Performance Analysis of PMSM Drive Using Intelligent Hybrid Fuzzy Controller

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Abstract: The Permanent Magnet Synchronous Motors are used in many applications that require rapid speed and torque response and high performance operations. The performance of the Permanent Magnet Synchronous Motor (PMSM) using PI Controllers and general fuzzy controllers are poor under load disturbances and transient conditions. To improve the dynamic performance of the PMSM drive, a novel implementation of speed controller based on modified fuzzy logic control is presented in this paper. A complete simulation of closed loop PMSM drive using Fuzzy logic control is implemented using MATLAB/Simulink. To enhance the performance of the system, a new control method, Intelligent Hybrid Fuzzy control and Accelerated fuzzy PI control is proposed. In this system, PI controller is used in inner current loop and modified fuzzy controller is used in speed loop instead of traditional PI controller. The effectiveness of proposed method is verified by simulation based on MATLAB. The Intelligent Hybrid Fuzzy controller has better performance than Accelerated fuzzy PI controller and fuzzy PID controller in PMSM drive system.

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Keywords: Fuzzy PID, Accelerated fuzzy PI, Intelligent Hybrid Fuzzy, PMSM, PWM.

1. Introduction

Recent development in power semiconductor technology, digital electronics, magnetic materials and control theory have enabled modern AC motor drives to face challenging high efficiency and high performance requirements in the industry. The Permanent Magnet Synchronous Motors (PMSM) is becoming popular in high performance applications compared to other types of AC motors due to its advantages features including high torque to current ratio, higher efficiency, low noise and robustness [1]. The fast and accurate response of motor and quick recovery of speed from disturbances are some of the important characteristics of high performance drive system used in robotics, rolling mills, traction, CNC machines and spindle drive [2].

Now-a-days, Fuzzy Logic Controller (FLC) based speed control is well known with its superior performance in the research community worldwide. It has proven by many simulations and experimental verifications by numerous publications with diversity of industrial drive applications such as high performance drives using vector controlled Induction motor [3]-[5],Permanent Magnet Synchronous Motor [6]-[9] and brushless DC motor. The vector controlled PMSM drives provides better dynamic response and lesser torque ripples. The outer speed loop in vector control greatly affects the system performance. Proportional plus Integral (PI) controllers are usually preferred but due to its fixed proportional gain (K_p) and integral time constant (T_i), the performance of the PI controllers are affected by parameter variations, load disturbances and speed variations.

These problems can be overcome by the fuzzy logic controllers [10], which do not require any mathematical model and are based on the experience of the system operator. But the performance of the fuzzy controller as compared to the PI controller is superior under transient conditions. The establishment of the simulation model of PMSM and its control system is of great significance to the verification of a variety of control algorithms and the optimization of entire control system. The entire PMSM control system as a whole will be divided into several independent functional modules: PMSM module, inverter module, co-ordinate transformation module and so on. The speed controller used in PMSM drive system plays an important role to meet the requirements of the drive system.

In this paper, a nonlinear fuzzy PI controller is proposed to improve the transient response of the PMSM system based on fuzzy control law suggested by Ying et al [11], [12]. Most of the popular fuzzy controllers developed so far with two inputs, such as error and rate of change of error about a set point. However, the nonlinear fuzzy PID controller proposed in this paper has an additional input named accelerated rate of change of error to improve the transient response of the PMSM system. The PMSM drive system with three types of controllers named as fuzzy

PI, Accelerated fuzzy PI and Intelligent Hybrid fuzzy controller are implemented to improve the transient response, load disturbances and speed variations.

2. Mathematical Model of PMSM

The equations of PMSM are developed in rotating reference frames. The stator of the PMSM and the wound rotor synchronous motor are similar. The permanent magnets used in the PMSM are of a modern rare-earth variety with high resistivity, so induced currents in the rotor are negligible. In addition, there is no difference between the back EMF produced by permanent magnet and that produced by an excited coil. Hence the mathematical model of PMSM is similar to that of the wound rotor Synchronous Motor [13]. The model of the PMSM is developed using the following assumptions

1. Saturation is neglected
2. The induced EMF is sinusoidal
3. Eddy current and hysteresis losses are negligible
4. There are no field current dynamics.

With these assumptions, the stator d, q equations of the PMSM in the rotor reference frame are [14],

$$V_q = R_s i_q + L_q p i_q + \omega_r L_d i_d + \omega_r \varphi_f \quad (1)$$

$$V_d = R_s i_d + L_d p i_d - \omega_r L_q i_q \quad (2)$$

Also flux linkage equation can be written as,

$$\varphi_d = L_d i_d + \varphi_f \quad (3)$$

$$\varphi_q = L_q i_q \quad (4)$$

Where V_d and V_q are the d, q axis voltages, i_d, i_q are the d, q axis stator currents, L_d, and L_q are the d, q axis inductances, φ_d and φ_q are the d, q axis stator flux linkages, R_s is the stator winding resistance per phase and ω_r is rotor electrical speed.

The electro mechanical torque is given by

$$T_e = (3/2)(P/2)[\varphi_f i_q - (L_d - L_q) i_d i_q] \quad (5)$$

and the equation of motor dynamics is,

$$T_e = T_L + B\omega_m + Jp\omega_m \quad (6)$$

Where P is the number of poles, T_L is the load torque, B is the damping co-efficient, ω_m is the rotor mechanical speed, J is the moment of inertia and p is the differential operator.

$$\omega_r = (P/2)\,\omega_m \quad (7)$$

The model equations of PMSM can be rearranged in the form of following first order differential equations as [15],

$$p i_d = (V_d - R_s i_d + \omega_r L_q i_q) / L_d \quad (8)$$

$$p i_q = (V_q - R_s i_q - \omega_r L_d i_d - \omega_r \varphi_f) / L_q \quad (9)$$

$$p\omega_m = (T_e - T_L - B\,\omega_m) / J \quad (10)$$

$$p\theta_m = \omega_m \quad (11)$$

$$\theta_m = \int \omega_m \quad (12)$$

θ_m is the position angle of rotor.

In order to achieve maximum torque per ampere and maximum efficiency with linear characteristics, direct axis current component i_d forced to zero [16] and the reluctance torque is zero.

$$T_e = (3/2)(P/2)\,\varphi_f\, i_q \quad (13)$$

The d, q variables are obtained from a, b, c variables through the park transform as [13],

$$V_q = 2/3[V_a \cos\theta + V_b \cos(\theta - 2\Pi/3) + V_c \cos(\theta + 2\Pi/3)] \quad (14)$$

$$V_d = 2/3[V_a \sin\theta + V_b \sin(\theta - 2\Pi/3) + V_c \sin(\theta + 2\Pi/3)] \quad (15)$$

The a, b, c variables are obtained from the d, q variables through the inverse of the park transform as,

$$V_a = V_q \cos\theta + V_d \sin\theta \quad (16)$$

$$V_b = V_q \cos(\theta - 2\Pi/3) + V_d \sin(\theta - 2\Pi/3) \quad (17)$$

$$V_c = V_q \cos(\theta + 2\Pi/3) + V_d \sin(\theta + 2\Pi/3) \quad (18)$$

The torque equation is similar to that of separately excited DC motor, and this completes the transformation of a PMSM to an equivalent separately excited dc motor [17].

3. Fuzzy PID Speed Controller

The Fuzzy PID controller is designed to replace the conventional PI controller. The Fuzzy PID controller is used to improve the performance of the system [18]. The fuzzy inference of Fuzzy PID controller is based on the fuzzy rule table set previously. So the algorithm of fuzzy inference is not complex. The parameters of PID can be adjusted on-line, which can be changed through the inquiry to fuzzy control rules table saved a forehand in the computer. The calculated speed of controller is very quick, which can satisfy the rapid need of controlled object. The block diagram of control system is shown in Figure1.

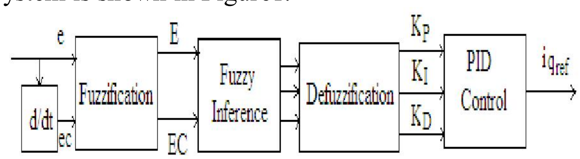

Figure 1 Block diagram of Fuzzy PID controller

The control algorithm of traditional PID controller can be described as

$$u(k) = k_p e(k) + k_i \int e(k) + k_d \frac{d}{dt} e(k) \quad (19)$$

The control algorithm of traditional PI controller can be described as,

$$u(k) = k_p e(k) + k_i \int e(k) \quad (20)$$

Where, k_p is the proportional gain, k_i is the integral gain, k_d is the differential gain and e(k) is the speed error. The design algorithm of Fuzzy PID controller in this paper is to adjust the k_p, k_i and k_d parameters online through fuzzy inference based on the speed error (e) and rate of change of speed error (ec) to make the control object attain the good dynamic and static performances.

(1) The input variables and output variables:

Speed error (e) and rate of change of speed error (ec) are used as fuzzy input and the proportional constant k_p the integral constant k_i, differential constant k_d are the fuzzy outputs.

(2) Fuzzy language of input and output variables:

The fuzzy variable of input variable e is E and ec is EC. The fuzzy variable of output variable k_p, k_i and k_d are K_P, K_I and K_D. The fuzzy sets of E and EC are all defined as {NB, NS,ZO, PS, PB}, where NB, NS, ZO, PS and PB represent Negative Big, Negative Small, Zero, Positive Small and Positive Big respectively. The fuzzy sets of K_P, K_I and K_D are defined as {Z, S, M, B}, where Z, S, M and B represent Zero, Small, Medium and Big. The membership functions of E, EC, K_P, K_I and K_D are triangular distribution functions. The membership functions for each variable are shown in Figure 2, Figure 3, Figure 4 and Figure 5 respectively.

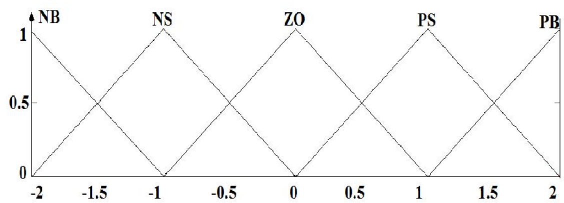

Figure 2 Fuzzy membership functions of E and EC

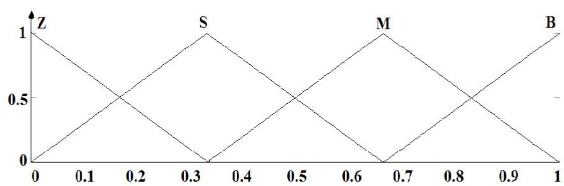

Figure 3 Fuzzy membership functions of K_P

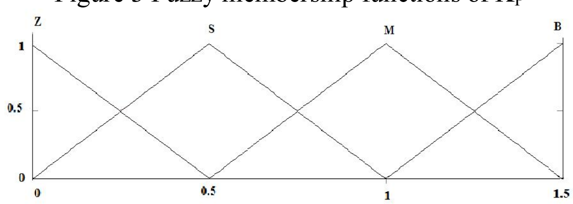

Figure 4 Fuzzy membership functions of K_I

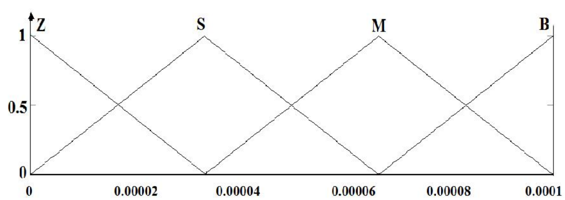

Figure 5 Fuzzy membership functions of K_D

(3)Fuzzy Rules Regulations:

The principle of designing fuzzy rules is that the output of controller can make the system output response dynamic and static performances optimal. The fuzzy rules are generalized as Table 1, Table 2 and Table 3 according to the expert experiment in PMSM servo system and simulation analysis of the system [18].

Table 1. Control Rules for K_P

K_P		EC				
		NB	NS	ZO	PS	PB
E	NB	B	B	B	B	M
	NS	M	B	S	S	S
	ZO	M	B	Z	S	B
	PS	S	S	S	S	S
	PB	M	B	B	M	B

Table 2 Control Rules for K_I

K_I		EC				
		NB	NS	ZO	PS	PB
E	NB	Z	Z	Z	Z	Z
	NS	M	M	M	M	M
	ZO	B	B	Z	B	B
	PS	S	M	M	M	M
	PB	Z	S	B	B	B

Table 3 Control Rules for K_D

K_D		EC				
		NB	NS	ZO	PS	PB
E	NB	Z	M	B	M	Z
	NS	S	M	B	B	S
	ZO	S	B	B	M	Z
	PS	S	B	M	M	S
	PB	Z	S	M	S	Z

The Mamdani inference method is used as the fuzzy inference mode. The inference can be written as "IF A AND B THEN C". For example "IF E is NS AND EC is PS THEN KP is S, KI is M KD is B ". K_P, K_I and K_D are written the same as 25 fuzzy condition statements. The output variable can be obtained by the MIN - MAX inference. The weighted average method is adopted for defuzzification.

3.1. Accelerated Fuzzy PI Speed Controller

This is a modified form of Fuzzy PI controller. The Accelerated Fuzzy PI controller is proposed in this paper to improve transient response of the PMSM drive system. The fuzzy PI controller uses only two inputs, speed error (e) and rate of change of speed error (ec). But in this model an additional input named 'accelerated rate of change of error' (acc) is used to improve the transient response of the system [19]. With these three inputs, the structure of the FLC is composed of two independent parallel fuzzy control blocks, each of which contains the corresponding fuzzy control rules and a defuzzifier. The incremental output of the FLC is formed by algebraically adding the outputs of the two fuzzy control blocks. Block diagram of the configuration is shown in Figure 6.

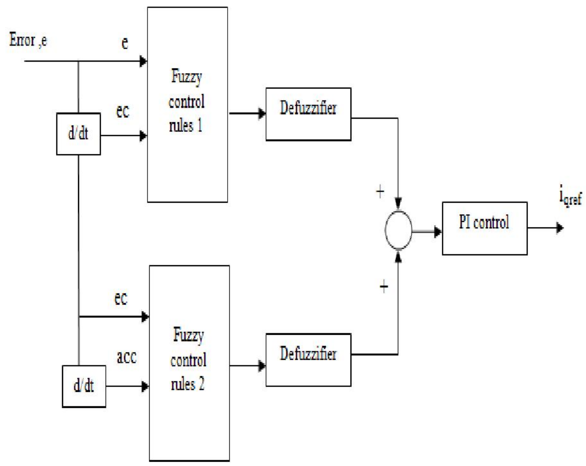

Figure 6 Block diagram of Accelerated Fuzzy PI controller

3.2. Intelligent Hybrid Fuzzy Controller

In Intelligent Hybrid Fuzzy controller, the Fuzzy PID and Accelerated fuzzy PI controllers are combined by a blending mechanism that depends on a certain function of actuating error is proposed. The difference between the actual speed and the reference value is the actuating error. A switching scheme is introduced on the blending mechanism that makes a decision on the priority of the two controller parts. The Intelligent Hybrid Fuzzy controller has the advantage of Fuzzy PID control and Accelerated fuzzy PI control. The Intelligent Hybrid Fuzzy controller offers better speed responses for large speed errors [20] [21]. The block diagram of PMSM control system with Intelligent Hybrid Fuzzy controller is shown in Figure 7.

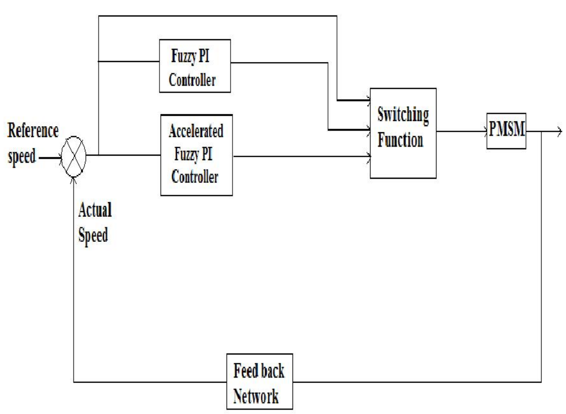

Figure 7 Block diagram of PMSM control system with Intelligent Hybrid Fuzzy controller

4. Simulation Model of PMSM Based on MATLAB

In this MATLAB simulation module, two control loops are used which are inner current loop using PI controller and the outer speed loop using Fuzzy based PI controller is built based on i_d=0. This PMSM control system mainly includes; PMSM module, three phase voltage inverter module, co-ordinate transformation module, speed loop controller, current loop controller etc.

4.1.PWM current controller

In this simulation model, PMSM fed by a current controlled PWM inverter is built by using six power semiconductor devices. The PWM current controllers [22] are widely used. The switching frequency is usually kept constant. They are based on the principle of triangular carrier wave of desired switching frequency and are compared with the error of controlled signal. The difference between reference signal generated in controller and the actual current are compared with the carrier signal. The obtained voltage signal triggers the gates of the voltage source inverter to generate the desire output. If the error command is greater than the carrier, the inverter leg is held switched to the positive polarity. When the error command is less, the inverter leg is switched to negative polarity. This will generate the PWM signal and the output voltage of the inverter is proportional to the current error command.

4.2. PMSM module

The inner structure of PMSM sub system which is used to calculate the direct axis current is shown in Figure 8 and the sub system which used to calculate the quadrature axis current is shown in Figure 9. The sub system shown in Figure 10 is used to calculate torque (T_e), electrical speed (ω_e) and mechanical speed of rotor (ω_m) and position signals (θ). The mechanical speed is converted into electrical speed by using number of pole pairs. The d-axis current and q-axis currents are converted into three phase currents by using transformation module [23]. The input of PMSM module is three phase voltage which is responsible for loading torque T_m. The three phase voltages are transformed into direct axis voltage and quadrature axis voltage using transformation module. The quadrature axis current produces electromagnetic torque [23]. The difference between electromagnetic torque and load torque is used to calculate acceleration by assuming damping co-efficient is zero. The speed can be obtained from first integral of acceleration and position signals are obtained from the first integral of speed. The Figure11 shows the complete simulation model of a PMSM drive with Intelligent Hybrid Fuzzy controller in the outer loop and PI current controllers in the inner loops.

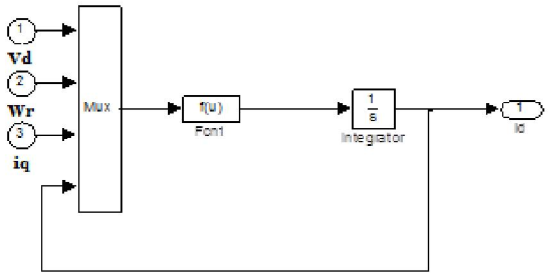

Figure 8 Simulation model of d-axis current

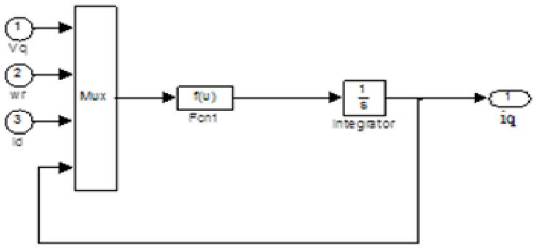

Figure 9 Simulation model of q-axis current

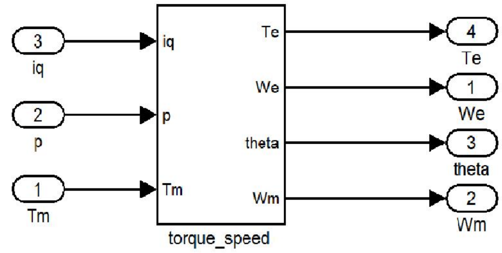

Figure 10 Simulation model of torque and speed

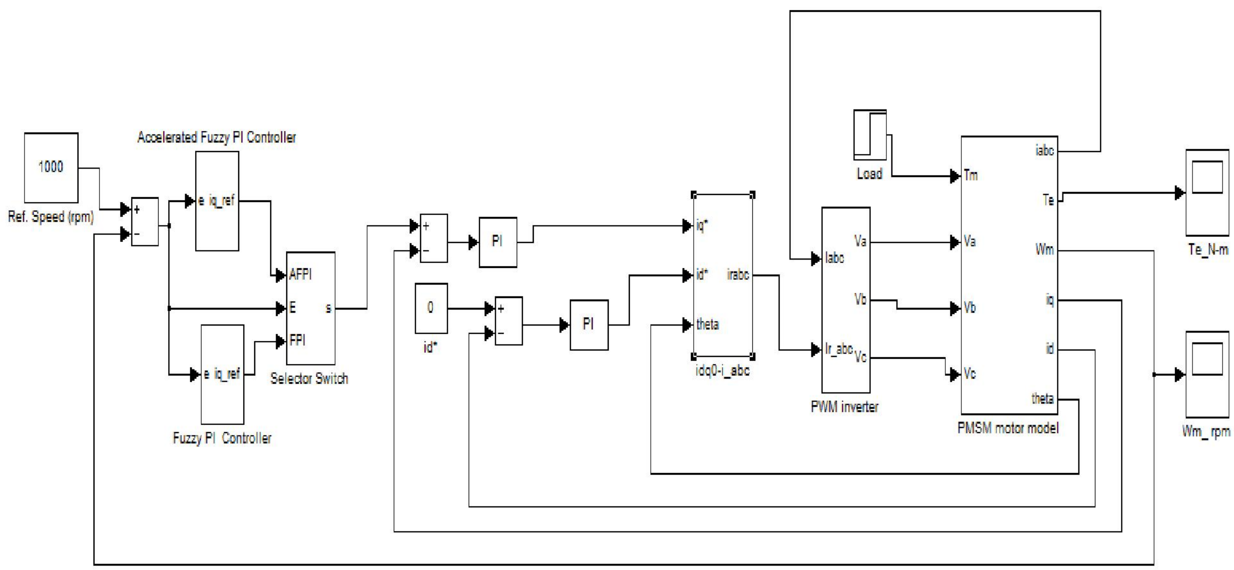

Figure 11 Simulation Model of PMSM Drive System with Intelligent Hybrid Fuzzy Controller

5. Results and Discussions

The simulation of PMSM drive system with Fuzzy logic controller algorithms has been carried out using MATLAB. The speed, torque and current responses of PMSM are observed with Fuzzy PID controller, Accelerated Fuzzy PI controller and Intelligent Hybrid Fuzzy controller. The performances are observed under various operating conditions such as change in speed, change in load etc., and the results are presented in this paper. The parameters of PMSM used in this simulation model are given in Table 4.

Table 4 Motor Parameters

Stator Resistance (R_s)	1.4Ω
Direct axis inductance (L_d)	6.6 mH
Quadrature axis Inductance (L_q)	5.8 mH
Moment of Inertia (J)	0.00176 Kg.m^2
Number of poles (P)	6

The results of PMSM drive system using Fuzzy PID controller, proposed Accelerated Fuzzy PI controller and Intelligent Hybrid Fuzzy controller for speed are shown in Figure 12, Figure 13 and Figure 14 respectively. The torque response of Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy controllers is shown in Figure 15, Figure 16 and Figure 17 respectively. The performance of this PMSM drive using Intelligent Hybrid Fuzzy has been improved when it is compared with Fuzzy PID and Accelerated Fuzzy PI controllers under loaded condition.

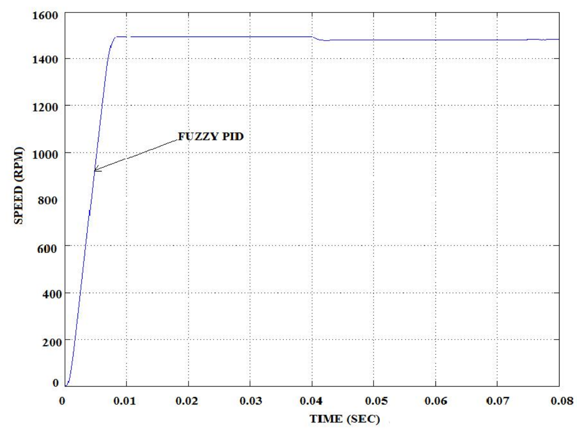

Figure 12 Speed Response of Fuzzy PID Controller

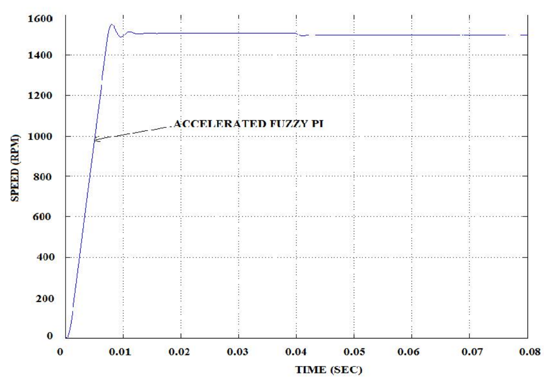

Figure 13 Speed Response of Accelerated Fuzzy PI Controller

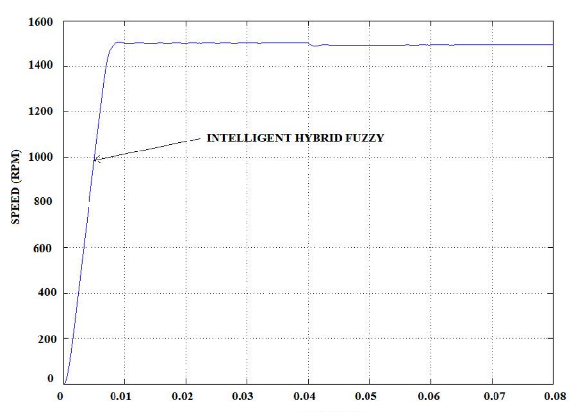

Figure 14 Speed Response of Intelligent Hybrid Fuzzy Controller

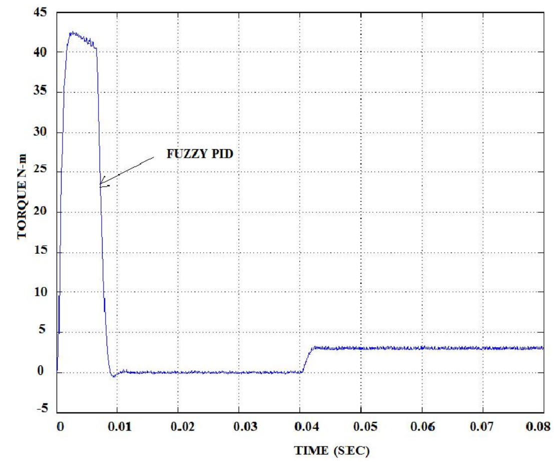

Figure 15 Torque Response of Fuzzy PID Controller

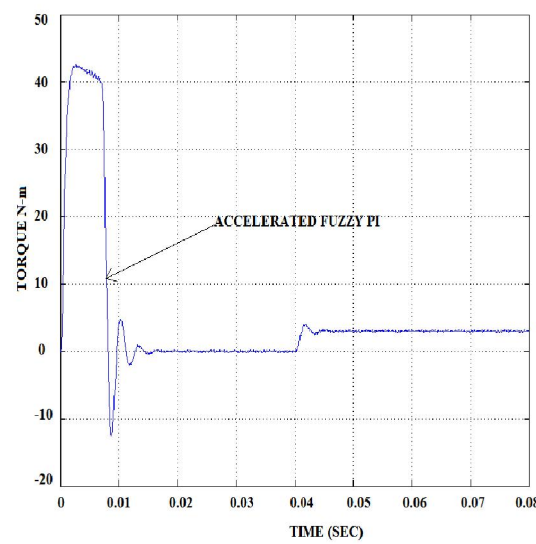

Figure 16 Torque Response of Accelerated Fuzzy PI Controller

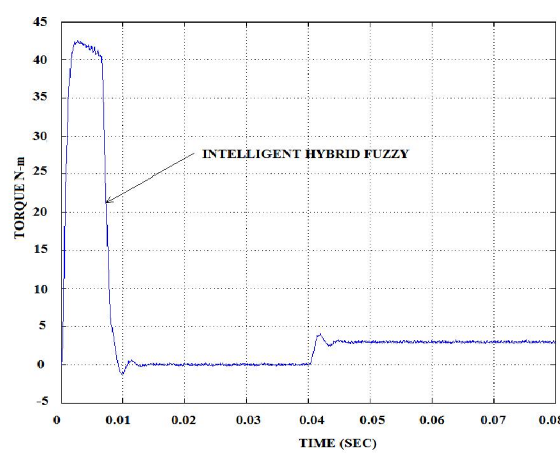

Figure 17 Torque Response of Intelligent Hybrid Fuzzy Controller

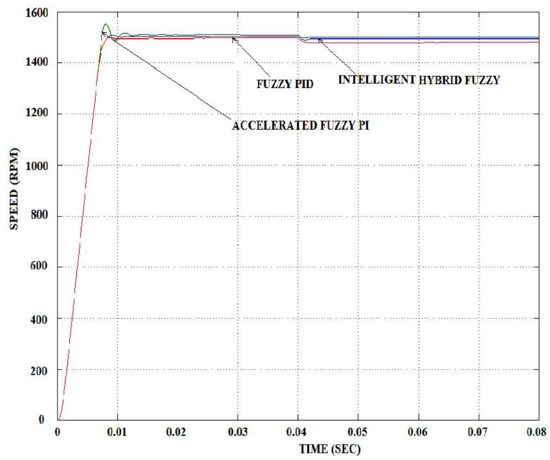

Figure 18 Comparison of Speed for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy Controllers

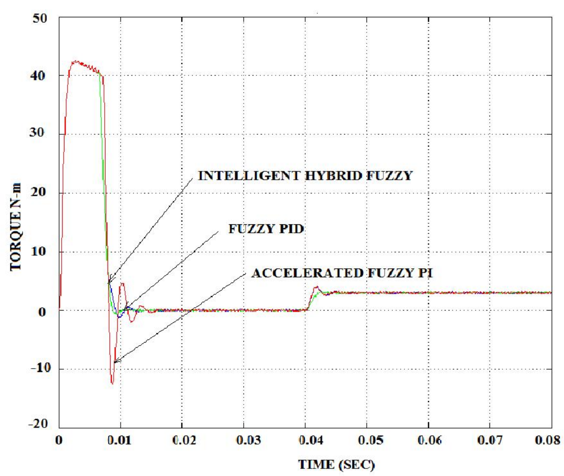

Figure 19 Comparison of Torque Response for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy Controllers

The speed and the torque response of Fuzzy PID, Accelerated Fuzzy PI controllers are compared with Intelligent Hybrid Fuzzy controller and shown in Figure18 and Figure 19 respectively. Speed drop under loaded condition for Fuzzy PID, Accelerated Fuzzy PI controllers are compared with Intelligent Hybrid Fuzzy controller and it is shown in Figure 20. The overshoots of Speed for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy controllers are shown in Figure 21. The performance Comparisons of Speed under loaded condition is shown in Figure 22.

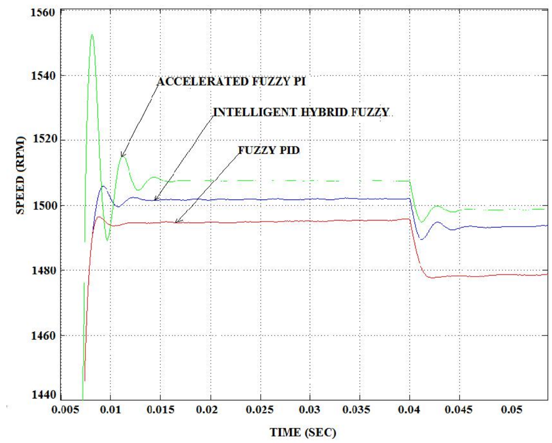

Figure 20 Comparison of Speed drop under load for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy Controllers

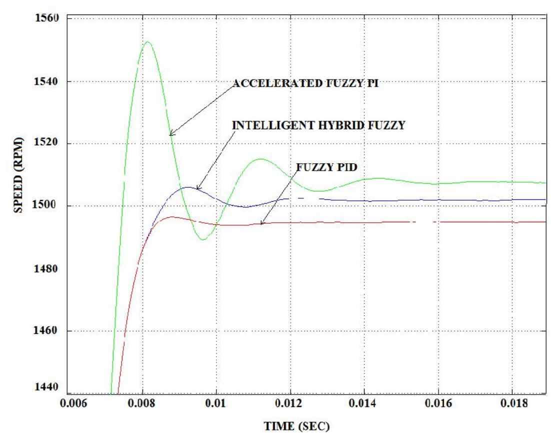

Figure 21 Comparison of overshoot of Speed for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy Controllers

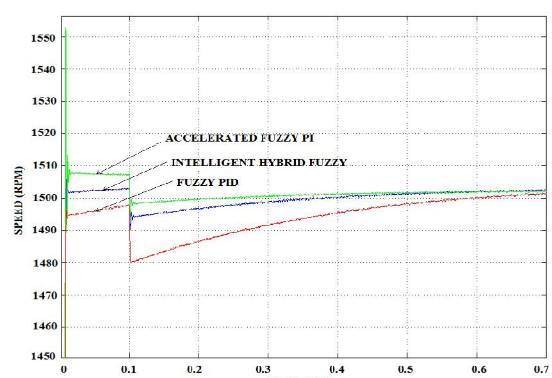

Figure 22 Comparison of Speed under load

The comparison of controller performance for speed ω_m = 1500 RPM using Fuzzy PID, Accelerated fuzzy PI and Intelligent Hybrid Fuzzy controllers are tabulated in Table 5.

Table 5. Comparison of Controller Performance

Name of Controller	Peak Overshoot at starting %	Steady State Error %	Speed drop at Load %	Settling time after Load sec
Fuzzy PID	0	0.53	1.33	0.5
Accelerated Fuzzy PI	3.53	0.33	0.53	0.25
Intelligent Hybrid Fuzzy	0.33	0.13	0.53	0.25

6. Conclusion

In this paper a novel desirable closed loop control system for PMSM is proposed and simulated. The three types of controllers, fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy controller are used as speed controllers in the PMSM control and their performances are compared. The performance differences due to the all the three types of controllers are examined for torque and speed. The simulation results proved that system performance had been improved by applying Intelligent Hybrid Fuzzy controller. The proposed system improves speed response and the control criteria such as overshoot, steady state error and settling time. More over it is less sensitive to load fluctuations. The transient response of speed under load fluctuations using Intelligent Hybrid Fuzzy controller is better than fuzzy PID controller with less settling time after load to reach rated speed and this leads to robust controller. The proposed Intelligent Hybrid Fuzzy controller based PMSM drive is suitable for industrial applications to maintain constant speed under loaded condition during machining operations in CNC machines and special machines in machine shops.

References

1. R. Krishnan., Selection criteria for servo motor drives, IEEE Trans.,Ind. App., Vol.IA 23, March/April 1987, pp. 270-275.
2. Pillay P., Krishnan R., Modelling, Simulation and Analysis of Permanent Magnet Synchronous Motor Drives, Part I: The Permanent Magnet Synchronous Motor Drive, IEEE Trans., Ind. App., Vol.25, March/April 1989, pp. 265-273.
3. V.Kumar, R.R. Joshi,Hybrid controller based intelligent speed control of Induction Motor, Journal of Theoritical and Applied Information Technology, 2005, pp. 71-75.
4. H.A.F. Mohamed, W.P.Hew, Fuzzy Logic Vector Control of Induction Motor, in.Proc.TECON2000, Vol.3, pp. 324-328.
5. M.N.Uddin, T.S.Radwan, M.A.Rahman, Performance of Fuzzy Logic Based Indirect Vector Control for Induction Motor Drive, IEEE Transactions on Industry Applications, Vol.38, Sep-Oct 2002, pp. 1219-1225.
6. A.Karakaya,E. Karakas, Performance Analysis of PM Synchronous Motor Using Fuzzy Logic and Self Tuning Fuzzy PI Speed Controls, The Arabian Journal for Science and Engineering, Vol.33, Apr-2008, pp. 153-177
7. A.G. Aissaoui, M. Abid, H.Abid, A.Tahour, A.K. Zeblah, A Fuzzy Logic Controller for Synchronous Machine, Journal of Electrical Engineering, Vol.58, 2007, pp. 285-290.
8. Patil.N.J, Chile. R.H, Waghmare.L.M, Fuzzy Adaptive Controllers for Speed Control of PMSM drive, International Journal of Computer Applications, Vol.1-11, 2010, pp. 94-101.
9. J.W.Jung, T.H.Kim, H.H.Choi, Speed control of a Permanent Magnet Synchronous Motor with a torque observer: a fuzzy approach, IET Control Theory Application, Vol. 4, 2010, pp. 2971–2981
10. M.N. Uddin and M.A.Rahman, Fuzzy Logic Based Speed Control of an IPM Synchronous Motor Drive, in Proc. IEEE Canadian Conf. Elect. Computer Engineering , Vol.9-12, 1999, pp. 1259-1264.
11. Siler W, Ying H (1989), Fuzzy Control theory: the linear case, Fuzzy sets and Systems, vol 33, pp. 275-290.
12. Ying H, Siler W, Buckley JJ (1990), Fuzzy control theory: the nonlinear case, Automatica, vol. 26, pp. 513-520.
13. Pillay P., Krishnan R., Modelling of Permanent Magnet Motor Drives, IEEE Transactions on Industrial Electronics, Vol.35, November 1988, pp. 537-541
14. Faiz J., Manoochehri M., Shahgholia Gh., Performance Improvement of a Linear Permanent Magnet Synchronous Drive using Fuzzy Logic Controller,Proceedings of the IEEE

International Conference on Power System Technology, 2010, pp. 1-5.
15. LIU Ting-Ting., TAN Yu., WU Gang., WANG Shu-mao., Simulation Model of PMSM Vector Control System Based on Matlab/Simulink, Proceedings of the IEEE International Conference on Measuring Technology and Mechatronics Automation, 2009, pp. 343-346.
16. Bhim Singh., B.P.Singh.,Sanjeet Dwivedi., DSP Based Implementation of Hybrid Speed Controller for Vector Controlled Permanent Magnet Synchronous Motor Drive, IEEE ISIE., July 9-12, 2006, pp. 2235-2241.
17. Anathamoorthy N. P ,Baskaran K, Simulation of PMSM based on current hysteresis PWM and Fed PI controller, Procceedings of International Conference on Computer Communication and Informatics (ICCCI)-Jan-10-12, 2012, pp. 804-808.
18. Limei Wang, Mingxiu Tian and Yanping Gao, Fuzzy Self-adapting PID Control of PMSM Servo System,IEEE Proceeding from Electric Machines & Drives Conference, Vol.1, No.10, 2007, pp.860-863.
19. J H Kim, S.J Oh, A Fuzzy PID Controller for Nonlinear and Uncertain Systems, Soft computing 4, Springer-Verlag, 2000, pp. 123-129.
20. Ananthamoorthy N. P., Baskaran K., Speed and Torque Control of PMSM using Hybrid Fuzzy PID Controller, European Journal of Scientific Research, Vol. 85 No 2, September 2012, pp. 160– 171.
21. Amit Vilas Sant and K. R. Rajagopal, PM Synchronous Motor Speed Control Using Hybrid Fuzzy-PI With Novel Switching Functions, IEEE Transactions on Magnetics, October 2009, Vol. 45, pp. 4672- 4675.
22. Junjie Ren., Hui Feng., Hongying Ren., Yi Huang., Simulation of PMSM Vector Control system Based on Propeller Load characteristic, Proceeding of the IEEE International Conference on Intelligent Control and Information Processing, August 13-15, 2010, pp. 735-737.
23. R.Krishnan, Electric Motor Drives Modeling Analysis and Control, Newyork (Pearson Education Publisher Company) 2003.

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