

A Comparative Study on Speed Control Techniques for PMBLDC Motor

D. Thiyaharajan^{1*}, N. Siddhara², P. Jeyashri³, T. Rajan⁴, T.V. Ramanujam⁵, S. Sakthi Vignesh⁶

¹Associate Professor, Department of Electrical and Electronics Engineering, Dr. Sivanthi Aditanar College of Engineering, Tiruchendur.

^{2, 3, 4, 5, 6}UG scholar, Department of Electrical and Electronics Engineering, Dr. Sivanthi Aditanar College of Engineering, Tiruchendur

siddharanarayanan@gmail.com , srisabari4444@gmail.com , helenrajaneee@gmail.com, ramarsr01@gmail.com, vicky00592@gmail.com

***Corresponding Author E-mail:** thiyaguavr@gmail.com

ABSTRACT: This paper describes a comparative study on speed control of Permanent Magnet Brushless DC Motor (PMBLDCM) using PI controller and Fuzzy Logic Controller (FLC). In industrial speed control applications, mostly conventional PI controller is preferred because of its simplicity and ease in installation. The conventional PI controller requires precise tuning and finds difficult to handle the non-linearity characteristics of PMBLDCM. It provides poor performance as it does not yield the better transient and the steady state responses under the operating conditions. To study the performance of a simple fuzzy logic controller versus PI controller, a Mamdani Fuzzy speed controller was built using 25 fuzzy rules. A good improvement in the operating conditions such as rise time, settling time, percentage of peak overshoot, stability phenomenon and speed response was observed. This comparative study was performed on MATLAB/Simulink environment.

Keywords: PMBLDCM, fuzzy logic controller, PI controller, speed response

1. Introduction

Permanent Magnet Brushless DC Motor (PMBLDCM) is considered as the future of the motor industry because of its wide range of applications. This motor becomes prominent in usage at places where the available power is in the form of low voltage DC. This motor possesses high efficiency mainly because of the permanent magnet rotor. As the rotor produces a high strength magnetic field, it draws only a small amount of current to maintain the torque when compared to all the other motors. Zero maintenance and high power to volume ratio are the major advantages of PMBLDC motors. As the motor is advantageous over many factors, it is used in domestic equipment, automobiles, information technology equipment, industries, public life appliances, transportation, aerospace,

defense equipment, power tools, toys, vision and sound equipment and medical and health care equipment ranging from microwatts to megawatts. PMBLDC motors can run beyond its rated speed unlike field-controlled motors. The speed of this motor can be controlled in an efficient way and easily to fit into the above applications. There are many speed control techniques for PMBLDC motors using which the speed of the motor can be easily controlled by forming a closed loop. PMBLDC motors are costlier because of permanent magnet rotors. But cost consideration becomes secondary when efficiency is considered [1]-[5]. The PI controllers are mostly used for speed control in industries. The speed error, the result of comparison of actual speed and set speed is fed to PI controller. It tries to reduce the error and settle the speed. But its performance is not the same

during the operating conditions. Fuzzy Logic Controller (FLC) is widely replacing all the other controllers because of its precise control with fuzzy rules. It does not require precise tuning. The FLC behaves as per the provided linguistic fuzzy rules and improves the operating condition of the system by providing better transient and the steady state response. The proposed systems having FLC as its speed controller is simulated in the MATLAB/Simulink environment and its results were compared with the results of PMBLDCM having PI controller.

2. Mathematical Modelling of PMBLDC Motor

Consider a three phase eight pole PMBLDC motor having Y-connected concentrated full pitched stator winding and inner rotor with non-salient pole structure. Three hall sensors are

placed at 120-degree intervals. Following assumptions are made for mathematical modeling of the PMBLDC motor [5] - [7].

- Ignore the core saturation, as well as the eddy current losses and the hysteresis losses.
- Ignore the armature reaction, and the distribution of the air-gap magnetic field is thought to be a trapezoidal wave with a flat-top width of 120 electrical angles.
- Ignore the cogging effect and suppose the conductors are distributed continuously and evenly on the surface of the armature.
- Power switches and flywheel diodes of the inverter circuit have ideal switch features.

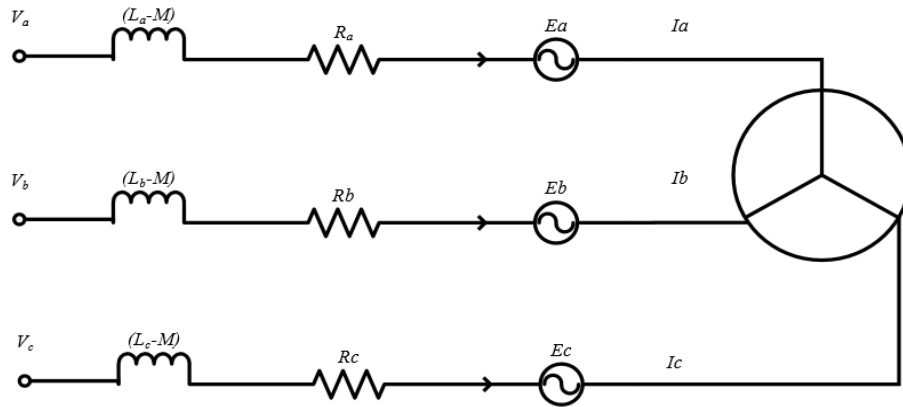


Figure 1: Equivalent circuit of PMBLDC Motor

The phase voltage of each winding, which includes the resistance voltage drop and the induced EMF, can be expressed as

$$V_a = R_a I_a + (L_a - M) \frac{d}{dt} (I_a) + e_a \quad (1)$$

$$V_b = R_b I_b + (L_b - M) \frac{d}{dt} (I_b) + e_b \quad (2)$$

$$V_c = R_c I_c + (L_c - M) \frac{d}{dt} (I_c) + e_c \quad (3)$$

Where

V_a, V_b, V_c - Phase voltages;

I_a, I_b, I_c - Phase currents;

e_a, e_b, e_c -Phase-induced EMFs;

R_a, R_b, R_c - Phase resistances;

For a three phase symmetrical winding, the resistance and inductance in all the phases are equal.

$$R_a = R_b = R_c = R \quad (4)$$

$$L_a = L_b = L_c = L \quad (5)$$

Therefore, the voltage equation of the three phases will be as follows

$$V_a = R I_a + (L - M) \frac{d}{dt} (I_a) + e_a \quad (6)$$

$$V_b = RI_b + (L - M) \frac{d}{dt}(I_b) + e_b \quad (7)$$

$$V_c = RI_c + (L - M) \frac{d}{dt}(I_c) + e_c \quad (8)$$

The back emf is expressed as

$$e_{abc} = (\omega_m K_b f_{abc}(\theta))/2 \quad (9)$$

Where K_b is the Back EMF constant and is represented as

$$K_b = 2P\psi_m$$

$f_{abc}(\theta)$ is the function of rotor position

The electromagnetic torque is expressed as

$$T_e = \frac{e_a I_a + e_b I_b + e_c I_c}{\omega_m} \quad (10)$$

Where e_a , e_b , e_c are the back EMFs of phase a, b and c respectively.

$$T_e = \omega_e \frac{[\psi_m f_a(\theta) i_a + \psi_m f_b(\theta) i_b + \psi_m f_c(\theta) i_c]}{\omega_m} \quad (11)$$

[since, $\frac{\omega_{\text{electrical}}}{\omega_{\text{mech}}} = P$]

$$T_e = \frac{P[\psi_m f_a(\theta) i_a + \psi_m f_b(\theta) i_b + \psi_m f_c(\theta) i_c]}{2} \quad (12)$$

Where, P represents the no. of poles

$f_a(\theta)$ represents the function of rotor position and it is given as

$$f_a(\theta) = \begin{cases} \frac{6\theta}{\pi} & , 0 < \theta \leq \frac{\pi}{6} \\ 1 & , \frac{\pi}{6} < \theta \leq \frac{5\pi}{6} \\ (\pi - \theta) \frac{6}{\pi} & , \frac{5\pi}{6} < \theta \leq \frac{7\pi}{6} \\ -1 & , \frac{7\pi}{6} < \theta \leq \frac{11\pi}{6} \\ (\theta - 2\pi) \frac{6}{\pi} & , \frac{11\pi}{6} < \theta \leq 2\pi \end{cases} \quad (13)$$

[since $P\psi_m = K_T/2$]

Therefore,

$$T_e = (I_{abc} f_{abc}(\theta) K_T)/4 \quad (14)$$

Under steady state operation, T_e (electromagnetic torque) is counter balanced by T_L (Load torque) which can be expressed as

$$T_e = T_L + J \frac{d}{dt}(\omega_m) + B\omega_m \quad (15)$$

$$\omega_m = \frac{1}{J} \int (T_e - T_L - B\omega_m) dt \text{ rad/sec} \quad (14)$$

The above equation represents electromechanical speed of PMBLDC motor.

Where,

T_L - load torque;

J - rotor moment of inertia;

B - viscous friction coefficient;

2.1 Block diagram of closed loop control of PMBLDC

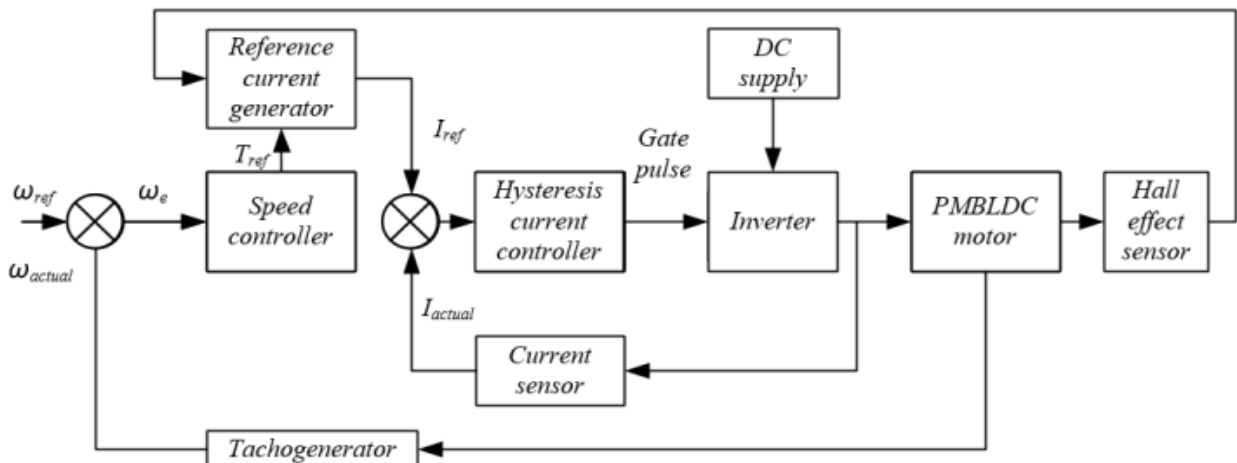


Figure 2: Block diagram of closed loop speed control

The actual speed of the motor is compared against the reference speed and the speed controller computes the reference torque signal. This is fed into the reference current generator circuit, which calculates the reference current required for the hysteresis current controller. The current controller produces required gate signal to switch the MOSFETs in the inverter. The six switch inverter produces commutation for driving the PMBLDC motor.

2.2 Reference Current Generator

The function of reference current generator is to obtain a three phase reference currents (i_a^*, i_b^*, i_c^*). The reference torque obtained is transformed into reference current using following expression.

$$i_{ref} = \frac{T_{ref}}{K_t} \quad (15)$$

Where

K_t is the torque constant.

The reference current is calculated by multiplying the reference torque with the position signals traced by the hall sensors placed inside the motor. PMBLDC motor is commutated based on its rotor position. The hall effect sensor signals and its corresponding back emf signals are tabulated below

By this way, three phase reference currents having the shape of a quasi-square wave in phase with respective back EMF are generated and are shown in Table 2

Table 1: Back EMF of Hall Effect sensor

Hall Effect Sensor Signals			Back EMF of Hall Effect Sensors		
H1	H2	H3	H_a	H_b	H_c
0	0	0	0	0	0
0	0	1	0	+1	-1
0	1	0	-1	+1	0
0	1	1	+1	-1	0
1	0	0	+1	-1	0
1	0	1	0	+1	-1
1	1	0	0	+1	-1
1	1	1	0	0	0

Table 2: Reference current with respect to Rotor position

Rotor Position	i_a^*	i_b^*	i_c^*
0-60°	i_{ref}	$-i_{ref}$	0
60°-120°	i_{ref}	0	$-i_{ref}$
120°-180°	0	$-i_{ref}$	i_{ref}
180°-240°	$-i_{ref}$	i_{ref}	0
240°-300°	$-i_{ref}$	0	i_{ref}
300°-360°	0	$-i_{ref}$	i_{ref}

2.3 Hysteresis Current Controller

Hysteresis current control is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within the hysteresis-band [8]-[11]. The control circuit generates a signal for current error with an upper and lower band for it and that signal is compared with the current error signal. Whenever the current error signal exceeds the upper band limit, the upper switch is turned off and lower switch is turned on. And similarly,

When the current error signal exceeds the lower band limit, the upper switch is turned on and the lower switch is turned off. This remains the same for all the phase current error signals.

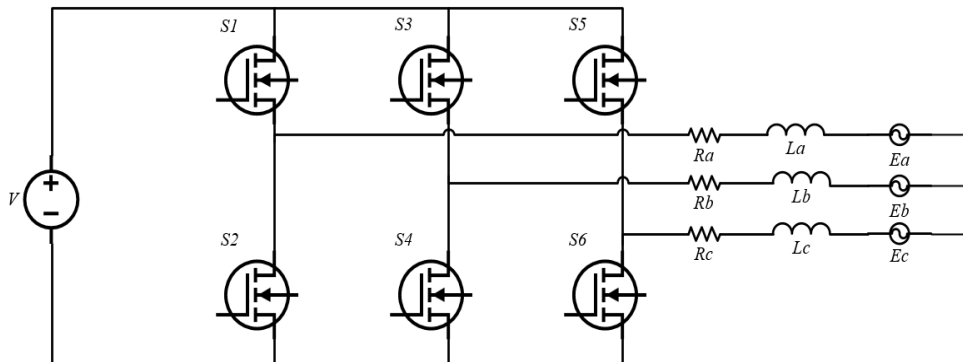


Figure 3: Six Switch Commutation Circuit

The switching logic is formulated as given below.

If $i_a < (i_a^* - h_b)$ switch S1 ON and switch S4 OFF

If $i_a < (i_a^* + h_b)$ switch S1 OFF and switch S4 ON

If $i_b < (i_b^* - h_b)$ switch S3 ON and switch S6 OFF

If $i_b < (i_b^* + h_b)$ switch S3 OFF and switch S6 ON

If $i_c < (i_c^* - h_b)$ switch S5 ON and switch S2 OFF

If $i_c < (i_c^* + h_b)$ switch S5 OFF and switch S2 ON

Where, h_b is the hysteresis band provided for three phase currents, i_a^*, i_b^*, i_c^* are the stator reference currents and i_a, i_b, i_c are the actual stator currents

3. Speed Controllers

This paper deals with comparative study on PI controller and Fuzzy Logic Controller whose operation, advantages and discussed as follows

3.1 Conventional PI Controller

A standard approach for speed control in industrial drives is to use a proportional plus integral controller. Although the commonly used PI control scheme is a conventional one, a PI controller is designed for the PMBLDC motor drive for the purpose of comparison of the responses of the drive with different controllers. Tuning of PI controller involves setting the proportional and integral values to get the best possible control for a particular process. A proportional controller gain (K_p) will have the

effect of reducing the rise time and will not eliminate the steady state error. An integral control gain (K_i) will have the effect of eliminating the steady state error but it may make the transient response worse. The error signal obtained by comparing the actual speed and set reference speed of the motor is sent to the controller and the controller will perform the proportional integral computation on the error signal and the error signal can be expressed as,

$$\omega(t) = \omega_{ref}(t) - \omega_{actual}(t) \quad (16)$$

The output from the controller is the sum of product of proportional gain and error signal and the product of integral gain and integral of error which can be expressed as

$$\text{Output}(t) = K_p \omega_e(t) + K_i \int_0^t \omega_e(t) dt \quad (17)$$

Where K_p and K_i are the proportional gain and integral gain of PI controller respectively [12]-[13]. The PI controllers can be tuned in many ways like trial and error method, Ziegler Nichols method, improved Ziegler Nichols method, Cohen-Coon method, genetic algorithm etc. Out of these methods, trial and error method is adopted in the PI controller of the motor.

3.2 Fuzzy Logic Controller

Fuzzy Logic is a rule-based decision-making technique. In Fuzzy Logic Controller a set of rules are framed so as to bring the error to zero and obtain a steady state response [14]-[18].

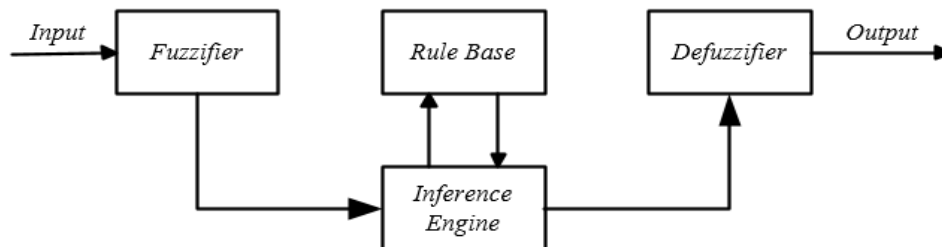


Figure 4: Fuzzy Logic Controller Architecture

Fuzzy logic expressed operational laws in linguistics terms instead of mathematical equations. Many systems are too complex to

model accurately, even with complex mathematical equations. Therefore, traditional methods become infeasible in these systems.

However a fuzzy logic linguistic term provide a feasible method for defining the operational characteristics of such systems and also provides a better performance when compared to PI controller.

The Mamdani type FLC has two inputs. One is error and the other one is change in error. The input data which is in the form of numerical values are transformed into linguistic variables. Such linguistic variables are used to create the rule base for Fuzzy Logic Controller. The linguistic variables are the notations provided to the membership functions (MF) having fuzzy sets. The membership function transforms the crisp input into fuzzy sets and this process is called fuzzification. The inputs of fuzzy logic controller are expressed in several linguistic levels. These levels can be described as Positive very large (PVL), Positive large (PL), Positive medium (PM), Positive small (PS), Zero (Z) or in other levels. Each level describes a fuzzy set. There are many types of membership functions like triangular MF, trapezoidal MF, Gaussian MF etc., The triangular MF is employed in FLC as it gives better results for speed control operation in motor.

The fuzzified input is given to inference Engine. The inference engine matches the desired rule for the fuzzified input in the rule base and gets the output. The output from the inference engine is given to the defuzzifier which transforms the fuzzy set into crisp output. This operation is the inverse of fuzzification and this process is called defuzzification. The rule base is designed based on the following considerations.

- If both Error (E) and Change in Error (CE) are zero, then maintain the present control setting as zero.
- If Error (E) is not zero but is approaching this value at a satisfactory rate, then maintain the present control setting.
- If Error (E) is growing, then change the control signal depending on the magnitude

and sign of error (E) and Change in Error (CE) to force E towards zero.

Table 3: Rule Base

E/CE	Z	PS	PM	PL	PVL
Z	Z	Z	Z	PS	PM
PS	Z	PS	PS	PM	PL
PM	Z	PS	PM	PL	PVL
PL	PS	PM	PL	PL	PVL
PVL	PM	PL	PVL	PVL	PVL

The fuzzy membership functions of input and output variables are shown below

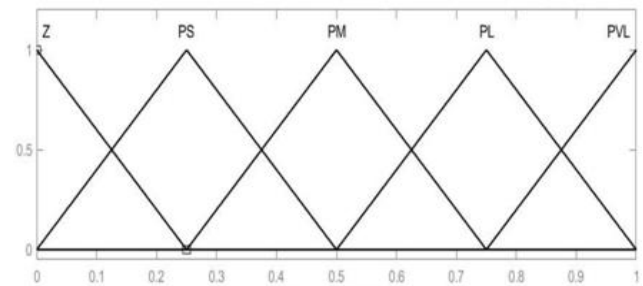


Figure 5: Membership Function of Input Variable 'Error'

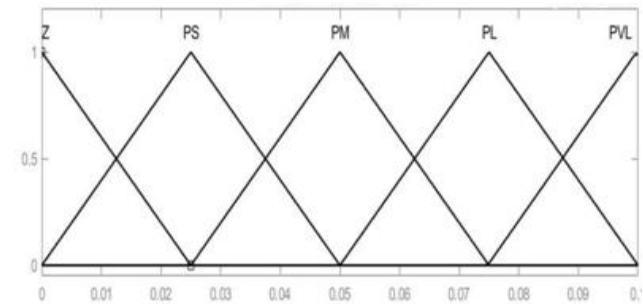


Figure 6: Membership Function of Input Variable 'Change in Error'

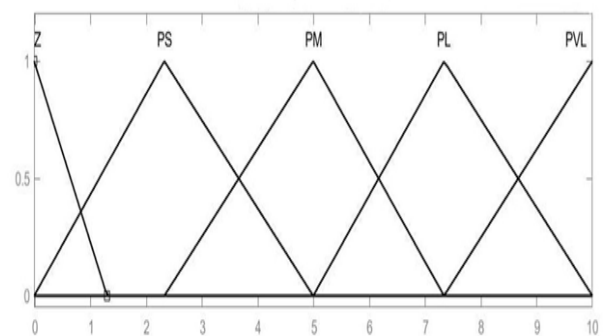


Figure 7: Membership Function of Output Variable 'Control'

4. Simulation and Results

In this paper the system is designed and simulated in the MATLAB/Simulink environment and its results are discussed below.

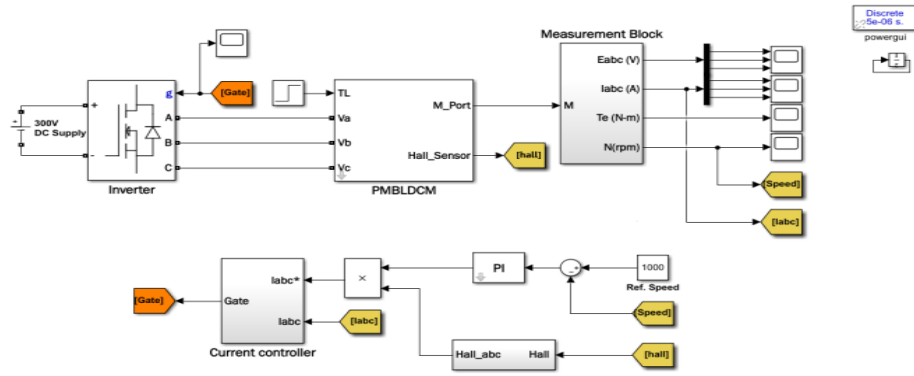


Figure 8: Simulation Model of Closed Loop Control of PMBLDC Motor Having PI Controller

The system shown in Fig 8 has PI controller as speed controller and its proportional gain (K_p) and integral gain (K_i) are 0.0471 and 1.66 respectively. The simulation result for speed reference input of 1000 rpm with a load torque of 0.3 N-m at 0.1 seconds are shown from Fig 9 to Figure 11.

The magnitude of stator current is initially minimum during no load condition. At 0.1 seconds, the load torque is introduced, due to which the current drawn by the motor from the supply is increased. This increased magnitude of current is maintained in order to have constant torque for motor operation.

Table 4: Motor Parameters

Stator Phase Resistance, R	3.07 Ω
Stator Phase Inductance, L	6.57 mH
No. of Poles, P	4
Back EMF Constant, K_b	0.48702 V/rad/sec
Torque Constant, K_t	0.48702 Nm/A
Rotor Inertia, J	1.8e-4 kgm ²
Friction Coefficient, B	1e-3
Input DC Voltage, V	300 V

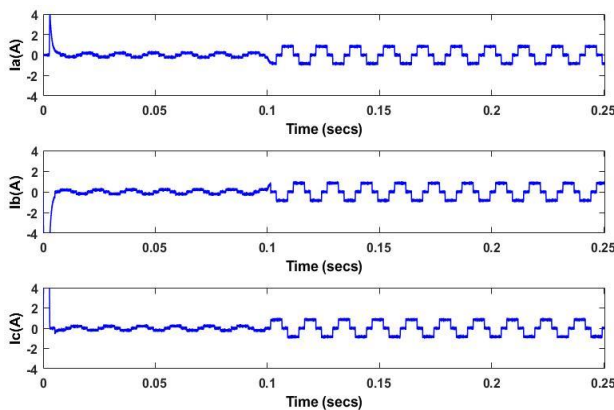


Figure 9: Stator Current Waveforms of Closed loop Control with PI Controller

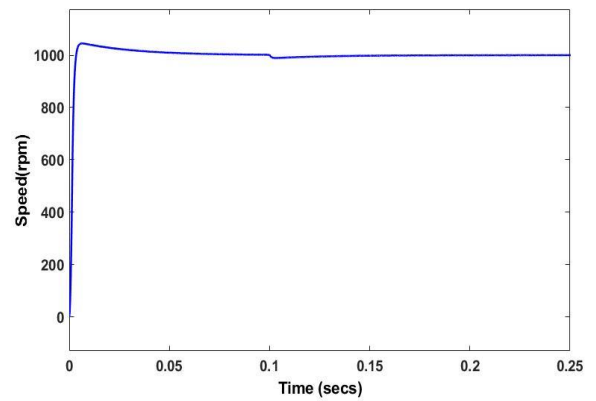


Figure 10: Speed waveform of closed loop control with PI

The dip caused at 0.1 seconds by the load torque is stabilized to attain its steady state after 0.1 seconds by the PI controller. The controlled response of the speed has a minimum peak overshoot of 4.5% with the peak time of 6.225ms

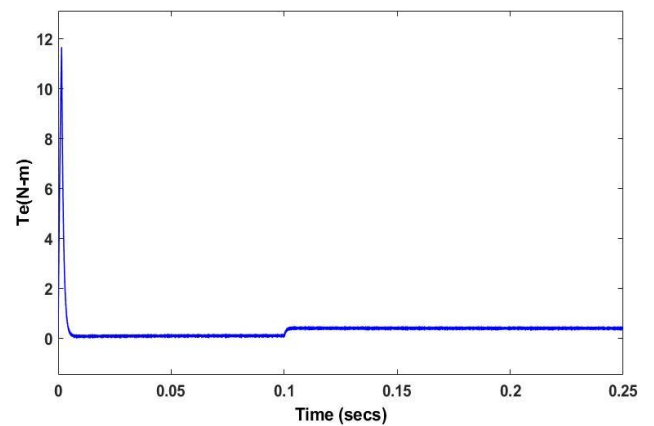


Figure 11: Torque waveform of closed loop control with PI

Initially the starting torque is very high and is gradually reduced as the speed increases. When the speed is settled and maintained constant, the torque is also maintained constant. Due to load torque of 0.3 N-m at 0.1 seconds, the torque

increases and the speed decreases as they are inversely proportional to each other. After which, the torque is maintained constant.

The simulation model of closed loop control of PMBLDC Motor having Fuzzy Logic Controller in MATLAB/Simulink environment is shown in the Fig 12.

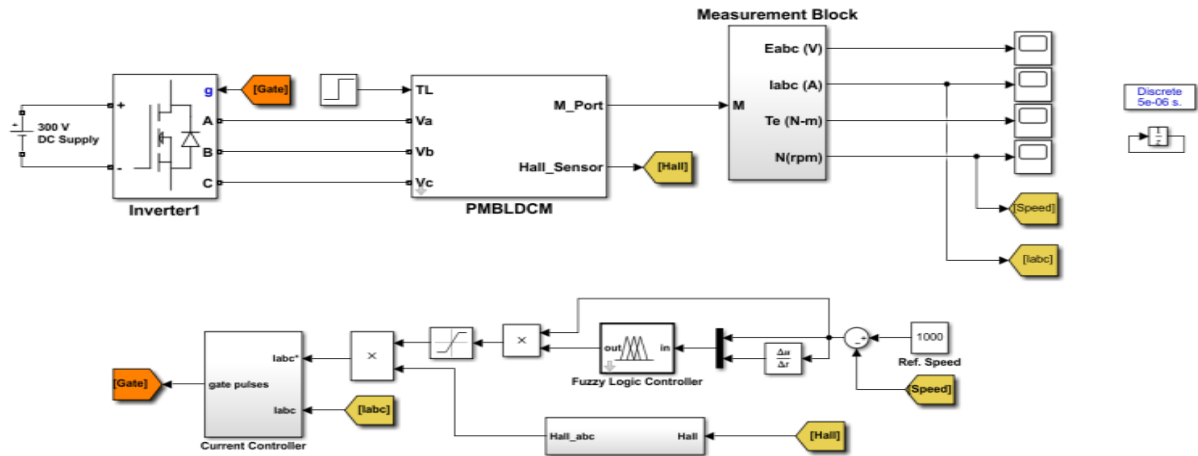


Figure 12: Simulation model of closed loop control of PMBLDCM having FLC

The simulation results of FLC are shown from Figure 13 to Figure 15

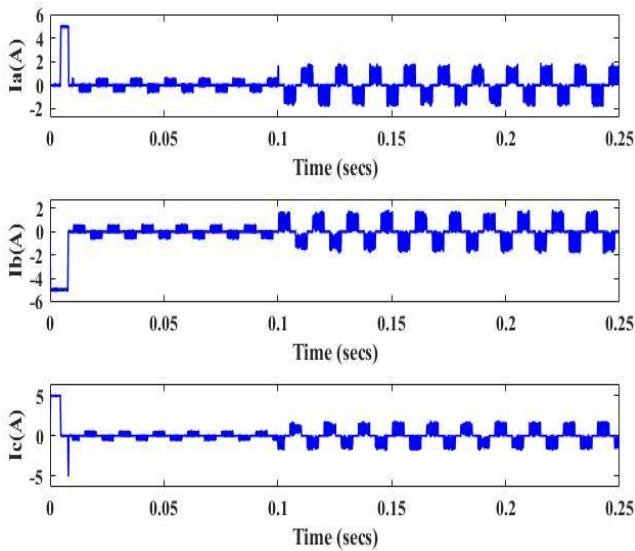


Figure 13: Stator current waveforms of closed loop control with Fuzzy logic controller

The simulation results obtained from the above simulation model has a peak overshoot of about 1% only with peak time of 8.23ms and settling time of speed is considerably reduced which is only 9.81ms.

The speed response characteristics obtained from both the controllers are shown in the Table 5

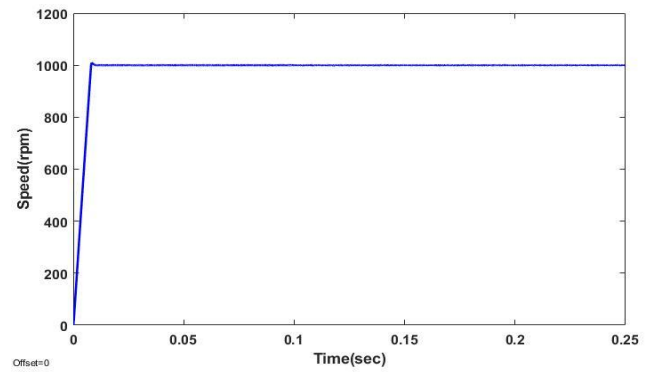


Figure 14: Speed waveform of closed loop with Fuzzy logic controller

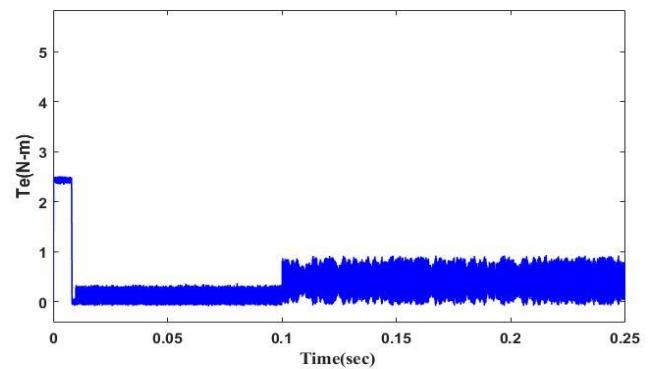


Figure 15: Torque waveform of closed loop with Fuzzy logic controller

Table 5: Characteristic response of controllers

Controller	Rise Time, T_r (sec)	Settling Time, T_s (sec)	% of Peak Overshoot
PI controller	0.003465	0.1299	4.5
FLC	0.00807	0.009815	1

5. Conclusion

A comparative study of speed control techniques was performed using PI and fuzzy logic controller. From the obtained response of the system, FLC provides smooth speed control in terms of settling time, rise time and peak overshoot in comparison with the PI controller. The non-linearity of the motor is well handled by FLC. Fuzzy Logic Controller also provides no considerable drop in speed when load torque is applied and also no considerable peak overshoot which shows the reliability of the controller. It improves the dynamic performance of the motor and yields better steady state response.

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