Issue 13, July-December 2008
p. 19-33

Fuzzy Adaptive Model Following Speed Control for Vector Controlled Permanent Magnet Synchronous Motor

Abdelkader MEROUFEL, Ahmed MASSOUM, Baghdad BELABES

Intelligent Control & Electrical Power Systems Laboratory (ICEPS).
Faculty of engineer sciences. Department of electrical engineering,
Djillali Liabes University, Sidi Bel Abbes, Algeria

E-mail: ameroufel@yahoo.fr

Abstract

In this paper a hybrid controller combining a linear model following controller (LMFC) and fuzzy logic control (FLC) for speed vector controlled permanent magnet synchronous motor (PMSM) is described on this study. The FLC is introduced at the adaptive mechanism level. First, an LMFC system is designed to allow the plant states to be controlled to follow the states produced by a reference model. In the nominal conditions, the model following is perfect and the adaptive mechanism based on the fuzzy logic is idle. Secondly, when parameter variations or external disturbances occur, an augmented signal will be generated by FLC mechanism to preserve the desired model following control performance. The effectiveness and robustness of the proposed controller is demonstrated by some simulation results.

Keywords

PMSM, Flux Oriented Control, FLC, LMFC and Adaptive Model Reference System

Introduction

With the development of the technology of power electronics control, rare earth magnetic materials and motor design, PMSM get wide applications in many control systems [1,2].They are perfect because the control system is usually less complex then that of field oriented induction motor drives. In typical PMSM drives, classical PI controllers have been used together with vector control method for speed control. However, the performances depend heavily on the motor parameters [3] which are time varying due to temperature rise and changes in motor drive operating conditions. Thus, it is desirable to have a robust controller for the drive system to reduce parameter sensitivity [4]. Adaptive control is an efficient technique for dealing with large parameter variations. The control input is designed to drive the controlled plant to track the response produced by the reference model [5,7]. Various control algorithms developed require the system states, thus they are not easy to implement [6]. To overcome this problem and to enhance the flexibility of changing control algorithm, a FLC is used to implement the adaptation mechanism. The main advantage of FLC resides in the fact that no mathematical modeling is required for the design of the controller. The FLC uses a control rules set that is based essentially on the knowledge of the system behavior and the experience of the control engineer. It has been pointed out that fuzzy controllers can provide high performance with reduced design and implementation complexity [7]. Then, in the proposed hybrid controller first LMFC is designed to allow the plant output to be controlled to follow the reference model output [8,9]. In the nominal conditions, the model following is perfect. But when parameters variations or external disturbance occur, an augmented signal will be generated automatically by the FLC adaptive mechanism which uses the error between plant output and the reference model output as input. The FLC adaptive mechanism output is added to LMFC system [9,10] in order to preserve the desired model following control performance. Under the proposed control Simulink scheme the decoupling control of torque and direct current in the field oriented mechanism is guaranteed and the robust control performance is obtained by the proposed hybrid controller.

This paper presents a theoretical study on an adaptive FLC for vector controlled PMSM drive using model reference adaptive approach. In the proposed controller, FLC is used to implement the adaptation mechanism.

Issue 13, July-December 2008
p. 19-33

Firstly, the model uncertainty of the PMSM is analyzed, and then vector control technique is presented and applied to drive the motor fed by PWM voltage source inverter. Secondly, the LMFC law is introduced for speed vector controlled PMSM, then FLC principle is proposed for the adaptation mechanism and its application to the speed control of adaptive model following controller. In order to simplify the realization, the controller is designed on the basis of the order-reduced model of the PMSM system. Finally, the control performance of the hybrid controller is evaluated by simulation under Matlab/Simulink software for different operating conditions. The results show that this method can control the PMSM system with uncertainty and parameter variations more effectively.

Control of PMSM

Mathematical Model of the PMSM

The electrical and mechanical equations of the PMSM in the rotor (dq) reference frame are as follows:

$$\begin{cases} \begin{cases} v_d = R_s i_d + L_d \dfrac{d}{dt} i_d \quad \omega_r L_q i_q \\ v_q = R_s I_q + L_q \dfrac{d}{dt} i_q + \omega_r (L_d i_d + \phi_f) \end{cases} & (a) \\ \begin{cases} \phi_d = L_d i_d + \phi_f \\ \phi_d = L_q i_q \end{cases} & (b) \end{cases} \qquad (1)$$

The mechanical equation can be written as:

$$\begin{cases} \dfrac{d}{dt}\omega_r = (C_e \quad T_L \quad f_r \omega_r)/J \\ C_e = \dfrac{3}{2} p[\phi_f i_q \quad (L_q \quad L_d) i_d i_q] \end{cases} \qquad (2)$$

Where R_s is the stator resistance, (L_d, L_q) are stator inductances in frame (d,q), ω_r is the rotor speed, (ϕ_d, ϕ_q) are stator flux, φ_f is the rotor flux, $((i_d, i_q)$ *and* (v_d, v_q) are respectively stator currents and stator voltages in the frame (d,q) , C_e is the electromagnetic torque, T_L is the load torque.

J *and* f_r are the rotor moment inertia and the friction coefficient.

Current Controller and Decoupling Compensation

If a voltage source PWM inverter is used, the stator currents need to be controlled to track the command currents. As can be seen from (1), the dynamics of the stator currents with stator voltages as input are coupled and nonlinear. However, if the stator voltages commands are given in the form

$$\begin{cases} v_d = u_d \quad u_{d\_comp} \\ v_q = u_q \quad u_{q\_comp} \end{cases} \tag{3}$$

Where the emfs compensation are

$$\begin{cases} u_{d\_comp} = \omega_r L_q i_q \\ u_{q\_comp} = \quad \omega_r (L_d i_d + \phi_f) \end{cases}$$

Then the stator currents dynamics reduce to

$$\begin{cases} v_d = R_s i_d + L_d \dfrac{d}{dt} i_d \\ v_q = R_s I_q + L_q \dfrac{d}{dt} i_q \end{cases} \tag{4}$$

Since the current dynamics in (4) are linear and decoupled, PI controllers can be used for current tracking

$$\begin{cases} v_d = k_{Pi_d}(i_{d\_ref} - i_d) + k_{Ii_d}\int (i_{d\_ref} - i_d)dt \\ v_q = k_{Pi_q}(i_{q\_ref} - i_q) + k_{Ii_q}\int (i_{q\_ref} - i_q)dt \end{cases} \tag{5}$$

Figure 1 shows the block diagram of the decoupling system

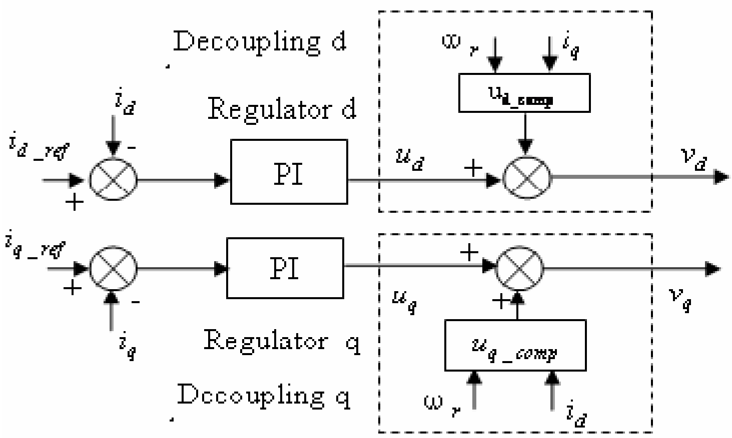

***Figure 1.** Decoupling system with emf compensation*

Vector Control of the PMSM

The objective of the vector control of PMSM is to allow the motor to be controlled just like a separately excited DC motor. So, the direct 'd' axis is aligned with permanent magnet flux linkage phase and the direct current 'i_d' is forced to be zero. Then 1(b) can be written as follows

$$\begin{cases} \phi_d = \phi_f \\ \phi_q = L_q i_q \end{cases} \tag{6}$$

And the electromagnetic torque is

$$\begin{cases} C_e = k_t i_q \\ k_t = \dfrac{3}{2} p \phi_f \end{cases} \tag{7}$$

Note that the electromagnetic torque equation is similar to that of DC motor

Pwm Inverter

Pulse Width Modulation (PWM) technique is used to generate the required voltage or current to feed the motor or phase signals. This method is increasingly used for AC drives with the condition that the harmonic current is small as large as possible. Generally, the PWM schemes generate the switching position patterns by comparing the three-phase sinusoidal wave forms with a triangular carrier. The inverter model is represented by the relationship between output phase voltages (v_a, v_b, v_c) and the control logic signals (s_1, s_2, s_3) as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \quad (8)$$

Where V_{dc} : rectified voltage, $s_i \ (i = 1,2,3) \in [0 \ \ 1]$: logic signals

LMFC for Vector Controlled PMSM

LMFC Theory

Suppose that the plant and the chosen reference model are expressed as [3-5]

$$\begin{cases} \dot{x}_p = A_p x_p + B_p u_p \\ y_p = C_p x_p \end{cases} \quad (9)$$

$$\begin{cases} \dot{x}_m = A_m x_m + B_m u_m \\ y_m = C_m x_m \end{cases} \quad (10)$$

Where $x_p \in R^n$, $x_m \in R^n, u_p \in R^p$, $u_m \in R^p$, $y_p \in R^q$, $y_m \in R^q$, and $A_p, B_p, C_p, A_m, B_m, C_m$ are constant matrices of appropriate dimensions. The pairs (A_p, B_p) and (A_m, B_m) are stabilizable and A_m is a stable matrix.

The objective is to find the control input u_p such that the plant states can track those of the reference model. Then the resulting y_p will fellow y_m automatically. For easy implementation, the control input u_p is chosen to be

$$u_{pl} = k_x x_m + k_e e_0 + k_u u_m \quad (11)$$

Where $e_0 = y_m - y_p$ is the error between the system output and the model output. Define the error vector

$$e = x_m - x_p \tag{12}$$

Then from (9), (10) and (11), we can obtain the following equation:

$$\dot{e} = (A_p - B_p k_e C_p)e + (A_m - A_p - B_p k_x)x_m + (B_m - B_p k_u)u_m \tag{13}$$

Equation (13) shows that if A_m, B_m, k_x, k_e, k_u are chosen to let

- $(A_p - B_p k_e C_p)$ be a Hurwitz matrix and (14)
- $k_x = B_p^+(A_m - A_p)$ (15)
- $k_u = B_p^+ B_m$ (16)

Where $B_p^+ = (B^T B_p)^{-1} B_p^T$ is the left pseudo inverse matrix of B_p, then the error system of (13) will be asymptotically stable and the output of the controlled plant will follow that of the reference model.

MRAFLC for PMSM

The linear model following control system proposed above can lead to perfect model following characteristics only when the plant is invariant. Thus, an adaptation signal u_{pa} is added to the control law (11). The added signal is generated from the adaptive fuzzy controller mechanism and it is included to the LMFC system to reduce the model following error due to the uncertainties in the plant. A block diagram of the proposed hybrid controller is shown in figure 2

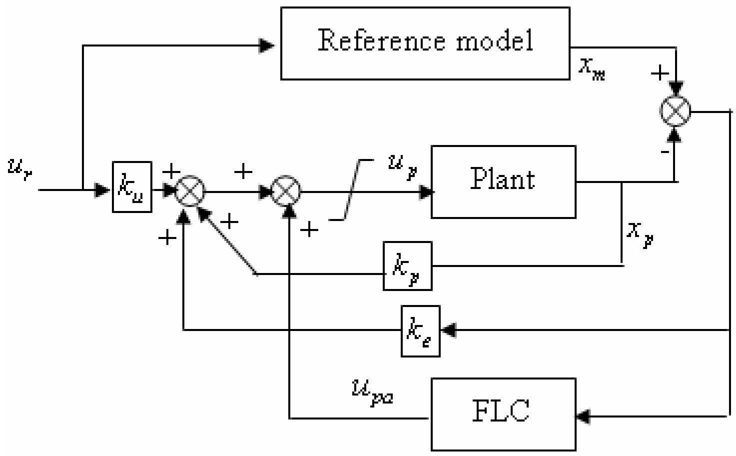

Figure 2. *Proposed adaptive fuzzy controller with LMFC*

The error between the model output ω_{rm} and the actual speed ω_r and its change are calculated every sampling period as

$$\begin{cases} e = \omega_{rm} - \omega_r \\ \Delta e = e(k) - e(k-1) \end{cases} \tag{17}$$

The error e and the change in error Δe will be processed by the fuzzy rule based adaptation system to produce a correction term u_{pa} which is added to the LMFC output u_{pl}. The hybrid controller output is thus modified so that the closed loop system behaves like the reference model. The control signal is a sum of two terms

$$u_p = u_{pl} + u_{pa} \tag{18}$$

Where

$$u_{pl} = k_u \omega_{ref} + k_p \omega_r + k_e e \tag{19}$$

u_{pa} is the fuzzy adaptive mechanism output

Principle of FLC

The design of FLC dos not requires mathematical modelling. The formulation of the control rules is based on the knowledge of the PMSM drive and the experience of the control engineer.

Fuzzy Logic Controller Structure

The FLC has three functional blocks as shown in figure 3

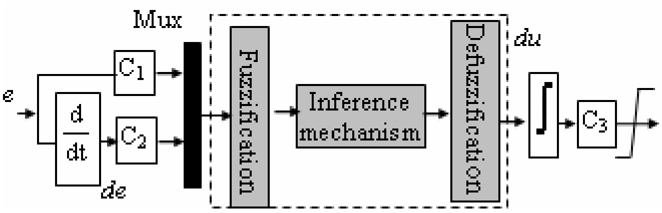

***Figure 3**. FLC internal structure*

In the fuzzification block, the inputs and output crisp variables are converted into fuzzy variables 'e', 'de' and 'du' using the triangular and the trapezoidal membership functions shown in figure 4 (a)

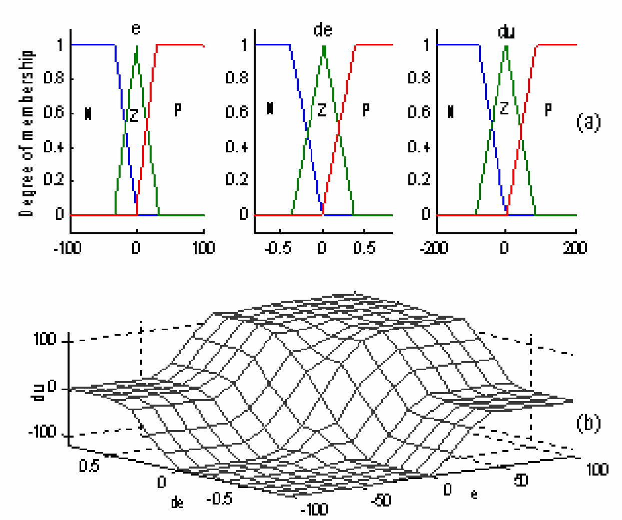

***Figure 4**. (a) Membership functions (b) Control surface*

Each universe of discourse is divided into three fuzzy sets: Negative (N), Zero (Z) and Positive (P). The fuzzy variable ‘e’ and ‘de’ produced the fuzzification block are then processed by an inference mechanism that executes a set of control rules contained in (3x3) table as shown in table 1.

Table 1 Fuzzy control rules for ‘du’

du		e		
		N	Z	P
de	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

The fuzzy rules are expressed under the IF-THEN form. The crisp output of the FLC is obtained by using Max-Min inference algorithm and the center of gravity defuzzification approach.

FLC Design

The fuzzy controller behaviour depends on the membership functions, their distribution and the rules that influence the fuzzy variable in the system. There is no formal method to determine accurately the parameters of the controller. Tuning the FLC is an iterative process requiring trial several combinations of membership functions and control rules. The adjustment can be done by observing the response of the system regulator and modifying the fuzzy sets in the universes of discourse of the input variables (e and $\dot{e}$) and output variable ($\dot{u}$) until satisfactory response is obtained. The control surface 4 (b), a three dimensional graphic showing the output variable corresponding to all combinations of values of the inputs can be used to facilitate the FLC tuning. The number of rules can be reduced in order to optimize the inference engine execution speed. In this paper, a trial and error approach is used to determine and adjust the weighting factors $C_i\,(i = 1,2,3)$ [6, 8].

Issue 13, July-December 2008
p. 19-33

Model Reference Adaptive Fuzzy Logic Controller

The reference model is used to specify the desired performance that satisfies design specifications. A fuzzy logic adaptation loop is added in parallel to the LMFC feedback loop [8-10]. In the nominal case, the model following is perfect and the fuzzy controller adaptation loop is idle. When parameter change an adaptation signal produced by adaptation mechanism will be added to the output signal of the LMFC to preserve the desired model following control performance [8-10]. Figure 5 shows a Simulink block diagram of the proposed hybrid controller for vector control PMSM. The reference model chosen is first order transfer function with time constant set at 0.7s.

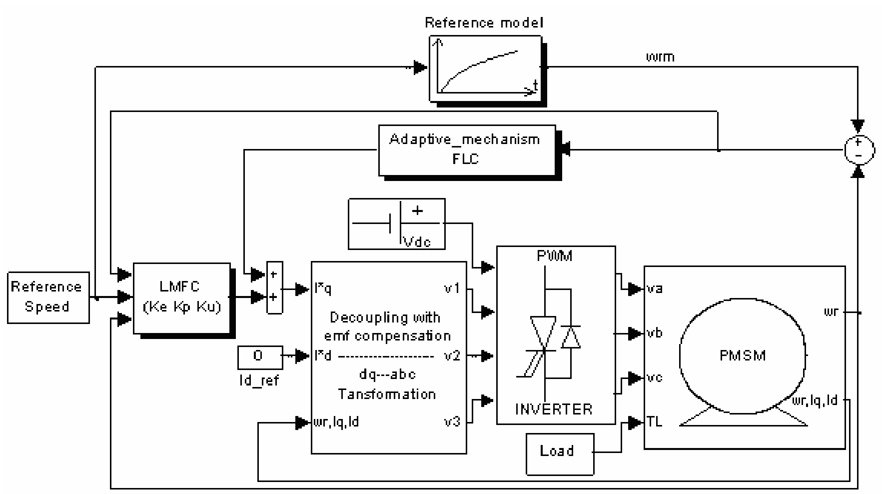

Figure 5. *Simulink model of proposed hybrid controller for vector controlled*

Simulation Results

The control performance of the proposed scheme in figure 5 is evaluated by simulation using Matlab/Simulink software. The parameters of the PMSM are as follows:

$$L_d = 1.4mH \quad L_q = 2.8mH \quad \phi_f = 0.12wb$$
$$p = 4 \quad J = 1.1*10^{-3}\,kg.m^2 \quad f_r = 1.4*10^{-3}\,Nm/rad.s^{-1}$$
$$C_e = 10Nm \quad R = 0.6\Omega \quad I_{qn} = 20A$$

In order to valid the adaptive control law method for a wide operating domain, we use the reference profiles shown in figure 6 as command input. The robustness is evaluated by using increasing inertia (3*J), stator resistance augmented +50% and variation load 10Nm.

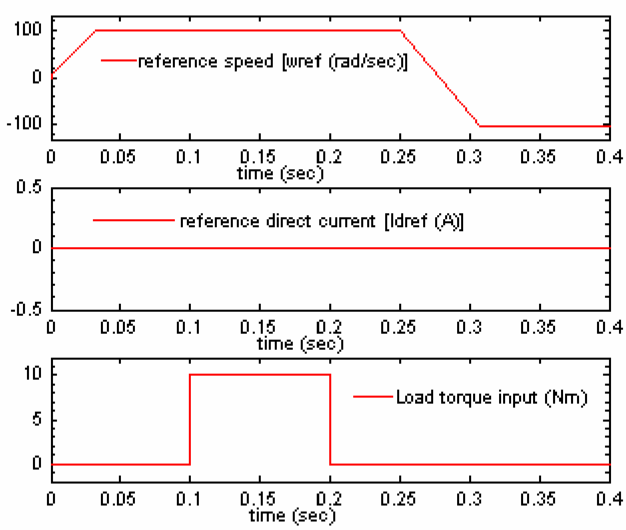

***Figure 6**.:Reference profile inputs*

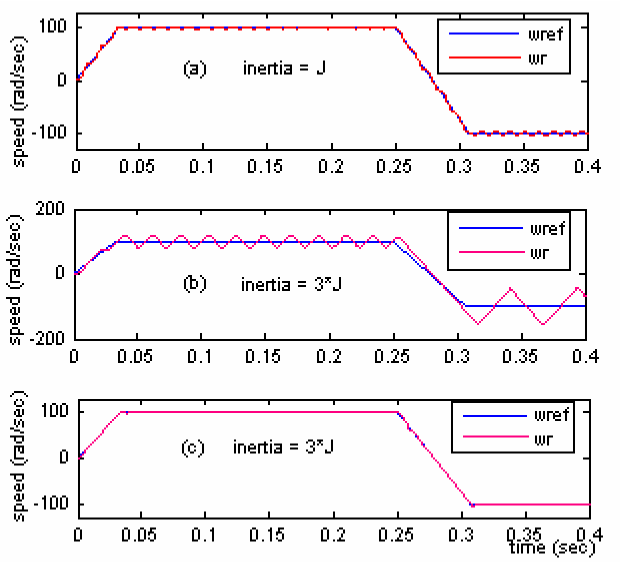

***Figure 7:** Speed responses for vector control of PMSM*
(a) and (b) LMFC, (c) hybrid controller

The simulation results without and with the proposed controller in the above three cases are shown in fig.7. When the moment of inertia increases (3*J) the LMFC response becomes oscillatory. Whoever, the robust control performance of the hybrid controller in the command tracking is obvious.

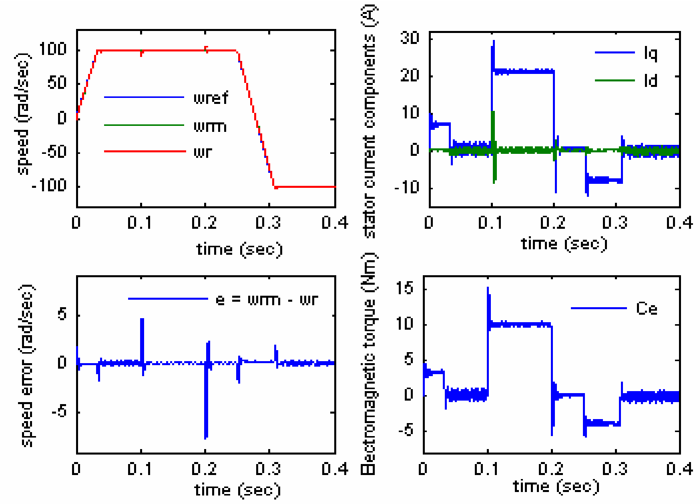

Figure 8. *Responses of MRAFLC for vector control of PMSM under abruptly step load variation*

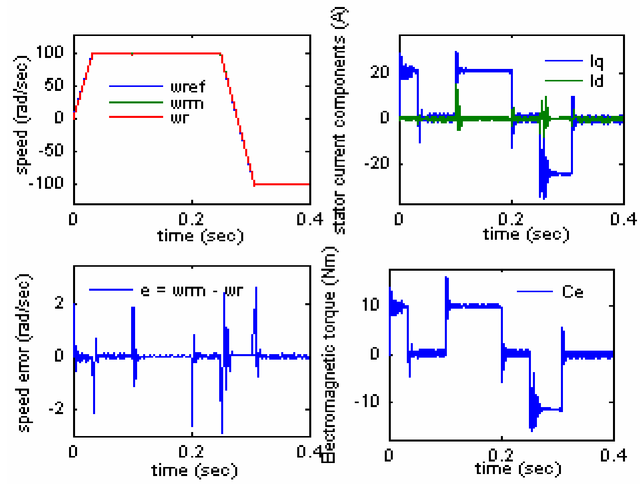

Figure 9. *Responses of MRAFLC for vector control of PMSM under abruptly step load variation, increasing inertia 3*J*

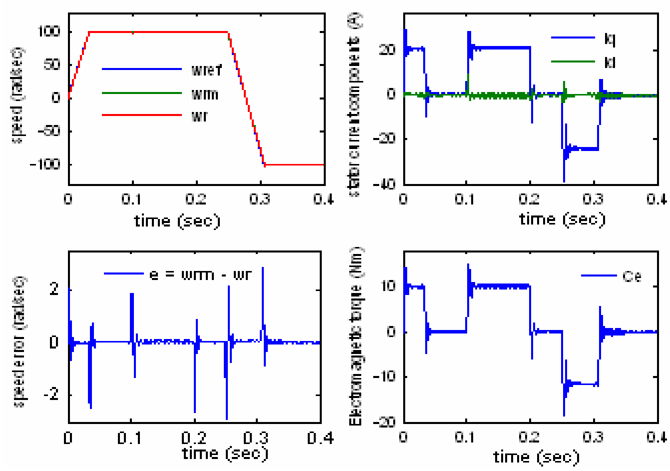

Figure 10*. Responses of MRAFLC for vector controlled PMSM under abruptly step load variation, augmented inertia 3*J, and increasing stator resistance +50%*

Fig.8, 9 and 10 show the robustness of the speed response in the case of external and internal disturbances. The system output tracks very closely the reference model even with increasing inertia, augmented stator resistance and load variations. The results prove the effectiveness of the fuzzy adaptive mechanism facing to the different perturbations.

Conclusion

A hybrid controller combining the advantages of fuzzy logic control and model reference adaptive control for speed vector controlled PMSM fed by voltage source inverter has been proposed in this paper. The proposed controller is insensitive to the external and internal system parameter variations and this proves its robustness. The results obtained show that

The decoupling is maintained under internal and external disturbances.

The combination of LMFC and FLC permit to ovoid the problem of flux orientation and the uncertainties in the model representatively

This strategy of control gives a stable system with a satisfactory performance either with or without load variation. The proposed scheme is effective only during transients since the parameters of the speed LMFC controller are not upgraded by the adaptation mechanism. The simulation results have been confirmed the efficiency of the proposed adaptation scheme in maintaining good performance under external and internal disturbances.

References

1. P. Pillay, R. Krishnan, *Application characteristics of permanent magnet synchronous and brushless DC motors for servo drives*, (Periodical style), IEEE Trans. Ind. Applications, Vol.27, , pp.986-996 dec/oct 1991
2. Dlanguo Xu, Yang Gao: An approach to torque ripple compensation for high performance permanent magnet synchronous motor servo system, 35 th annual IEEE, Power electronics specialists conference, Auchen, Germany, pp.3256-3259. 2004

3. Ying Shich Koing, and Pin Ging Huang: High performance position controller for permanent magnet synchronous motor drives based on TM5320F2818 DSP, Proc. Of the 2004 IEEE Int. Conf. on Control applications. Torpei, Taiwan, pp.290-295 Sept.2-4, 2004
4. Chang-Ming Liaw, Kuci-Hsiang Chao and Paa-Jeng Lin: A discrete adaptive field oriented induction motor drive, IEEE Trans. On Power Electronics, Vol. 7, N^{o}2, , pp.411-419 April 1992
5. Sidney R. Bowes, and Jian Li: New robust adaptive control algorithm for high performance Ac drive, IEEE Trans. Electronics, Vol. 47, N^{o}2, pp.325-336 April 2000
6. Liu Mingji, Lai Zhongqin, Cheng Ximing, and Ouyang Minggao: Adaptive position servo control of permanent magnet synchronous motor, Proceeding of the 2004 American control conference Boston, Jun 30- July 2, 2004
7. D. I. Kim, J. W. Lee, and S. Kim: Control of permanent magnet ac servo motors via fuzzy reasoning,IEEE/IAS'92 Industry Applications Society Annual Meeting Conference Record pp. 482-489 October 1992,
8. Faa-Jeng Lin: Fuzzy adaptive model following position control for ultra sonic motor, IEEE Trans. On Power Electronics, Vol. 12, N^{o}2, , pp.261-268 March 1997
9. Faa-Jeng Lin,Ho-Ming Su, and Hong-Pong Chen: Induction motor servo drive with adaptive rotor time constant estimation, IEEE Trans. On Aerospace and Electronic systems, Vol. 34, N^{o}1, pp.224-232 January 1998
10. Faa-Jeng Lin, and Liaw C.M: Reference model selection and adaptive control for induction motor drives, IEEE Trans., AC-38, pp.1954-1600. 1993