R_L: If ω is LS, then e_L is e (18)

R_M: If ω is MS, then e_M is e (19)

R_H: If ω is HS, then e_H is e (20)

R_L, R_M, and R_H are the control rules in different speed. e_L, e_M, and e_H are the outputs of fuzzy logic. Ω is the speed error.

Defuzzification

To calculate the output, a multiplication is used for defuzzification.

$e_L = e.\ y_L$ (21)

$e_M = e.\ y_M$ (22)

$e_H = e.\ y_H$ (23)

From the scaled speed error (e_L, e_M and e_H), the three PI controllers can calculate three voltage commands. Each of the fuzzy logic scale speed error is given as the input to the PI controller.

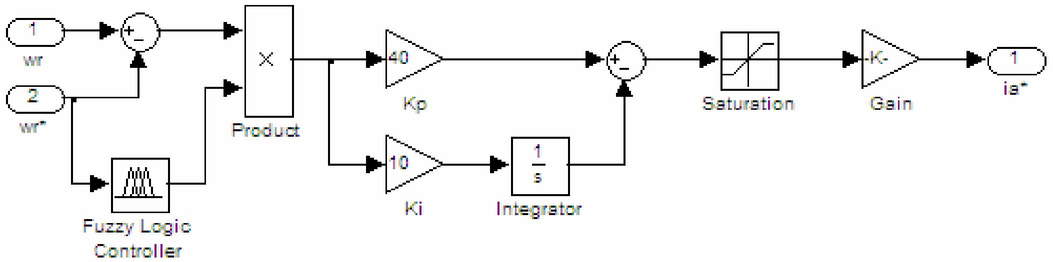

Figure-8. Fuzzy logic PI controller.

The three outputs of the PI controller are summed and given to the current controller.

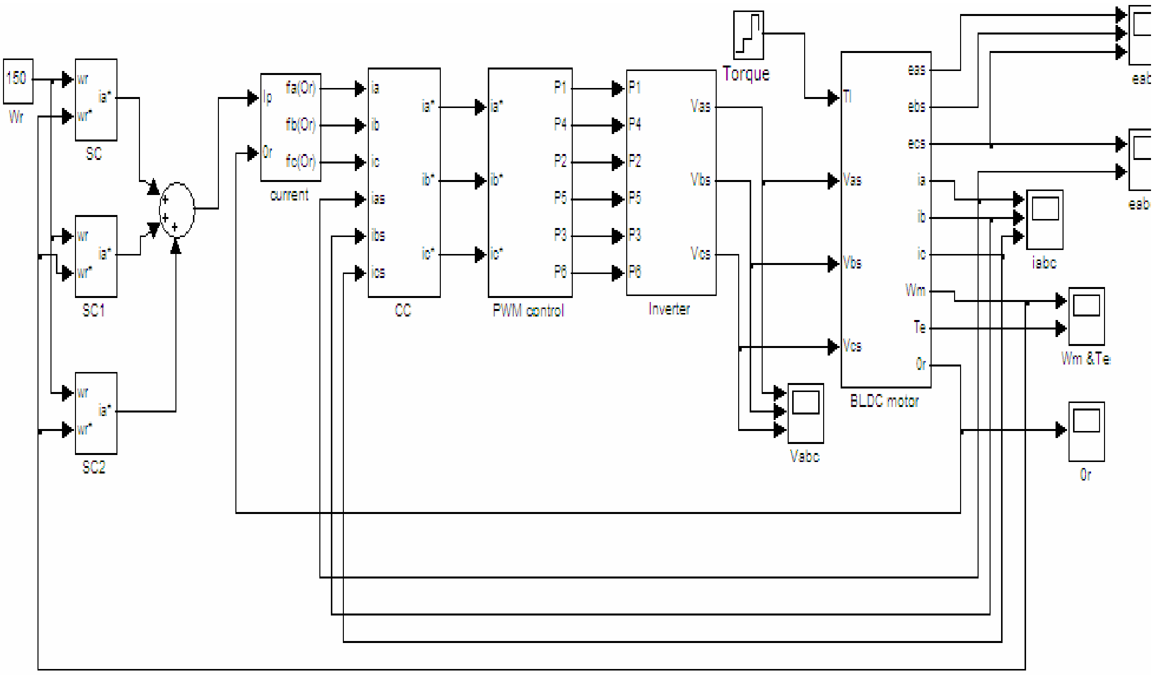

Figure-9. Simulated block diagram of fuzzy logic.

VOL. 6, NO. 9, SEPTEMBER 2011 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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6. SIMULATION RESULTS

The simulation results includes variation of different parameters of BLDC motor like total output electrical torque, rotor speed, rotor angle, three phase stator currents, three phase back EMF's with respect to time. Figures 10, 11 and 12 shows the simulated Back EMFs waveforms, Figures 13, 14 and 15 shows the simulated stator currents waveforms, Figure-16 shows the rotor speed, Figure-17 shows the electromagnetic torque and Figure-18 shows the rotor position. Trapezoidal back EMFs waveforms are obtained because of the implementation of the proposed commutation scheme. From the Figure-18 it is observed that the ripples are reduced in the developed electrical torque as load torque increases. The rotor position varies from 0 to 6.28 radians corresponding to 0˚ to 360˚. The rotor speed is kept constant with the variable load torque. The waveforms shown here is wit respect to variable load torque. The rotor ratings are as below,

Table-I. Motor ratings.

Specifications	Units
No. of poles	4
Moment of inertia, J	0.00022 Kg-m^2
Flux density, B	0
Stator resistance, R	0.7
Stator inductance, L	5.21mH
Terminal voltage, V	160
Motor constant	0.10476

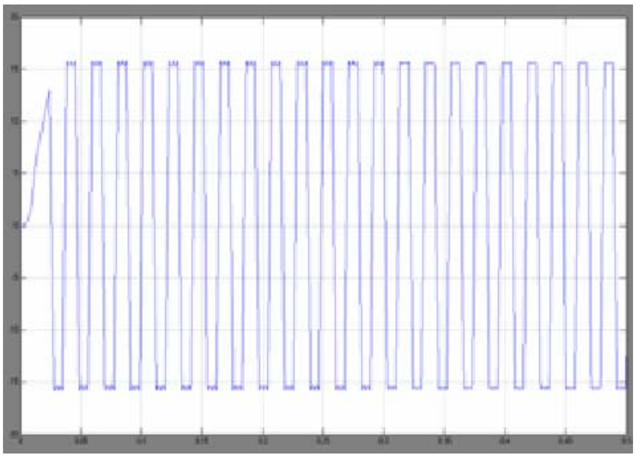

Figure-10. A phase back EMF with variable load torque.

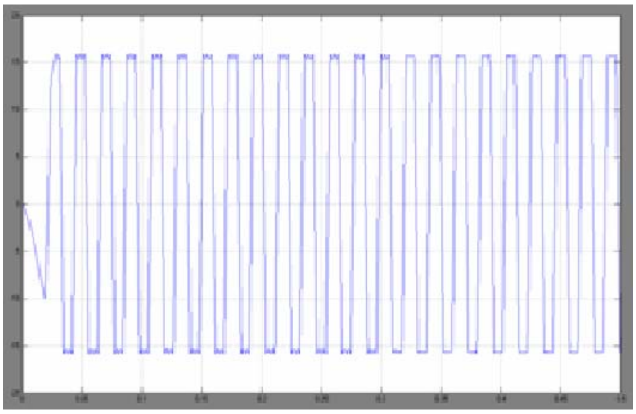

Figure-11. B phase back EMF with variable load torque.

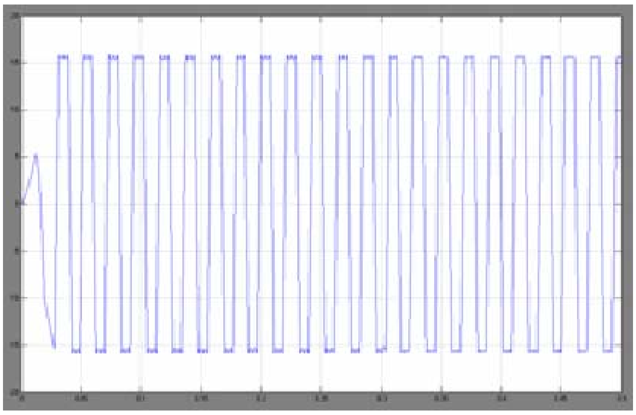

Figure-12. C phase back EMF with variable load torque.

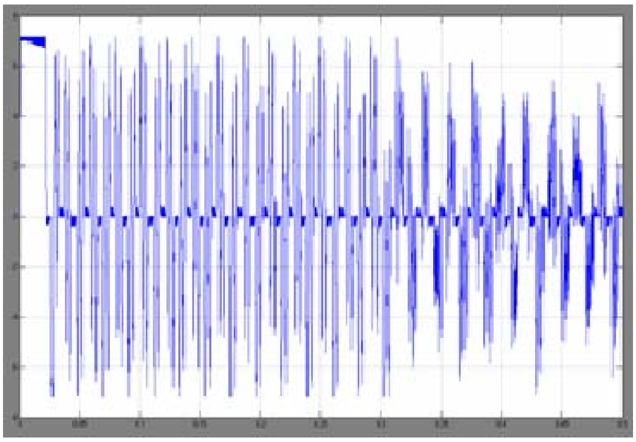

Figure-13. A phase stator current with variable load torque.

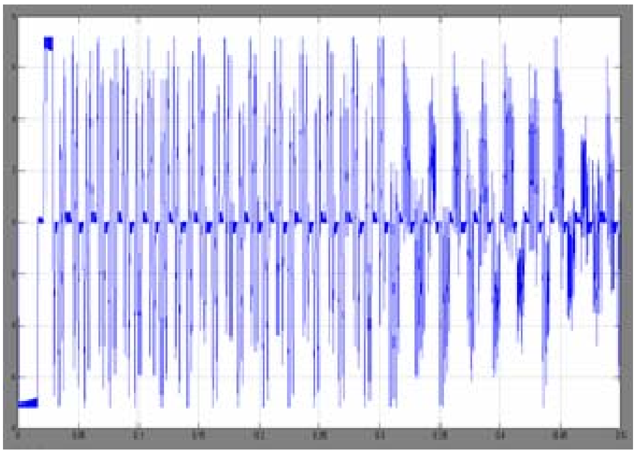

Figure-14. B phase stator current with variable load torque.

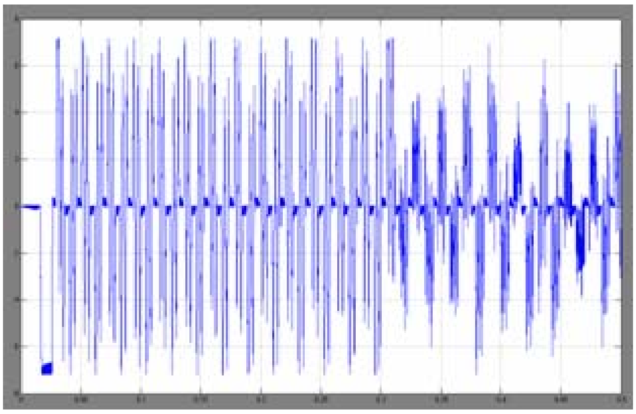

Figure-15. C phase stator current with variable load torque.

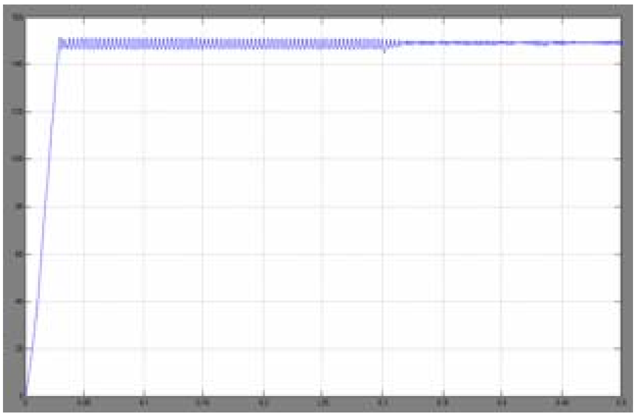

Figure-16. Rotor speed with variable load torque

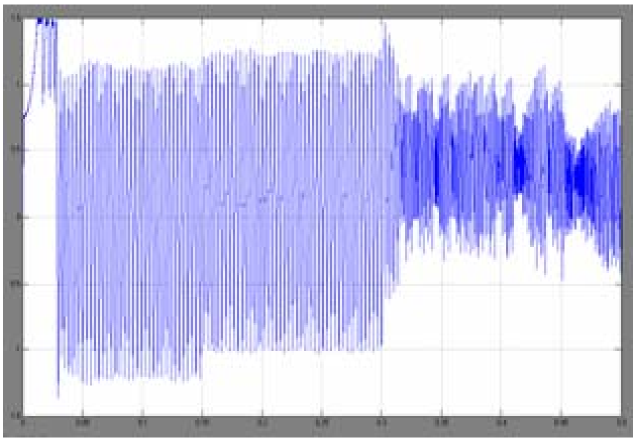

Figure-17. Electromagnetic Torque with variable load torque

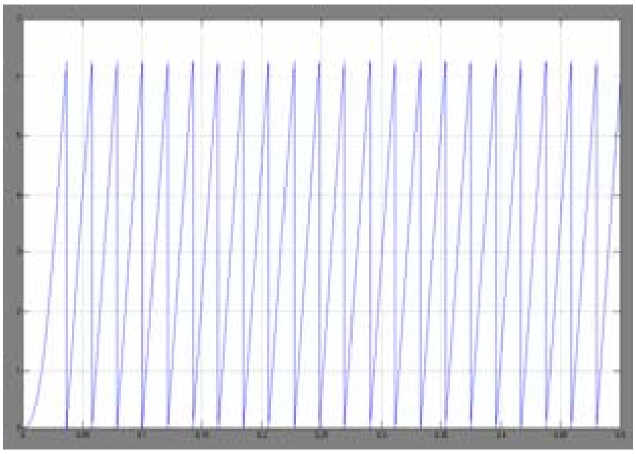

Figure-18. Rotor position.

7. CONCLUSIONS

In this paper, fuzzy logic PI controller for speed control of BLDC motor is proposed. In this paper, it uses three fuzzy logics to scale speed error for the three PI controllers. The simulation results demonstrate the fuzzy logic control at different load torque. As the load torque varies the speed of the BLDC motor remains constant. The mathematical modeling of BLDC motor is done and the speed control of the BLDC motor by using fuzzy logic speed controller and current controller is proposed. The results have been presented and analyzed for various load conditions.

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