A Fuzzy Logic Controller Based Vector Control of IPMSM Drives

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ABSTRACT:

This paper explores a fuzzy-logic based speed controller of an interior permanent magnet synchronous motor (IPMSM) drive based on vector control. PI controllers were mostly used in a speed control loop based field oriented control of an IPMSM. The fundamentals of fuzzy logic algorithms as related to drive control applications are illustrated. A complete comparison between two tuning algorithms of the classical PI controller and the fuzzy PI controller is explained. A simplified fuzzy logic controller (FLC) for the IPMSM drive has been found to maintain high performance standards with a much simpler and less computation implementation. The Matlab simulink results have been given for different mechanical operating conditions. The simulated results confirmed that the FLC-PI has a lower ripple than the conventional PI controller.

Keywords: fuzzy logic controller, vector control, PID controller, IPMSM.

محاكاة السيطرة باستخدام المنطق المضبب للمحركات التزامنية ذو المغناطيس الدائمي

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الخلاصة:

عرض هذا البحث وحدة تحكم السرعة في المكائن المتزامنة ذو مغناطيس الدائمي (PMSM) وفق سيطرة المتجه . ان وحدات تحكم السيطرة PI التقليدي تستخدم للسيطرة على سرعة المكائن المتزامنة ذو المغناطيس الدائمي. ان اساسيات خوازميات المنطق المضبب قد تم تقديمها في هذا العمل لتحسين الاداء والحصول على تحكم بسرعة الماكنة بشكل افضل. حيث تم مقارنة كاملة بين المتحكم باستخدام PI الكلاسيكية مع المتحكم باستخدام قوانين المنطق المضبب. وكانت النتائج تبين ان المتحكم باستخدام المنطق المضبب ذو اداء عالي ناهيك عن بساطة تنفيذ الخوازميات. هذا وقد أعطيت Matlab/SIMULINK نتائج جيدة لمحاكاة FLC -PI بعد ان تم تشغيل الموديل لظروف تشغيل ميكانيكية مختلفة .

الكلمات الرئيسية:

المسيطر ذو المنطق المضبب، سيطرة المتجه، مسيطر PID، المكائن المتزامنة ذو المغناطيس الدائمي (PMSM).

1. INTRODUCTION

Power electronics system models are often ill-defined thus far. Even for a known plant there may be parameter variation problems. Vector or field- oriented control (FOC) of a drive can overcome this problem and it is very widely used for high performance PMSM drive applications as well; however an accurate vector control is quite difficult [Bilmal, 2002]. The vector control is used to obtain the fast torque response for interior permanent magnet synchronous motor (IPMSM) drive, thus the current and speed controllers both play an important role for the drive performance [Blaschke, 1972].

PI controllers are mostly used for speed control due to their simple structure and also for providing a good performance over a wide speed range. However, tuning the PI controller is the main problem. The system parameters were changed through the operating conditions. In addition the PI control method is a linear control method and could not be worked with a discrete system.

A variety of control techniques have been developed to solve the aforementioned problems, offline PI and PID tuning, nonlinearity compensation, modeling, parameters estimation [Uddin et al. (2002) , Rubaai (2002), Yubazaki (1993), Ko (1993), Wai (2001), Lin et al. (1998) and Jae et al. (2007)]. Among all of the control techniques Fuzzy Logic Control (FLC) was mostly utilized in industrial applications. FLC is an adaptive and nonlinear control method, which gives robust performance for a linear and nonlinear plant with parameter variation.

Recently, a fuzzy logic controller (FLC) has been widely applied in various drive applications including the speed control. The fault detection sensitivity is improved by using fuzzy logic controller [Quiroga et al., 2008]. Sometimes it is not easy to get a satisfied control characteristic by using normal linear PI controller because of the nonlinearity of the systems; hence an integral separated self-tuning fuzzy PI controller has been developed [Sun Qiang and Zhou, 2003]. The major feature of FLC's doesn't depend on the mathematical model of the plant (which could be very complicated), but only on expert operator knowledge.

In this paper, a vector control scheme based on FLC for IPMSM drives is proposed. The control rules and the membership functions have been designed and explained.

2. PMSM MODELING

The space vector diagram is shown in Figure (1) the electrical equations for the IPMSM in the synchronously rotating frame (d-q) model are given as [Azizur Rahman et al., 2003]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + w_r \begin{bmatrix} -\lambda_q \\ \lambda_d \end{bmatrix}$$
(1)

$$\begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\lambda_m \\ 0 \end{bmatrix}$$
(2)

The electromagnetic torque Te depends on the interlinkage flux and the difference between the d- and q-axis inductance (L_d-L_q) is given as:

$$T_e = \frac{3}{2} P[\lambda_m i_q - (L_q - L_d) i_d i_q]$$
(3)

The conventional control of IPMSM is done by linearizing the q-axis current expression by setting the d-axis current equal to zero. Then the electromagnet torque equation becomes:

$$T_e = \frac{3}{2} P \lambda_m i_q$$
(4)

$$\frac{dw_m}{dt} = (T_e - T_L - Bw_m)/J$$
(5)

$$\frac{d\theta_r}{dt} = w_r$$
(6)

3. SYSTEM DESCRIPTION

IPMSM is controlled by a Space vector PWM inverter [M.N. Uddin et al., 2000]. The motor drives a mechanical load characterized by moment of inertia (J), viscosity friction coefficient (B), and load torque (TL). The speed control loop uses a fuzzy logic controller instead of a simple proportional-integral PI controller to produce the quadrature-axis current (iq) which controls the motor torque whereas the motor flux is controlled by the direct-axis current (id). Figure (2) shows the block diagram of the standard PMSM drive system.

4. THE FUZZY CONTROLLER

Fuzzy logic is an extension of a multi-valued logic based on the theory with unshaped boundaries and in which membership is a matter of degree. The basic of fuzzy logic are linguistic variables, whose values are words rather than numbers [Dubois and Prade, 1980]. The first step for controller design is a determination of condition variable number and fuzzy partition of state space. From this, the membership function is given with the fuzzification. And then, a fuzzy inference is done by giving control input. Finally, defuzzification is needed to obtain the crisp control input. The coarse and fine rule tables given by off-line calculation are used to guarantee short sampling time. A rule in fuzzy logic can be based on the experience of experts and that it represents a combination of the operating system and quantitative knowledge of the motor conditions.

4.1 Fuzzy Logic Controller Structure

FLC block diagram is illustrated in Fig.3 consists from four blocks:
-Fuzzification: transforms crisp to fuzzy input.
-Inference engine: decides which rules from knowledge base are fired.

-Defuzzification: transforms fuzzy output to crisp output.
-Knowledge base consists of rule base [Nguyen et al., 1995].

4.1.1 Fuzzification

Fuzzification is the process of taking the numerical (crisp) value of a (crisp) variable and relating it to a fuzzy set through a membership function. In the FLC for PMSM drive, the error between the actual rotor speed and the reference speed command and the error during the sampling time are chosen for the condition variables.

The actual inputs to the fuzzy system are e_1 and e_2 which represent the speed error and the change in speed error respectively as defined by Eqs. (7) and (8). The gains G_1 and G_2 can be varied to tune the fuzzy controller for the desired performance [Uddin et al., 2002]. The output gain G_3 can also be tuned.

$$\Delta w_r(n) = \omega_r(n) - \omega_r(n-1)$$

$$e_1(n) = G_1(\omega_r(n) - \omega_r(n-1))$$

$$(7)$$

$$e_2(n) = G_2(\Delta\omega_r(n) - \Delta\omega_r(n-1))$$

$$e_2(n) = G_2(e_1(n) - e_1(n-1)) \qquad (8)$$

In discrete form equation 8 becomes:

$$e_2(n) = G_2\left(\frac{e_1(n) - e_1(n-1)}{T_s}\right) \qquad (9)$$

Using Z-transform

$$e_2(Z) = G_2\left(\frac{Z-1}{T_s Z}\right)e_1(Z) \qquad (10)$$

Where Ts is the sampling time and G_1 and G_2 are the input scaling factors and k is the

output scaling factor. Their values affect the membership functions [10].

The output of the FLC is the torque producing current relating to the change in the torque producing current at the n-th sampling time, where k is the FLC gain as defined in Eq. (11) by:

$$i_q(n) = i_q(n-1) + k\Delta i_q(n))$$
(11)

In this system, the universe of discourse for e_1, e_2 as a control inputs are given as [-500 500   rad/sec],   [-500   500   rad/sec^2], respectively and the output variable as [-400 400 A].

4.1.2 Controller Linguistic Terms and Memberships Functions

A membership function is normally expressed graphically and tends to illustrate how completely a crisp variable belongs to a fuzzy set. Trapezoids and triangles are the two most popular membership functions. The ideal membership function is a bell-shaped curve with a Gaussian distribution. The trapezoid function comes fairly close to a bell-shaped curve and is a lot easier to implement and faster to execute. Five linguistic terms for each one of the input $e_1(n)$, $e_2(n)$ and the output $\Delta i_q(n)$ are chosen. These terms are Negative Big(NB), Positive Big(PB), Negative Small(NS),   Positive Small(PS), Zero(ZE). The memberships are shown in Fig.4 where the input e1 and e2 are normalized to the range [500,-500].   These memberships use a Gaussian membership function whereas a single spike is used for the output $\Delta i_q(n)$ since the sugeno fuzzy system type is used to construct a fuzzy controller.

The fuzzy membership functions of the input variables and output variable are shown in Fig. 4a and 4b respectively,   and the corresponding fuzzy logic rule is shown in Table (1).

The fuzzy rules have the form as :
Rule 1: IF is NB and is PB THEN is ZE ,

An easier way to visualize a 1st order system by defining the location of a moving singleton, means the singleton output spikes can move around linearly depending on the input signals (see Figure (5) which shown the ruler viewer). Nevertheless the control rules are contributed as follows [Jae et al., 2007]:

a- When the actual rotor speed is lower than the reference value then $\Delta i_q(n)$ should be large in order to bring the speed to the reference value.

b- When the actual rotor speed is near to the reference speed then $\Delta i_q(n)$ should be a little small.

c- When the actual rotor speed approaching the reference speed is within a short time then $\Delta i_q(n)$ should be kept constant so as to avoid the overshooting.

d- When the actual rotor speed has the same value of the reference speed without a sensible changing then $\Delta i_q(n)$ is required to be changed gradually to avoid the output from moving away.

e- When the actual rotor speed reaches the reference value and remains steady then $\Delta i_q(n)$ should remain unchanged.

f- When the speed is higher than the reference speed $\Delta i_q(n)$ should remain negative.

4.1.3 Defuzzification

Defuzzification is the process of taking a fuzzy value and converting it into a numerical (crisp) value (quantifications). Defuzzification is required for generating a real-world output. Various methods have been used for defuzzification [Blaschke, 1972]. Among the defuzzification methods the sugeno method is very simple [Nguyen et al., 1995].

5. SIMULATION RESULTS

Table (2) shows the parameters of IPMSM which   used   in   the   simulation   test.   The

simulation has been carried out using Matlab/ Simulink and Fuzzy Logic Toolbox. Speed and torque command transient responses to repetitive step changes in the speed command have been obtained for different load operating conditions and at nominal moment of inertia. The responses have been obtained for step speed commands (500rpm to - 500rpm).

   The FLC gains are affected on the membership functions, in this paper these gains are set $G_1=2$, $G_2=5$, $G_3=150$, k=0.5, $T_s=100\mu sec$. Under these values, a dequate response has been observed. The value of k affects the rise time while the small value of k increases the rise time. The dynamic response under different operating conditions is illustrated. Figures (6) and (7) show the step response of the speed and torque for the conventional PI controller for full-load and half-load operating conditions at nominal inertia for 500 to -500 rpm command. Figs. 8 and 9 show the step response of the FLC for full-load and half-load torque at nominal inertia for 500 to -500rpm. As shown in Figures (8) and (9), the dynamic response has a lower ripple than that for PI controller. It is obvious that also the proposed digital FLC system with FLC-PI is of better performance than the conventional PID controller. Furthermore, since the conventional PI speed controller is a linear controller the gain of the PI controller can not be varied. However, FLC is nonlinear can confirmed with the surface shown in Figs. 8c and Fig. 9c under half and full load operations.

6. CONCULSION

   This paper investigates the performance of a fuzzy logic controller (FLC) based on vector control method of an interior permanent magnet synchronous motor (IPMSM) for high performance industrial applications. The fundamentals of fuzzy logic algorithms as related to motor control applications are illustrated. The conventional control of IPMSM linearizes the q-axis current expression by setting the d-axis

current equal to zero. It is obvious from the simulated results that the proposed system with FLC is of better performance and be more robust for applications in IPMSM than the conventional PID controller. The simulation was done by using matlab/ simulink .

REFERANCES

A. Rubaai, D. Rickattes, & M.D. Kankam,"Development and implementation of an adaptive fuzzy-neural network controller for brushless drives", IEEE Transactions on Industry Applications, 38 (2), 2002, 441–447.

Bilmal K.Bose," Modern Power Electronic and AC Drives", ISBN 7-111-11296-2, Prentice Hall, Inc. 2002.

D. Dubois, and H. Prade, Fuzzy Sets and Systems, "Theory and Applications", Academic Press, New York, 1980.

F. Blaschke, "The principle of field orientation as applied to the new transvector closed-loop control system for rotating field machines", Siemens Review, 1972, 217–220.

F.J. Lin & R.J. Wai, "Hybrid controller using a neural network for a PM synchronous servo-motor drive", IEE Proceedings Electric Power Applications, 145 (3), 1998, 223–230.

H.T. Nguyen, M. Sugeno, R. Tong, & R.R. Yager, "Theoretical Aspects of Fuzzy Control", John Wiley & Sons, Inc., 1995.

Jae-Sung Yu, Student, Sang-Hoon Kim, Byoung-Kuk Lee, Chung-Yuen Won, and Jin Hur, "Fuzzy-Logic-Based Vector Control Scheme for Permanent-Magnet Synchronous Motors in Elevator Drive Applications", IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 54, NO. 4, AUGUST 2007.

J. Quiroga, Li Liu, and D. A. Cartes, "Fuzzy Logic based Fault Detection of PMSM Stator Winding Short under Load Fluctuation using Negative Sequence Analysis", 2008 American Control Conference USA,June 11-13, 2008.

J.S. Ko, J.G. Hwang, & M.J. Youn, "Robust position control of BLDD motors using integral-proportional plus fuzzy logic controller", Proc. IEEE IECON, 1993, 213–218.

M.N. Uddin, T.S. Radwan, & M.A. Rahman, "Performances of fuzzy logic based indirect vector control for induction motor drive", IEEE Transactions on Industry Applications, 38 (5), 2002, 1219–1225.

M. Azizur Rahman, D. Mahinda Vilathgamuwa, M. Nasir Uddin,and King-Jet Tseng, "Nonlinear Control of Interior Permanent-Magnet Synchronous Motor", IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 39, NO. 2, MARCH/APRIL 2003.

M.N. Uddin, T.S. Radwan, G.H. George, & M.A. Rahman, "Performance of current-controllers for VSI-fed IPMSM drive", IEEE Transaction on Industry Applications, 36 (6), 2000, 1531–1538.

M. N. Uddin, T. S. Radwan, and M. A. Rahman, "Performances of fuzzy-logic-based indirect vector control for induction motor drive", IEEE Trans. Ind. Appl., vol. 38, no. 5, pp. 1219–1225, Sep./Oct. 2002.

N. Yubazaki, M. Otani, T. Ashida, & E. Kitamura," Fuzzy motion drive method of induction motor using position sensor", Proc. IEEE IECON, 1993, 170–175.

R.J. Wai, "Development of intelligent position control system using optimal design technique", Power Electronics Specialists Conf., 2, 2001, 760–765.

Sun Qiang, Cheng Ming, and Zhou E," Integral-Separated Self-Tuning Fuzzy PI Control of A Novel Doubly Salient Permanent Magnet Motor Drive", Electrical Machines and Systems, 2003. ICEMS 2003. Sixth International Conference on Volume 2, 9-11 Nov. 2003 Page(s), 570 – 573.

LIST OF SYMBLES

|	
V_d, V_q	Stator d-and q-axes voltages
i_d, i_q	Stator d-and q-axes currents
λ_d, λ_q	Stator d-and q-flux linkages
λ_m	Magnetic flux linkage
R_s	Stator resistance
L_d, L_q	Stator d-and q-axes inductances
T_e, T_L	Electromagnetic and load torque
ω_r	Electrical rotor speed
ω_m	Mechanical rotor speed
P	No. of pole pairs
θ_r	Electrical rotor position
J	Rotary inertia
B	Friction coefficient
T_s	Samplingtime
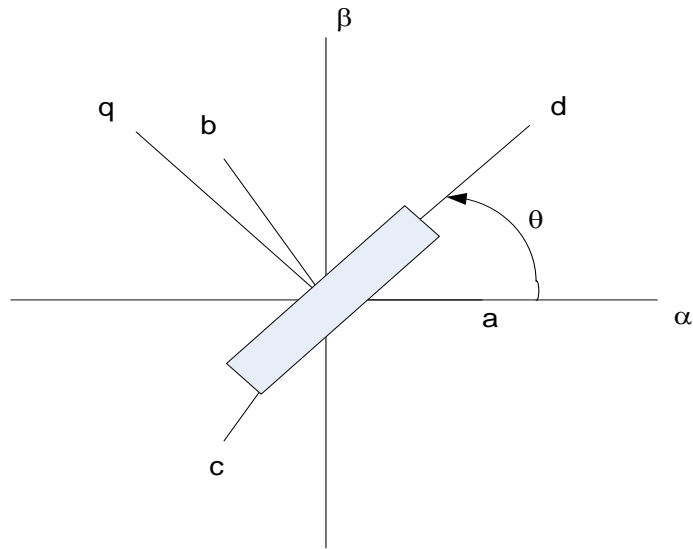
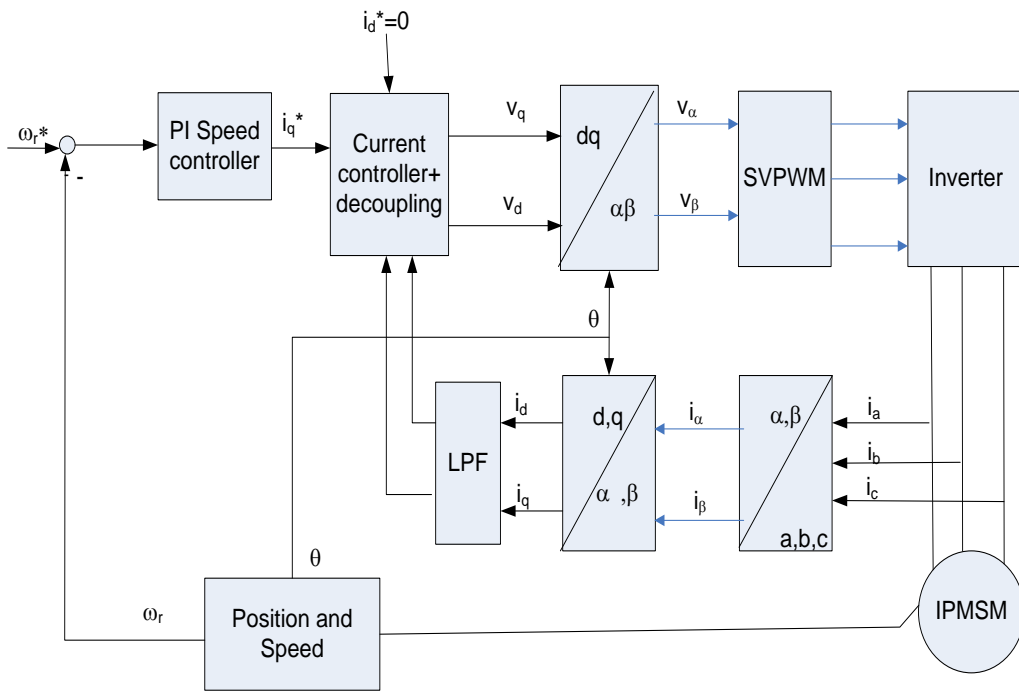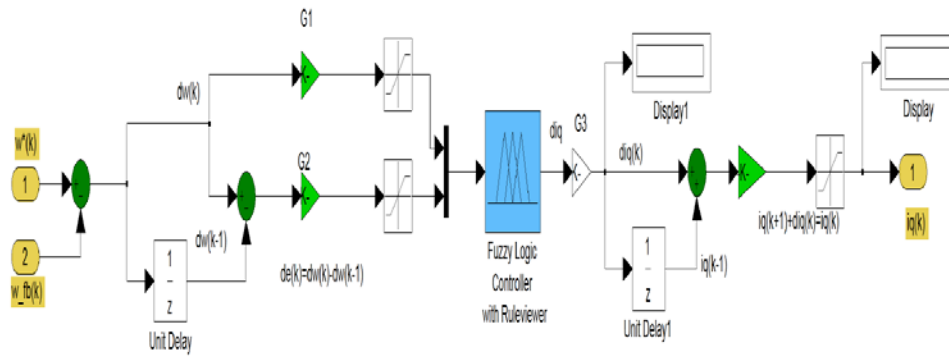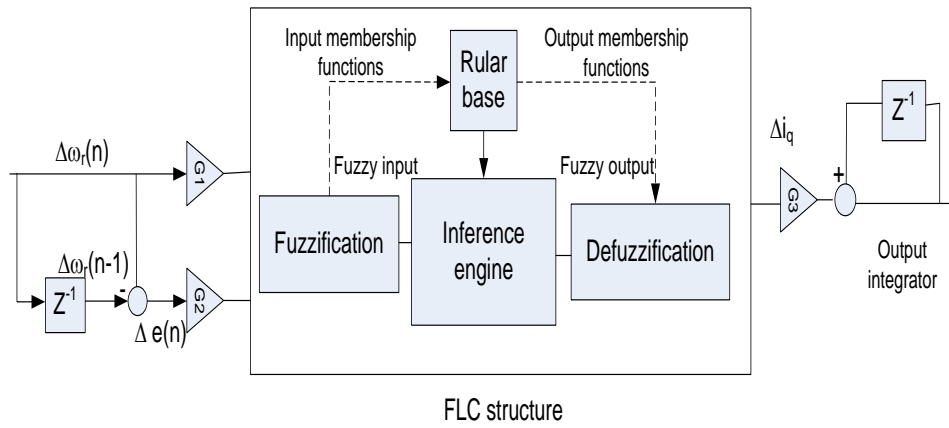**Figure (1) Vector diagram of the PMSM**

Figure (2) Block diagram of standard PMSM control system

(a) Matlab / Simulink for FLC

(b) FLC structure
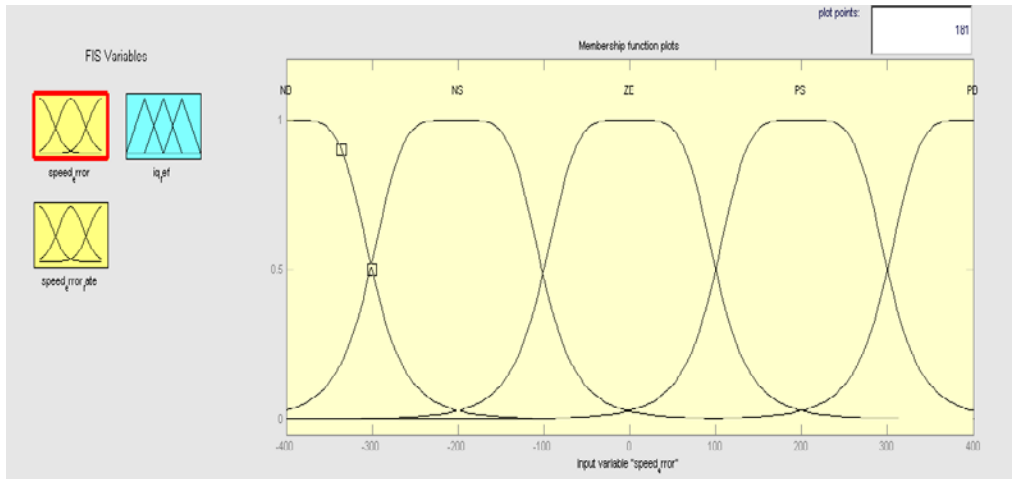
Figure (3) FLC structure with Matlab/Simulink
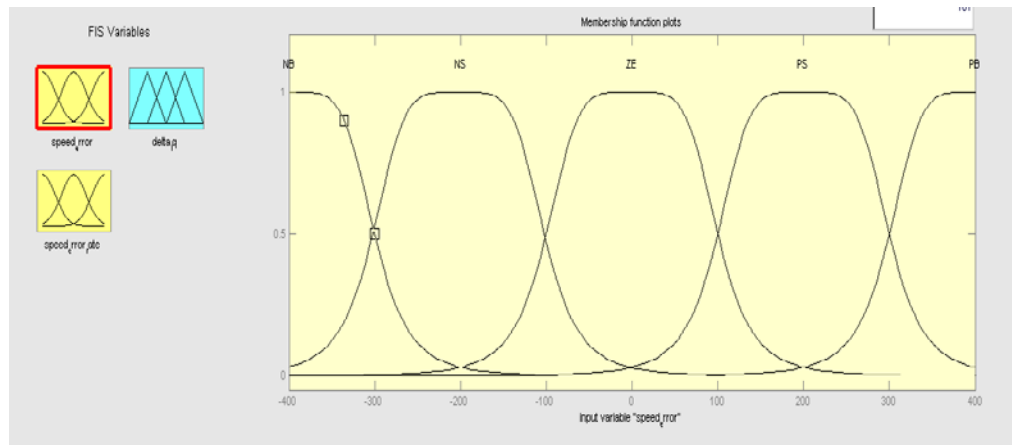
Figure (4, a)Input membership functions

Figure (4, b)Output membership functions

Table (1) Fuzzy Controller Rules base

Δi_q		e₁				
		NB	NS	ZE	PS	PB
e₂	PB	ZE	PS	PS	PB	PB
	PS	NS	ZE	PS	PS	PB
	ZE	NS	NS	ZE	PS	PS
	NS	NB	NS	NS	ZE	PS
	NB	NB	NB	NS	NS	ZE

1295
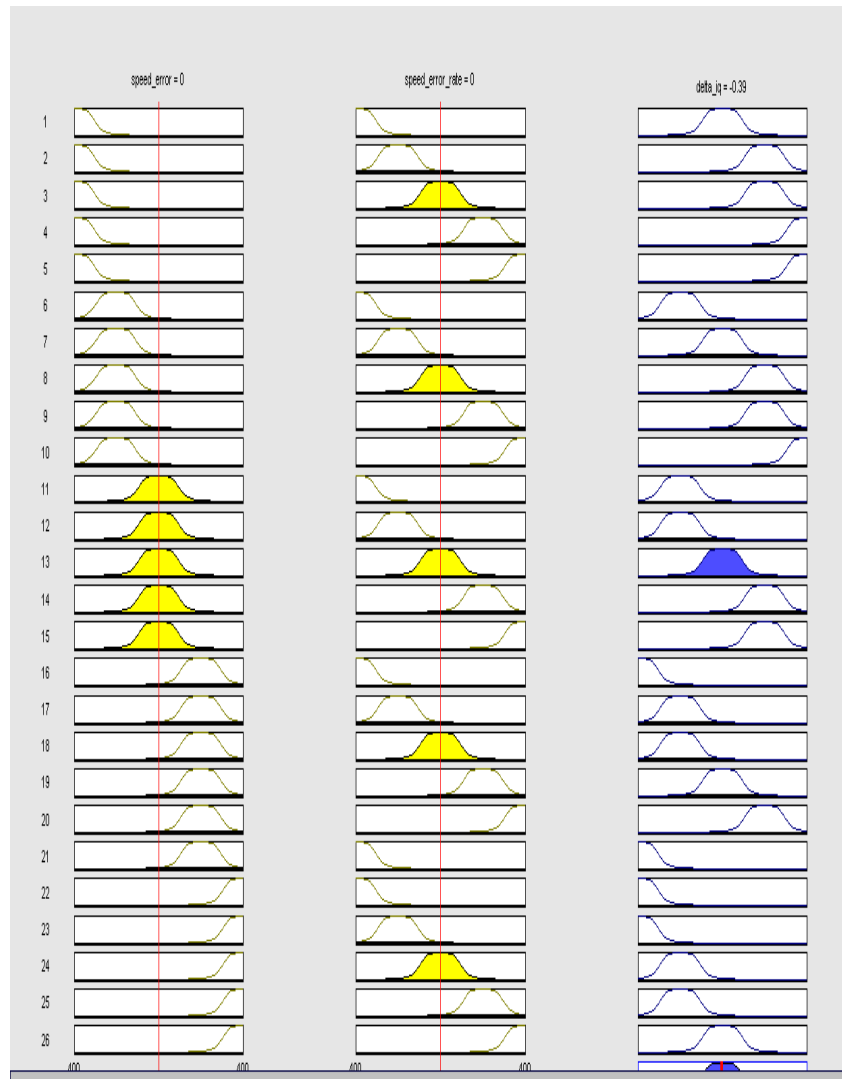
Figure (5) Ruler viewer

Table (2) IPMSM parameters

Pole-pairs	4	Stator resistance R_s	0.00402464Ω
d-axis inductance Ld	0.0986mH	Friction coefficient B	0.0001Nm/rad/sec
q-axis inductance Lq	0. 292723mH	Magnetic flux Φ_m	0.0558537volts/rad/sec
Moment of inertia J	0.062kgm^2		
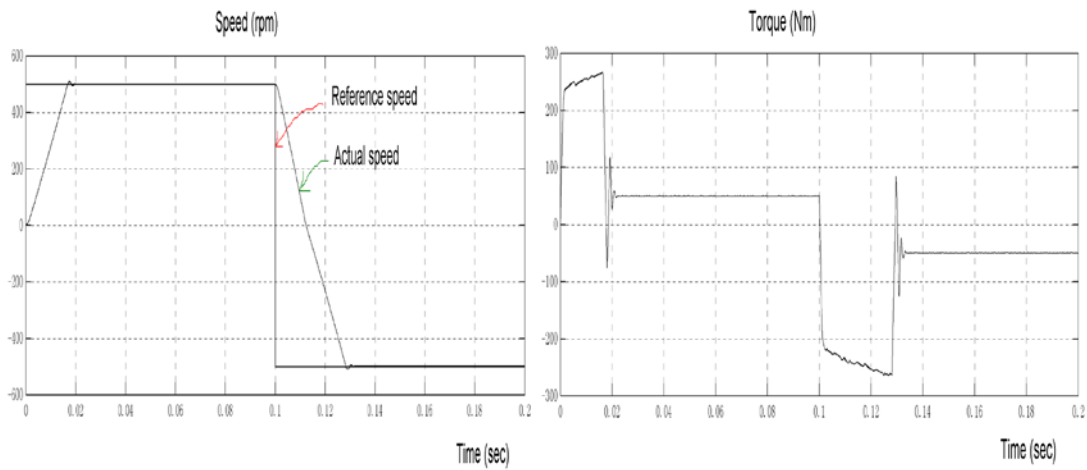
Figure (6) Conventional PI controller response for (500 to -500)rpm at 50%load. a-speed response, b-torque response c-idq currents.
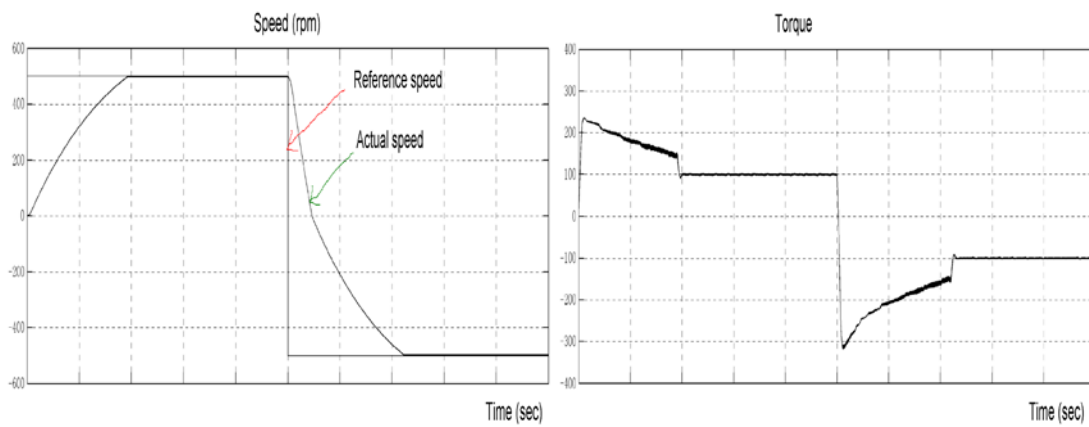

Figure (7) Conventional PI controller response for (500 to -500) rpm at 100%load. a-speed response, b-torque response, c-idq currents.
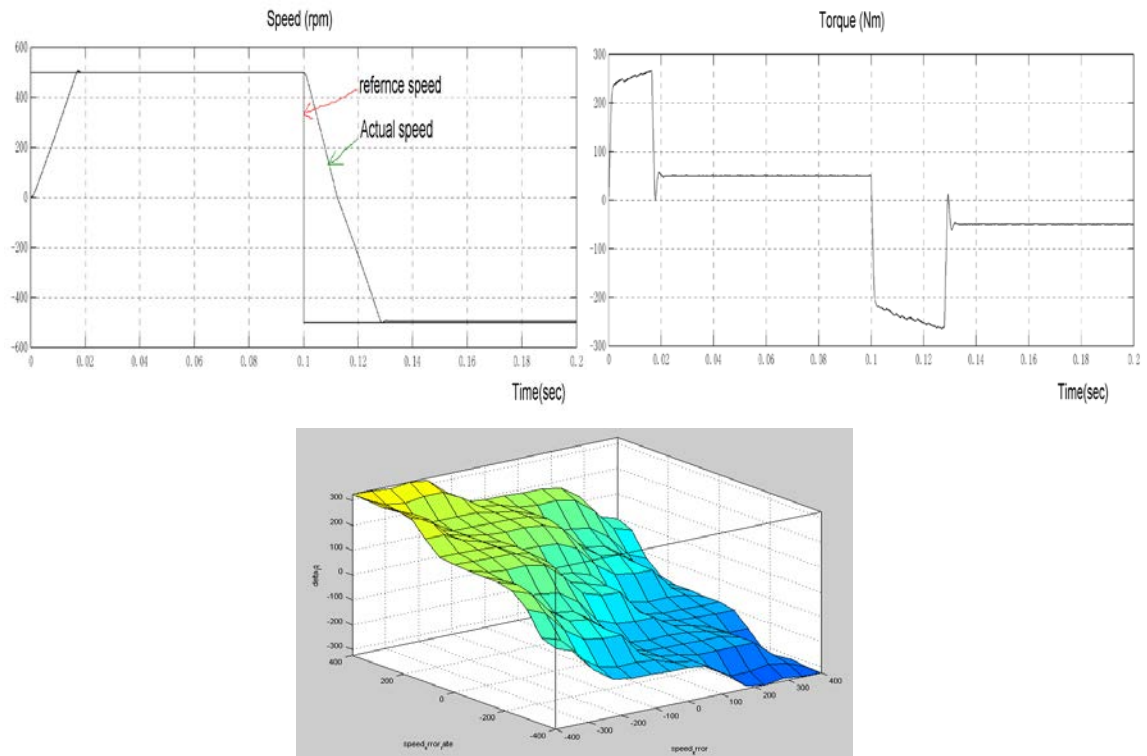
Figure (8) The FLC responses for (500 to -500) rpm at 50% load torque. a- speed response, b-torque response, c-surface viewer
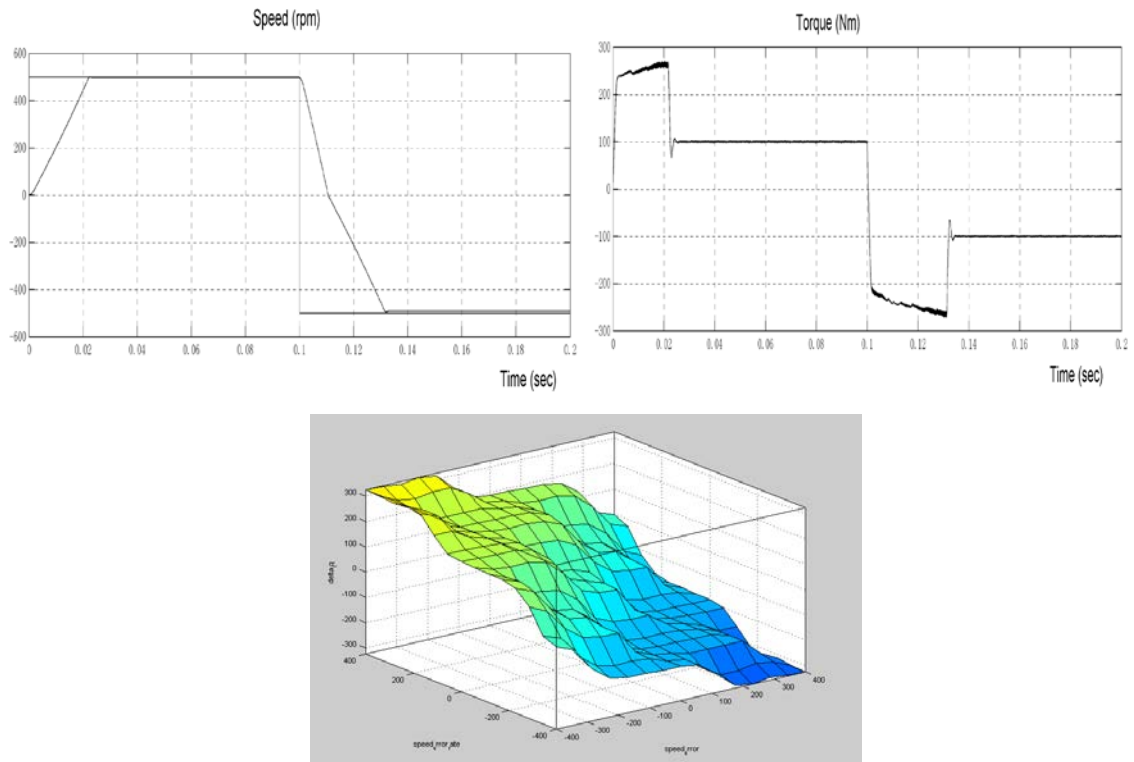
Figure (9) The FLC responses at 100% load torque for (500 to -500) rpm. a- speed response, b-torque response, c-surface viewer