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Brushless DC Motor Speed Control Scheme Operated by Fuzzy Logic Controller

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Abstract:

The article presents a fuzzy PI controller for controlling the rotational speed of a BLDC motor. The controller uses three fuzzy logic controllers and three PI controllers. The output of the PI controllers is summed up and fed as the input to the current controller. The current controller uses a P controller. Mathematical modeling of the BLDC motor is also presented. The BLDC motor is powered by an inverter where the inputs are the rotor position and the current regulator. The fuzzy logic control is continuously trained and gradually becomes the main effective control. The Simulink software was used to simulate the proposed scheme. The results were obtained for a variable load moment.

Keywords —: **BLDC Motors, Speed Control, PI Controllers, P controllers, fuzzy logic controller.**

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I. INTRODUCTION

Since the 1980s, a new design concept for permanent magnet brushless motors has been developed. Permanent magnet brushless motors are divided into two types based on the EMF back wave waveform, brushless AC (BLAC) and brushless DC (BLDC) motors [1]. The BLDC motor has a trapezoidal back EMF and a quasi-rectangular current waveform. BLDC motors are rapidly becoming popular in industries such as home appliances, HVAC industry, medical, electric traction, automotive, aircraft, military equipment, hard drive, industrial automation equipment and instrumentation due to their high efficiency, high power factor, quiet operation, compactness , reliability and low maintenance costs [2]. To replace the function of commutators and brushes, a BLDC motor requires an inverter and a position sensor that senses the position of the rotor for proper current commutation. The rotation of the BLDC motor is based on rotor position feedback, which is obtained from Hall sensors. A BLDC motor typically uses three Hall sensors to determine the commutation sequence. In a BLDC motor, 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-to-torque characteristics, high response dynamics, high efficiency, long life, quiet operation; higher speed ranges [3]. To date, more than 80% of the controllers are PI (proportional and integral) controllers because they are simple and easy to understand [4]. Speed controllers are conventional PI controllers and the current controllers are P controllers to achieve high drive efficiency. Fuzzy logic can be considered as a mathematical theory that combines multi-valued logic, probability theory, and artificial intelligence to simulate a human approach to solving various problems by using approximate reasoning to relate different sets of data and make decisions. It has been reported that fuzzy controllers are more resistant to changes in plant parameters than classical PI or controllers and have better noise rejection capabilities. In the article, a fuzzy logic controller (FLC) was used to control the speed of a BLDC motor. We propose a BLDC motor drive based on PI fuzzy logic. It is not only easy to understand, but also more reliable. We use three fuzzy logic PI controllers at the same time. The speed of the BLDC motor is given as input to the fuzzy logic PI controller. The article has the following structure: Chapter 2 explains the construction and principle of operation of the BLDC motor, Chapter 3 discusses the modeling of the BLDC motor, Chapter 4 presents the speed and current controller, Chapter 5 describes the PI controller with fuzzy logic. The simulation results are detailed in Chapter 6 and Chapter 7 summarizes the article.

II CONSTRUCTION AND OPERATIONAL DETAILS

BLDC motors are a type of synchronous motor. This means that the magnetic field generated by the stator and the magnetic field generated by the rotor rotate at the same frequency. BLDC motors do not experience the "slip" that usually occurs in induction motors. The BLDC motor consists of a permanent magnet rotor and wire stator poles. Stator The stator of a BLDC motor consists of stacked steel layers with windings placed in slots that are cut axially along the inner circumference as shown in Figure 1. Most BLDC motors have three stator windings connected in star. Each of these windings is made up of multiple coils connected together to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding..

BLDC Motor

The rotor is made of a permanent magnet and can have from two to eight pairs of poles with alternating north (N) and south (S) poles. On the basis of the required density of the magnetic field in the rotor, the appropriate magnetic material is selected to make the rotor. Ferrite magnets are used to make permanent magnets. Currently, rare earth magnets are gaining popularity.

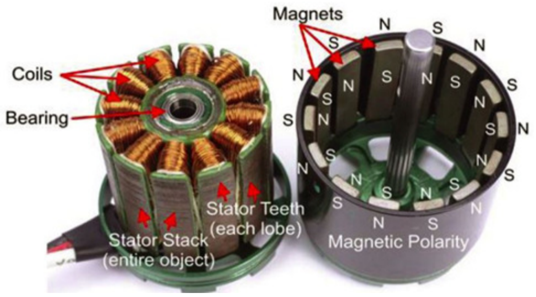

Fig. 1 Construction of the BLDC motor

Hall sensors

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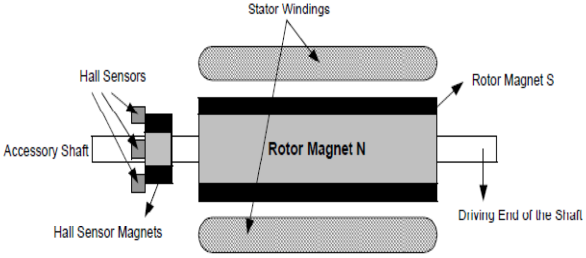


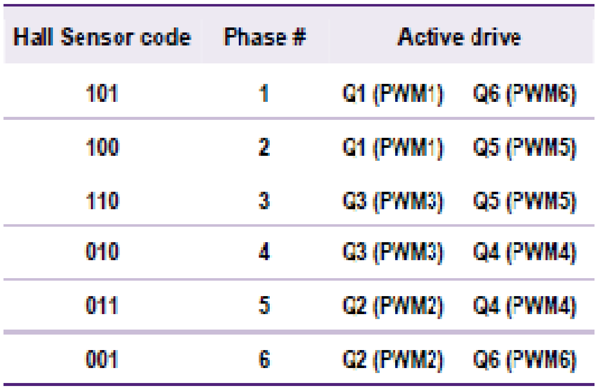
Fig 2 Hall Sensors

Operation Theory

Each commutation sequence has one of the windings energized with positive power, the second winding is negative, and the third is in a de-energized state. The torque is produced by the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, torque peaks when the two fields are at 90° to each other and decreases when the fields move together. For the motor to work, the magnetic field generated by the windings should change position as the rotor moves to catch up with the stator field [3].

Commutation sequence

Every 60 degrees of electrical rotation, one of the Hall sensors changes state. Six steps are required to complete an electrical cycle. In synchronous mode, 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 that must be repeated to complete a mechanical rotation is determined by the rotor pole pairs. One electric cycle is completed for each pair of rotor poles. So the number of electrical cycles/revolutions is equal to 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 toggled based on the hall sensor inputs. Pulse-width modulation techniques are used to turn switches on and off. To change 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 the maximum motor frequency. As the PWM duty cycle varies within the sequence, the average voltage supplied to the stator decreases, thus reducing the speed. Another advantage of PWM is that if the DC bus voltage is much higher than the motor's rated voltage, the motor can be controlled by limiting the percentage of PWM duty cycle that corresponds to the motor's rated voltage. This increases the flexibility of the controller in terms of connecting motors with different rated voltages and adjusting the average output voltage by the controllerrated motor 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 motor windings, which depend on the current flowing through them. Therefore, adjusting the rotor voltage (and current) will change the speed of the motor.



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)

Fig.3 Commutation Sequence

III. MODELLING OF BLDC MOTOR

The flux distribution in a BLDC motor is trapezoidal and therefore the d-q rotor reference frame model is not applicable. Given the non-sinusoidal flux distribution, it is reasonable to derive the PMBDCM model in phase variables. The derivation of this model is based on the assumption that the currents induced in the rotor due to stator harmonic fields are neglected, as well as iron and stray losses. The motor is considered to have three phases, although there is a derivation procedure for any number of phases. BLDC motor modelling is done using classical modelling equations, making the motor model very flexible. These equations are described based on the dynamic equivalent circuit of a BLDC motor.

For the purposes of modeling and simulation, a star connection of the stator windings, a three-phase balanced system and a uniform air gap were assumed. Mutual inductance between stator phasesthe windings are negligible compared to the self-inductance and therefore are neglected in the design of the model [5]. Equation modeling includes the equation of the dynamic model of motor motion,

$W_m = (T_e - T_l) / Js$ (1)

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

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

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

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

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

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

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

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

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

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

R = resistance per phase, L = inductance per phase

Electromagnetic torque developed,

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

IV. 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.

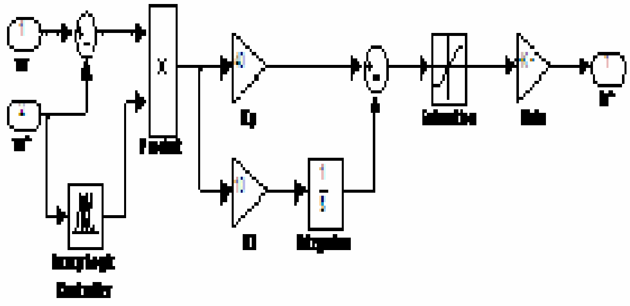


Fig. 4 Speed Controller Block

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)

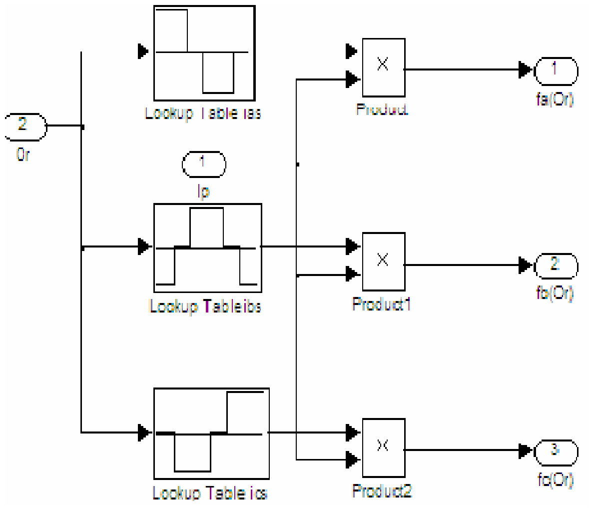


Fig. 5 Current Controller

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)

V. FUZZY LOGIC PI CONTROLLER FOR BLDC MOTOR

Fuzzy logic techniques have gained a lot of interest in the application of control systems in the last decade. They have a real-time basis as a human-type operator that makes decisions on its own basis. We present a controller that contains three dual inputs, but one fuzzy logic rule, and three PI controllers at different sampling times as shown below .

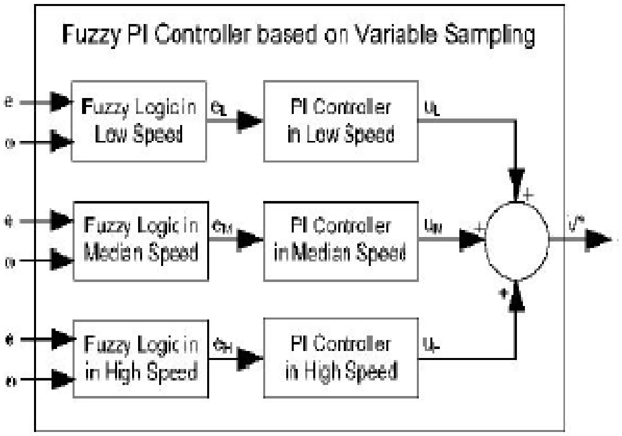


Fig. 6 Fuzzy Logic Controller

Fuzzification, control rule and defuzzification are based on rotor speed. The main task of fuzzy logic is to scale the speed error for the PI controller.

Fuzzifying

The three fuzzy logics are based on the rotational speed of the rotor, and the speed is defined in the universe of discourse from 0 to 3000 rpm. The input membership functions of fuzzy sets are trapezoidal and triangular exceptions.

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

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

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

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.

VI. SIMULATION RESULTS

The simulation results include variations of various parameters of the BLDC motor, such as total output electric torque, rotor speed, rotor angle, three-phase stator currents, three-phase reverse EMFs with respect to time. Figures 10, 11 and 12 show the waveforms of simulated reverse electromagnetic fields, Figures 13, 14 and 15 show the waveforms of simulated stator currents, Fig. 16 shows the rotor speed, Fig. 17 shows the electromagnetic moment and Fig. 18 shows the position of the rotor. Trapezoidal waveforms of the reverse electromagnetic field are obtained by implementing the proposed commutation scheme. Figure 18 shows that the ripple decreases in the developed electric torque as the load torque increases. The position of the rotor varies from 0 to 6.28 radians, which corresponds to 0° to 360°. The rotor speed is kept constant by varying the load torque. The waveforms shown here refer to a variable load torque. Motor ratings are as below,

Table –I

. 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

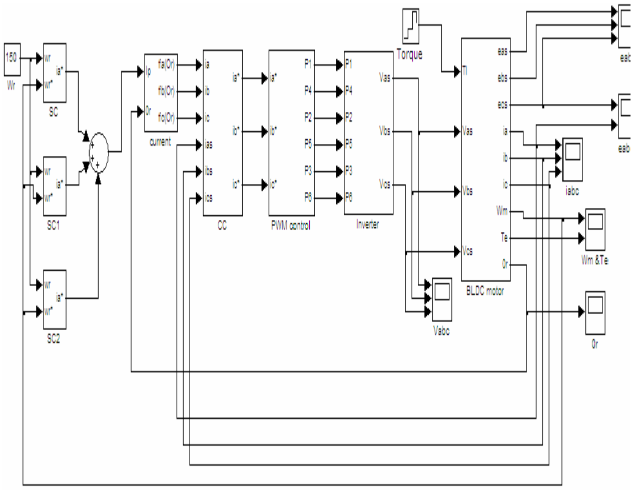


Fig. 7 Simulated block diagram of fuzzy logic.

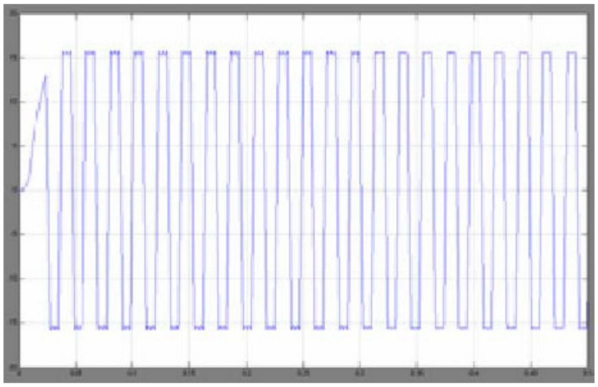


Fig. 8 Phase back EMF with variable load torque.

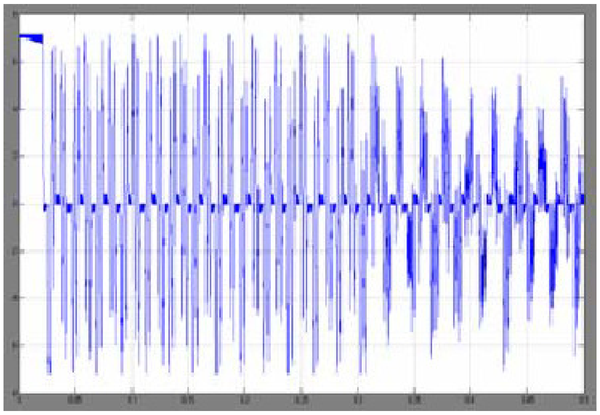


Fig. 9 Phase Current with variable load torque

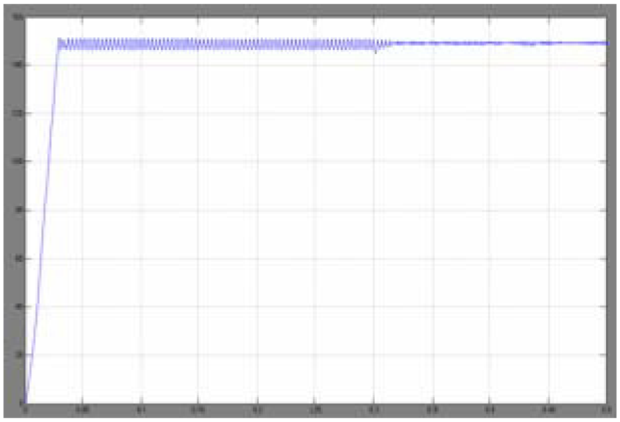


Fig.10 Rotor speed with variable load torque.

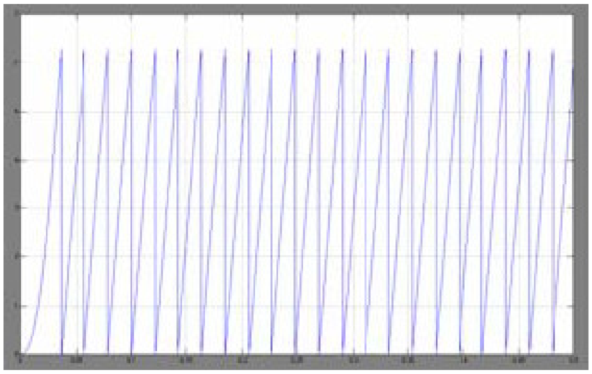


Fig. 11 Rotor position.

7. CONCLUSIONS

The article proposes a fuzzy logic PI controller to control the speed of a BLDC motor. This article uses three fuzzy logics to scale the speed error for three PI controllers. The simulation results demonstrate fuzzy logic control at different load times. When the load torque changes, the speed of the BLDC motor remains constant. Mathematical modelling of the BLDC motor was performed and it was proposed to control the speed of the BLDC motor using a speed controller with fuzzy logic and a current controller. The results were presented and analysed for various load conditions.

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