ISSN: 2229-6956(ONLINE)
DOI: 10.21917/ijsc.2011.0039

ICTACT JOURNAL ON SOFT COMPUTING: SPECIAL ISSUE ON FUZZY IN INDUSTRIAL AND PROCESS AUTOMATION,
JULY 2011, VOLUME: 02, ISSUE: 01

PERFORMANCE STUDIES OF INTEGRATED FUZZY LOGIC CONTROLLER FOR BRUSHLESS DC MOTOR DRIVES USING ADVANCED SIMULATION MODEL

C. Subba Rami Reddy[1] and M. Surya Kalavathi[2]
[1]*Department of Electrical & Electronics Engineering, KSRM College of Engineering, Andhra Pradesh, India*
Email: c_subbramireddy2020@yahoo.com
[2]*Department of Electrical & Electronics Engineering, JNTUH College of Engineering, Andhra Pradesh, India*
Email: munagala12@yahoo.co.in

Abstract

This paper introduces an Integrated fuzzy logic controller (IFLC) for brushless dc (BLDC) motor drives using advanced simulation model and presents a comparative study of performances of PID controller and IFLC. The dynamic characteristics of speed and torque are effectively monitored and analyzed using the proposed model. The aim of IFLC is to obtain improved performance in terms of disturbance rejection or parameter variation than obtained using PID controller. The IFLC is constructed by using Fuzzy logic controller (FLC) and PID controller. A performance comparison of the controllers is also given based on the integral of the absolute value of the error (IAE), the integral of the squared error (ISE), the integral of the time-weighted absolute error (ITAE) and the integral of the time-weighted squared error (ITSE). The results show the effectiveness of the proposed controller.

Keywords:
Brushless DC Motor, PID, Integrated Fuzzy Logic Controller

1. INTRODUCTION

The brushless DC (BLDC) motor is becoming widely used as a small horse power control. This device has the physical appearance of a 3-phase permanent magnet synchronous machine. It is generally driven from a six step inverter which converts a constant voltage to 3-phase voltages with frequency corresponding instantaneously to the rotor speed. The inverter machine combination has the terminal and output characteristics resembling those of a DC shunt motor, hence the name brushless DC motor [1, 2].

Recent developments in permanent magnet materials, power electronics and modern control technologies have significantly influenced the widespread use of Permanent Magnet BLDC (PMBLDC) motor in order to meet the competitive world wide market demands of manufactured goods, devices, products and processors. Large, medium, small as well as micro PMBLDC motors are extensively sought for applications in all sorts of motion control apparatus and systems [3]. The marvelous increase in the popularity of the PMBLDC motor among engineers bears testimony to its industrial usefulness in terms of superior performance and relative size. High efficiency due to reduced losses, low maintenance and low rotor inertia of the PMBLDC motor have increased the demand of PMBLDC motors in high power servo and robotic applications. The invention of modern solid state devices like MOSFET, IGBT and high energy rare earth permanent magnets have widely enhanced the applications of PMBLDC motors in variable speed drives [4].

2. MATHEMATICAL MODEL OF THE BLDC MOTOR DRIVE SYSTEM

The complete BLDC motor drive system consists of a permanent magnet motor fed by a three-phase PWM inverter, rotor position sensor, hysteresis current controller and speed controller. The inverter which is connected to the dc supply feeds controlled power to the motor. The magnitude and frequency of the inverter output voltage depends on the switching signals generated by the hysteresis controller [5]. The state of these switching signals at any instant is determined by the rotor position, speed error and winding currents. The controller synchronizes the winding currents with the rotor position. It also facilitates the variable speed operation of the drive and maintains the motor speed reference value even during load variations and supply fluctuations [6]. Fig.1 shows the block diagram of the closed loop drive of the PMBLDC motor.

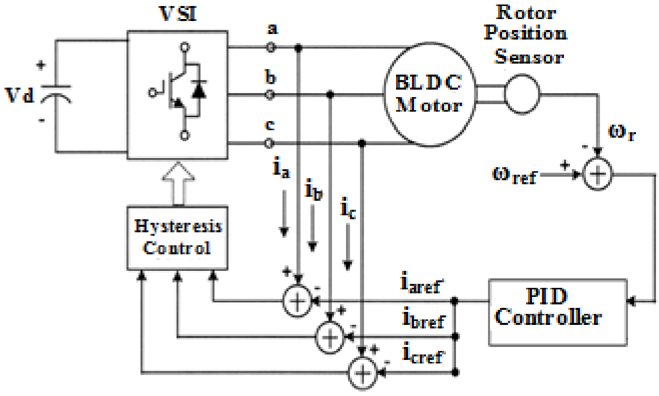

Fig.1. Block Diagram of Closed loop PMBLDC Motor Drive

2.1 MODELING OF PERMANENT MAGNET BRUSHLESS DC MOTOR

The mathematical model of the motor is developed based on the assumption in [7]. Fig.2 shows the overall system configuration of the three phase PMBLDC drive. The armature voltages obtained from Fig.2 can be expressed as

$$v_a = Ri_a + L_a \frac{di_a}{dt} + e_a\ , \tag{1}$$

$$v_b = Ri_b + L_b \frac{di_b}{dt} + e_b\ , \tag{2}$$

$$v_c = Ri_c + L_c \frac{di_c}{dt} + e_c\ , \tag{3}$$

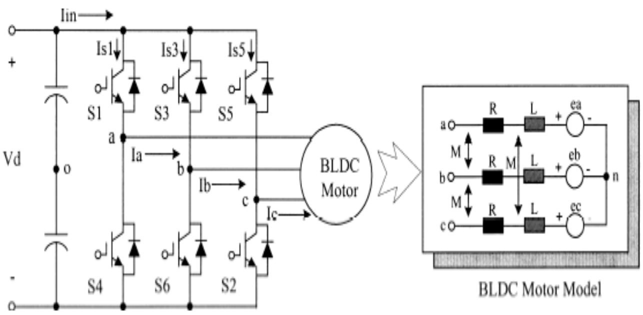

Fig.2. Configuration of PMBLDC motor drive system

where, $L = L_a = L_b = L_c$ is the inductance of each phase, R is the resistance of each phase, V_a, V_b, V_c are the phase voltages and e_a, e_b, e_c are the rotor position dependent back EMFs of phase a, b and c respectively.

The back EMF is a function of rotor position (θ) and has the amplitude $E=K_e\omega_r$ (K_e is the back EMF constant and ω_r is the angular speed). The back EMFs of phase a, b and c are given by equations (4), (5) and (6) obtained from Fig.3,

$$e_a = \begin{cases} (6E/\pi)\theta & (0<\theta<\pi/6) \\ E & (\pi/6<\theta<5\pi/6) \\ -(6E/\pi)\theta+6E & (5\pi/6<\theta<7\pi/6) \\ -E & (7\pi/6<\theta<9\pi/6) \\ (6E/\pi)\theta-12E & (11\pi/6<\theta<2\pi) \end{cases}, \tag{4}$$

$$e_b = \begin{cases} -E & (0<\theta<\pi/2) \\ (6E/\pi)\theta-4E & (\pi/2<\theta<5\pi/6) \\ E & (5\pi/6<\theta<7\pi/6) \\ -(6E/\pi)\theta+10E & (9\pi/6<\theta<11\pi/6) \\ -E & (11\pi/6<\theta<2\pi) \end{cases}, \tag{5}$$

$$e_c = \begin{cases} E & (0<\theta<\pi/6) \\ -(6E/\pi)\theta+2E & (\pi/6<\theta<\pi/2) \\ -E & (\pi/2<\theta<7\pi/6) \\ (6E/\pi)\theta-10E & (7\pi/6<\theta<9\pi/6) \\ E & (9\pi/6<\theta<2\pi) \end{cases}. \tag{6}$$

Fig.3. Back EMF and phase current waveforms of PMBLDC motor

The phase currents i_a, i_b and i_c are given by equations (7), (8) and (9),

$$i_a = \frac{1}{(L-M)}\int (V_a - Ri_a - e_a), \tag{7}$$

$$i_b = \frac{1}{(L-M)}\int (V_b - Ri_b - e_b), \tag{8}$$

$$i_c = \frac{1}{(L-M)}\int (V_c - Ri_c - e_c). \tag{9}$$

The electromagnetic torque developed is given by,

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_r. \tag{10}$$

The torque balance equation is expressed as,

$$T_e = T_L + B\omega_r + (2J/P)d\omega_r/dt \tag{11}$$

where, J is the inertia of the rotor, B is the damping coefficient associated with the rotational system of the motor and T_L is the mechanical load torque.

The rotor position θ is a function of ω_r and is expressed as,

$$\frac{d\theta}{dt} = \omega_r. \tag{12}$$

2.2 PID SPEED CONTROLLER

A PID speed controller has been chosen with gain parameters k_p, k_i and k_d. The speed of the motor is compared with the reference value and the error in speed is processed by the speed controller. The output of the PID controller at any instant is the reference torque given by,

$$T_{ref} = \left(k_p + \frac{k_i}{s} + k_d s\right)(\omega_{ref} - \omega_r) \tag{13}$$

where, T_{ref} is the reference torque, k_p is the proportional gain, k_i is the integral gain, k_d is the derivative gain, ω_{ref} is the reference speed in rad/s and ω_r is the actual speed in rad/s.

2.3 REFERENCE CURRENT GENERATION

The magnitude of the reference current I_{ref} is determined from the reference torque (T_{ref}) and the torque constant (K_t),

$$I_{ref} = \frac{T_{ref}}{K_t} \tag{14}$$

Depending upon the rotor position, the reference current generator generates the three phase reference currents (i_{aref}, i_{bref}, i_{cref}) by taking the value of the reference current magnitude as I_{ref}, $-I_{ref}$ and 0 as shown in Table.1.

2.4 HYSTERESIS CURRENT CONTROLLER

The control logic of hysteresis current controller for one of the three Phases is shown in Fig.4. The same logic is applicable to the other two phases. The switching logic of the hysteresis current controller for all the phases is as follows,

If ($ia < i_{aref} - h_b$), switch 1 ON, switch 4 OFF
If ($i_a > i_{aref} + h_b$), switch 1 OFF, switch 4 ON
If ($i_b < i_{bref} - h_b$), switch 3 ON, switch 6 OFF
If ($i_b > i_{bref} + h_b$), switch 3 OFF, switch 6 ON
If ($i_c < i_{cref} - h_b$), switch 5 ON, switch 2 OFF
If ($i_c > i_{cref} + h_b$), switch 5 OFF, switch 2 ON

where, h_b is the hysteresis band around the 3 phase reference currents.

Table.1. Reference current generation based on rotor position

Rotor position angle	**i_{aref}**	**i_{bref}**	**i_{cref}**
0 – 30	0	$-I_{ref}$	I_{ref}
30 – 90	I_{ref}	$-I_{ref}$	0
90 – 150	I_{ref}	0	$-I_{ref}$
150 – 210	0	I_{ref}	$-I_{ref}$

210 – 270	$-I_{ref}$	I_{ref}	0
270 – 330	$-I_{ref}$	0	I_{ref}
330 – 360	0	$-I_{ref}$	I_{ref}

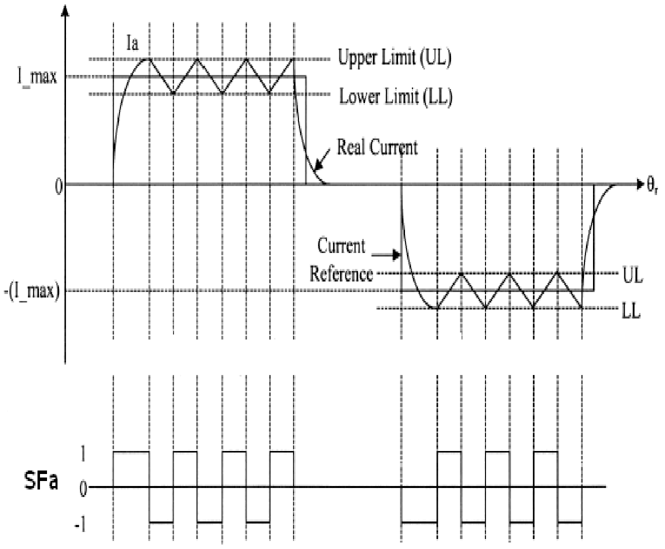

Fig.4. Hysteresis current control for phase A

2.5 THREE PHASE VOLTAGE SOURCE INVERTER

The inverter phase voltages are generated from switching functions SF_a, SF_b and SF_c, which are obtained from hysteresis controller block and are as follows,

$$V_a = \frac{V_d}{2} SF_a \tag{15}$$

$$V_b = \frac{V_d}{2} SF_b \tag{16}$$

$$V_c = \frac{V_d}{2} SF_c \tag{17}$$

3. SIMULATION OF BLDC MOTOR USING PID CONTROLLER

The simulation of speed control of BLDC Motor is done by using conventional PID controller using MATLAB simulink, a software package, for modeling, simulating and analyzing dynamical systems. The Fig. 5 shows the simulink model of speed control of BLDC Motor by using conventional PID controller. The control circuit determines the switching action to be performed based on rotor position feedback. The speed controller and the hysteresis current controller are used to maintain the speed and the current at the specified reference value. The hysteresis band is taken as 0.1 and DC voltage of 160V is applied to the inverter.

3.1 PARAMETERS OF PID CONTROLLER

Proportional gain $k_p = 0.2$

Integral gain $k_i = 0.02$

Derivative gain $k_d = 0.0000012$

3.2 PMBLDC MOTOR SPECIFICATIONS

Rating : 1 HP
Rated speed : 3500 rpm
Rated voltage : 160 V dc
Rated Torque : 0.662N-m
Number of poles : 4
Rated current : 5 A
Type of connection : star
Resistance / phase : 0.75 Ω
Self & Mutual inductance : 3.05 x 10^{-3} H / Phase
Moment of inertia : 0.82614x10^{-4} J
Torque constant : 0.21476N-m/A
Back emf constant : 0.10743Vsec/rad

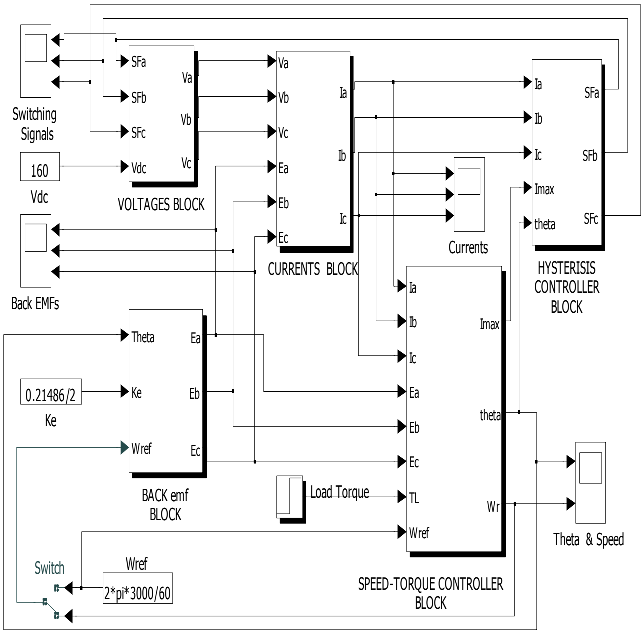

Fig.5. Simulink model of PMBLDC motor drive with PID controller

3.3 RESPONSE OF THE BLDC DRIVE DURING STARTING AND SPEED REVERSAL

Figures 6, 7, and 8 show the rotor speed, phase currents and developed torque of PMBLDC motor with PID controller from standstill to a speed of 3500 rpm and when the motor is suddenly changed to other direction from steady state at t=0.05 sec.

3.4 PERFORMANCE OF THE DRIVE UNDER LOAD CHANGE

Figures 9, 10, and 11 show the performance of the of PMBLDC motor with PID controller under load perturbation (applying load at t=0.04 sec and removal at t=0.06 sec.).

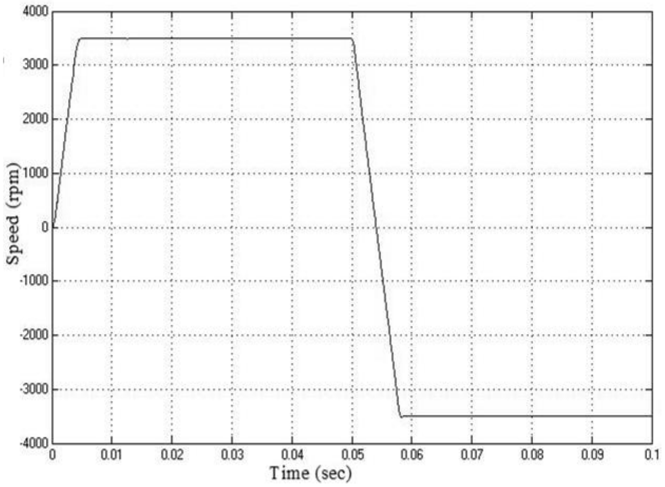

Fig.6. Rotor speed with PID controller during starting and speed reversal

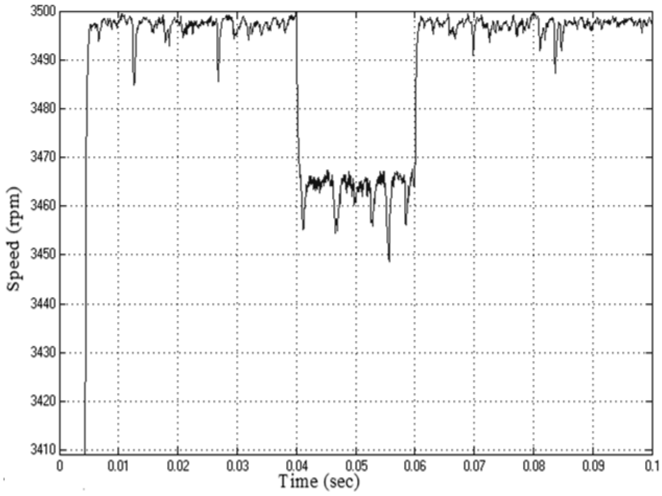

Fig.9. Rotor speed with PID controller during load perturbation

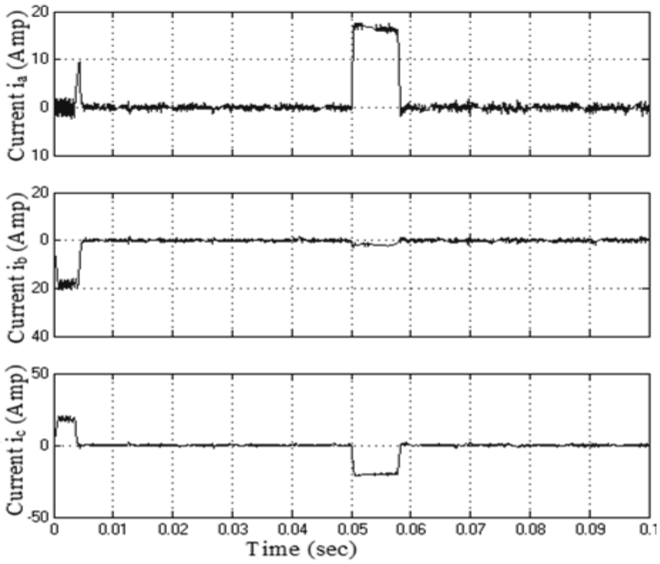

Fig.7. Phase currents with PID controller during starting and speed reversal

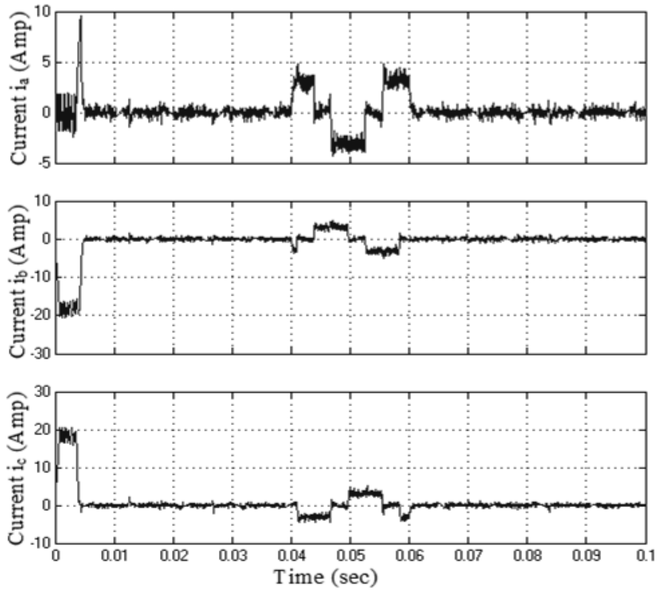

Fig.10. Phase currents with PID controller during load perturbation

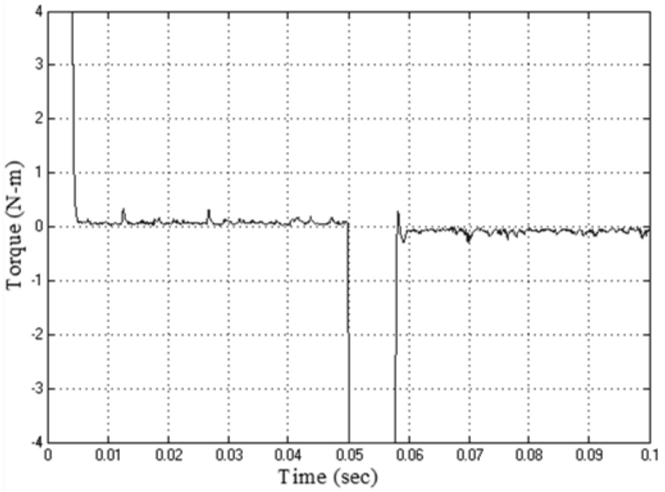

Fig.8. Electromagnetic torque with PID controller during starting and speed reversal

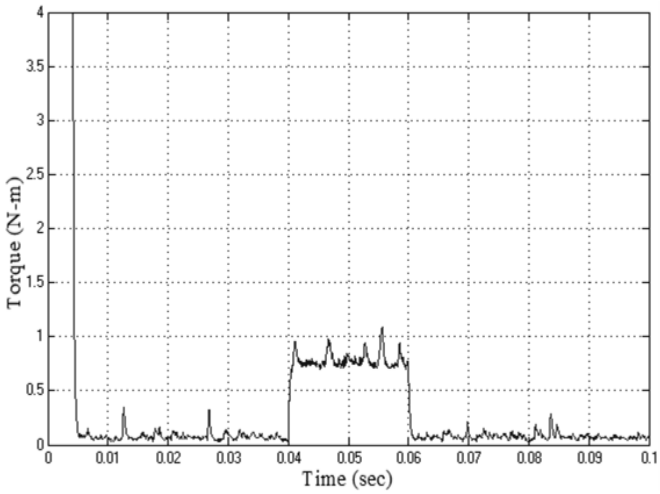

Fig.11. Electromagnetic torque with PID controller during load perturbation

4. SIMULATION OF BLDC MOTOR USING INTEGRATED FUZZY LOGIC CONTROLLER

Fuzzy logic has been developed about fifty years. During the past several years, fuzzy logic control technology has been widely and successfully utilized in numerous industrial applications and consumer products. Since fuzzy logic with human like but systematic property can convert the linguistic control rules based on expert knowledge into automatic control strategy, it can be well applied to control the systems with uncertain or unmodelled dynamics [8], [9]. On the basis of these properties of fuzzy logic, this paper proposes an integrated fuzzy logic concept to improve the performance of some other existed control systems. The fuzzy logic controller (FLC) which depends on fuzzy logic provides a way of converting a linguistic control strategy based on expert knowledge into automatic control strategy. The integrated fuzzy logic controller (IFLC) consists of incorporating the FLC into some other existing control system. The main advantage of using integrated fuzzy logic control structure is that one does not have to redesign the existed control system but also acquire the satisfactory response when disturbances and noises enter [10], [11].

4.1 INTEGRATED FUZZY LOGIC CONTROL SYSTEM

The integrated fuzzy logic controller (IFLC) system is organized by using the FLC to control the existed control system (such as PID control system). The PID control system for BLDC motor drive does not give the performance in the desired range during load perturbation or/and some disturbances. However, the redesign of PID controller for various load conditions, sudden disturbances and parameter variations during on line is much complex and troublesome. It is fortunate that IFLC structure gives satisfactory results in these cases. It is seen that to incorporate the FLC into the PID controlled BLDC motor drive system is better than redesigning the original PID controlled system, even if we do not understand the dynamics of original PID controlled BLDC motor drive system. The basic configuration IFLC is shown in Fig. 12. The purpose of using IFLC structure is that the IFLC system is cheaply realized and is easily adjusted by modifying the rules. All membership functions of the FLC inputs, error (e) and change in error (Δe), and the output (Δu) are defined on the common normalized domain [-1, 1]. The characters NB, NM, NS, ZE, PS, PM and PB stand for negative big, negative medium, negative small, zero, positive small, positive medium and positive big respectively. Here triangular membership functions are chosen for NM, NS, ZE, PS, PM fuzzy sets and trapezoidal membership functions are chosen for fuzzy sets NB and PB. The rule base for computing the output Δu is in Table.2. This is a very often used rule base designed with a two dimensional phase plane [12], [13]. The control rules in Table.2 are built based on the characteristics of the step response. Since the present control system (PID control system) nears our desired situation, we only provide a little control action to the control system. However, we should still adjust several fuzzy rules to adapt particular controlled system. The simulation of speed control of PMBLDC motor is done by using IFLC and the parameters of the IFLC are same as the conventional PID controller.

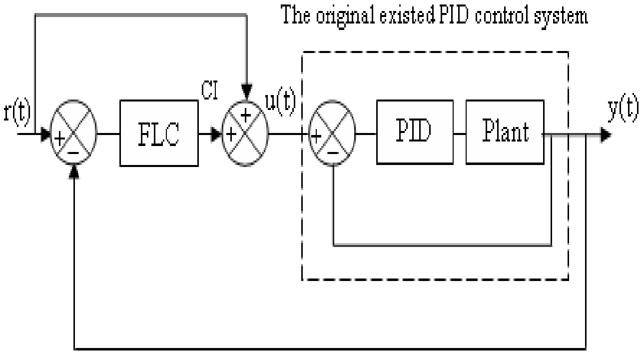

Fig.12. Basic block diagram of IFLC system

Table.2. Fuzzy rules for computation of Δu

e/Δe	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

4.2 RESPONSE OF THE BLDC DRIVE DURING STARTING AND SPEED REVERSAL

Figures 13, 14 and 15 show the rotor speed, phase currents and developed torque of PMBLDC motor with IFLC from standstill to a speed of 3500 rpm and when the motor is suddenly changed to other direction from steady state at t=0.05 sec.

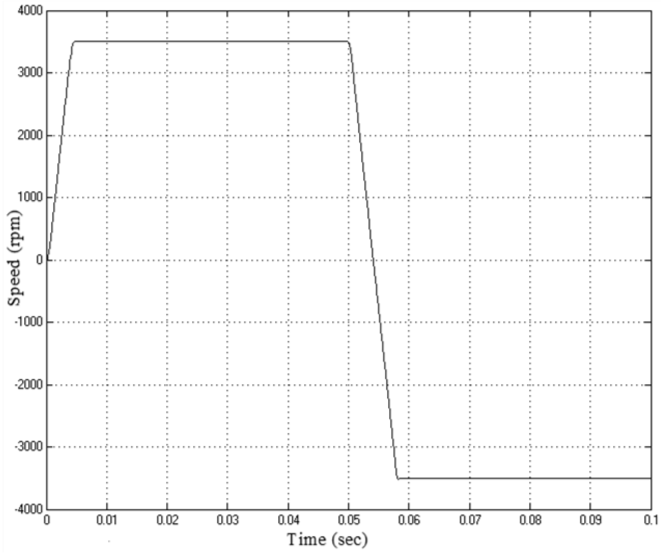

Fig.13. Rotor speed with IFLC during starting and speed reversal

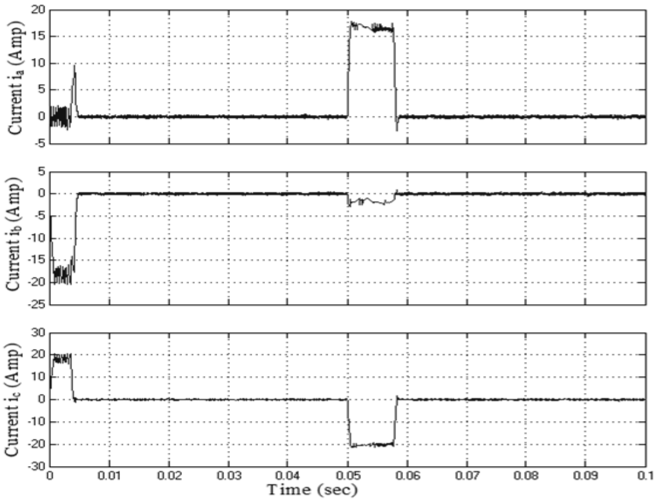

Fig.14. Phase currents with IFLC during starting and speed reversal

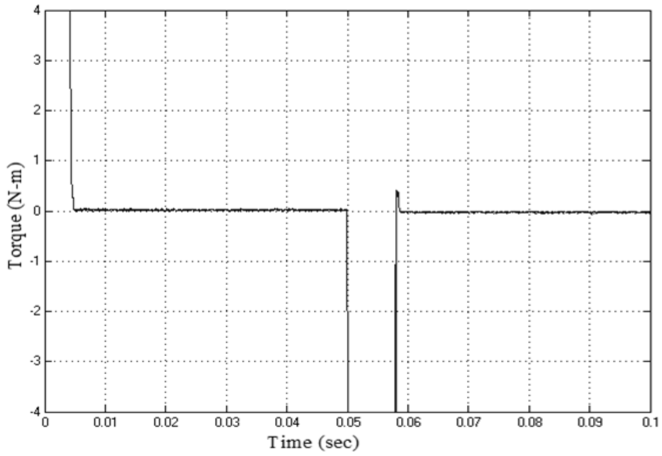

Fig.15. Electromagnetic torque with IFLC during starting and speed reversal

4.3 PERFORMANCE OF THE DRIVE UNDER LOAD CHANGE

Figures 16, 17 and 18 show the performance of the of PMBLDC motor with IFLC under load perturbation (applying load at t=0.04 sec and removal at t=0.06 sec.).

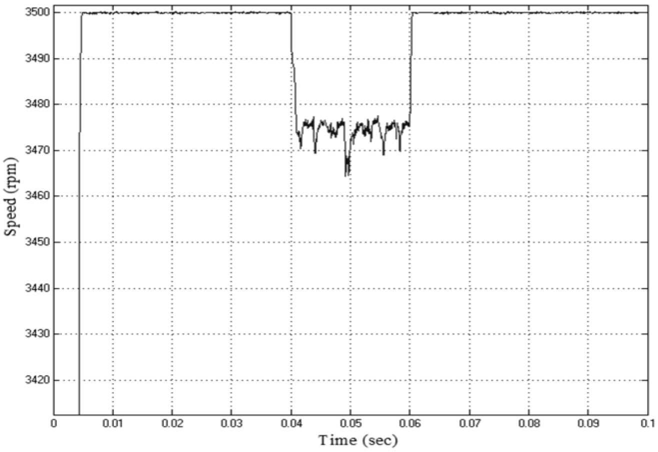

Fig.16. Rotor speed with IFLC during load perturbation

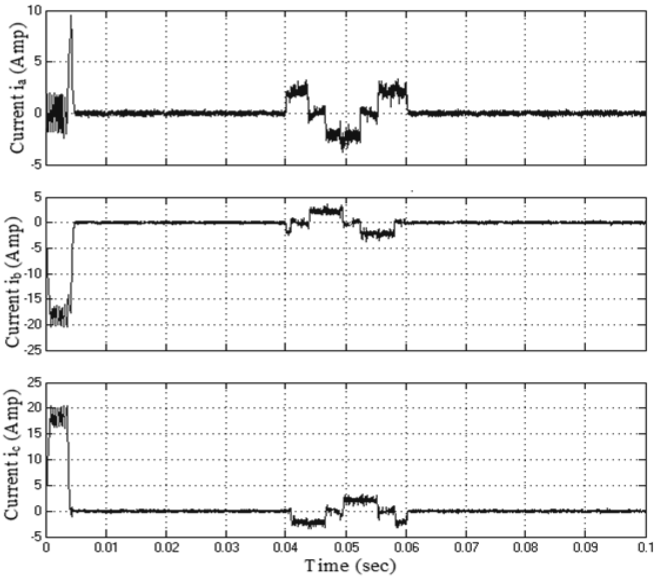

Fig.17. Phase currents with IFLC during load perturbation

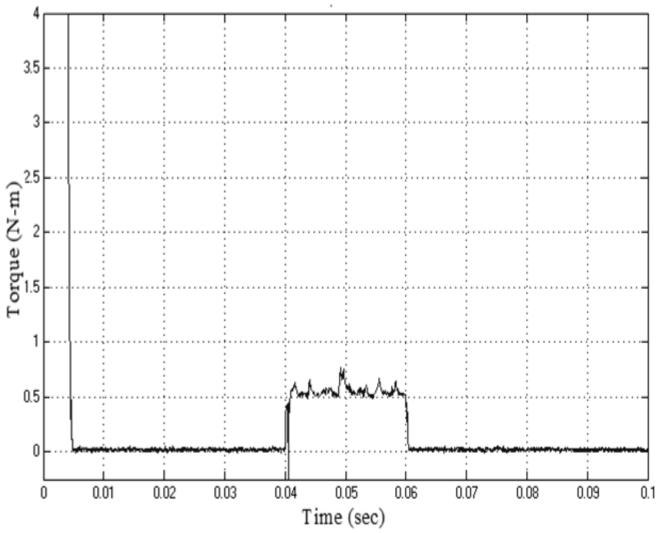

Fig.18. Electromagnetic torque with IFLC during load perturbation

5. RESULTS AND DISCUSSION

The performance of PID controller and IFLC is evaluated for the speed control of PMBLDC motor during different operating conditions. The performance specifications such as settling time, peak over shoot, steady state error, time taken to reach the set speed in the reverse direction and dip in speed when rated load torque applied are shown in Table.3 from the observations of transient and steady state response of the PMBLDC motor for the set speeds of 3500 rpm, 3000 rpm, 2500 rpm, 2000 rpm, 1500 rpm and 1000 rpm for both the PID controller and IFLC. It is found that the steady state error for PID controller is 14 rpm whereas for IFLC, it is only 0.5 rpm which is very less as compared to PID controller. Also notice that each performance measure value in Tables 3 and 4 corresponding to the IFLC is smaller than the corresponding value for the PID controller. It is also seen that the IFLC leads to a faster response and a smaller overshoot than PID controller.

Table.3. Comparison of performance specifications between PID and IFLC

Reference speed	**Type of Controller**	**Time taken to reach the set speed(settling time) in sec.**	**Steady state error in rpm.**	**Dip in speed when a load of 0.662N-m is applied in rpm.**	**Peak Overshoot**	**Time to reach set speed in the reverse direction in sec.**
3500	PID	0.0053	14	50	2.5	0.009
	IFLC	0.00485	0.5	35	0.2	0.0086
3000	PID	0.0048	5	60	40	0.007
	IFLC	0.0045	0.3	25	37	0.007
2500	PID	0.0044	1	40	38	0.0065
	IFLC	0.004	0.2	30	36	0.006
2000	PID	0.004	3	35	65	0.0058
	IFLC	0.0036	0.2	30	60	0.0055
1500	PID	0.00357	2	35	40	0.0048
	IFLC	0.003	0.05	30	35	0.0047
1000	PID	0.0028	2	32	100	0.0037
	IFLC	0.0027	0.3	30	100	0.0036

It is observed that IFLC starting response is good for all the speeds and for most of the speeds overshoot is less. The improved performance of BLDC motor is obtained by minimizing the overshoot present in the transient response and settling time using the IFLC as compared with PID controller by obtaining the step response. The transient deviation of the response from the set reference following variation in load torque is found to be negligibly small along with a desirable reduction in settling time for the IFLC. The response is smooth and no oscillation in the case of IFLC. This is due to robust and accurate control structure of the IFLC. The results show significant improvement in the response of PMBLDC motor with the IFLC.

5.1 COMPARISON OF PERFORMANCE INDICES

A performance comparison of PID and IFLC controllers is also given based on the integral of the absolute value of the error (IAE), the integral of the squared error (ISE), the integral of the time-weighted absolute error (ITAE) and the integral of time-weighted squared error (ITSE) for the speeds 3500 rpm, 3000 rpm, 2500 rpm, 2000 rpm, 1500 rpm and 1000 rpm. The Table.4 shows a comparison of the performance indices for all the three controllers [14], [15].

Table.4. Comparison of performance indices between PID and IFLC

Reference speed	**Type of Controller**	**IAE**	**ISE**	**ITAE**	**ITSE**
3500	PID	0.8998	222	0.0037	0.243
	IFLC	0.8488	221	0.0013	0.236
3000	PID	0.6805	151	0.0019	0.1481
	IFLC	0.6519	150	0.0008	0.1427
2500	PID	0.4672	86.6	0.0010	0.0699
	IFLC	0.4504	86.3	0.0005	0.0691
2000	PID	0.3208	48.5	0.0006	0.0332
	IFLC	0.3068	48.4	0.0003	0.0329
1500	PID	0.1973	22.3	0.0006	0.0121
	IFLC	0.185	22	0.0002	0.0118
1000	PID	0.1125	7.93	0.0008	0.0034
	IFLC	0.0896	7.73	0.0001	0.0034

6. CONCLUSION

PID controller and IFLC have been employed for the speed control of PMBLDC motor. A performance comparison of PID controller and IFLC has been carried out by several simulations confirming the superiority of IFLC. The results have shown that IFLC is better than the PID controller for all the speeds. It is also found that the IFLC is robust to external load disturbances. The conclusion is that IFLC is found to be superior, more robust, faster and flexible and is insensitive to the parameter variations as compared with PID controller.

ACKNOWLEDGEMENT

The authors would like to thank the managements of JNTUH, Hyderabad and K.S.R.M College of engineering, kadapa, A.P for providing facilities with the required software to do this work.

REFERENCES

[1] T. J. E Miller, "*Brushless permanent magnet and reluctance motor drives*", Oxford Science publications, 1989.

[2] Paul C. Krause, "*Analysis of Electric Machinery*", McGraw Hill New York, 1986.

[3] A. Kusko and S. M. Peeran, "Definition of the brushless DC motor", *Proceedings of the IEEE Industry Application Society Annual Meeting IAS'88,* pp. 20–22, 1988.

[4] P. Pillay and R. Krishnan, "Modeling of permanent magnet motor drives", *IEEE Transactions on Industrial Electronics*, Vol. 35, No. 4, pp. 537-541, 1988.

[5] B. K. Lee and M. Ehsani, "A simplified functional model for 3-phase voltage-source inverter using switching function concept", *Proceedings of the Annual Conference*

of the IEEE Industrial Electronics Society, Vol. 1, pp. 462–467, 1999.

[6] Byoung-kuk Lee and Mehrard Ehsani, "Advanced Simulation Model for Brushless DC Motor Drives", *Electric Power Components and Systems*, Vol. 31, No. 9, pp. 841-868, 2003.

[7] S. K. Safi, P. P. Acarnley, and A. G. Jack, "Analysis and simulation of the high-speed torque performance of brushless DC motor drives", IEE Proceedings – Electric Power Applications, Vol. 142, No. 3, pp. 191–200, 1995.

[8] L. A. Zadeh, "Fuzzy sets", *Information and control*, Vol. 8, No. 3, pp. 338-353, 1965.

[9] C. Lee, "Fuzzy Logic in control systems, Fuzzy Logic controller, parts I and II", *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 20, No. 2, pp. 404-435, 1990.

[10] Ming – Yuan Shieh and Tzuu-Hseng, S. Li, "Integrated Fuzzy Logic Controller Design", *Proceedings of the IEEE International Conference on Industrial Electronics, Control and Instrumentation*, Vol. 1, pp. 279-284, 1993.

[11] Ming-Yuan Shieh and Tzuu-Hseng S. Li, "Implementation of Integrated Fuzzy Logic Controller for servomotor system", *Proceedings of IEEE International Conference on Fuzzy Systems*, Vol. 4, pp. 1755-1762, 1995.

[12] Kelvin M. Passino and Stephen Yurkovich, "*Fuzzy Logic Control*", Addison Wesley, 1998.

[13] M. N. Cirstea, A. Dinu, M. McCormick and J. G. Khor, "*Neural and Fuzzy Logic Control of Drives and Power Systems*", Newnes, 2002.

[14] Yanan Zhao and Emmanuel G. Collins Jr., "Fuzzy PI Control Design for an Industrial weigh Belt Feeder", *IEEE Transactions on Fuzzy Systems*, Vol. 11, No. 3, pp. 311-319, 2003.

[15] I.J. Nagrath and M. Gopal, "*Control systems engineering*", New Age International (p) Limited, Publishers, New Delhi, 3rd Edition, 2001.