An Adaptive Fuzzy Based Control applied to a Permanent Magnet Synchronous Motor under Parameter and Load Variations (ICCAS 2004)

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Abstract: This paper presents a speed controller based on an adaptive fuzzy algorithm for high performance permanent magnet synchronous motor (PMSM) drives under parameter and load variations. In many speed tracking control systems PI controller has been used due to its simple structure and easy of design. PI controller, however, suffers from the electrical machine parameter variations and disturbances. In order to improve the tracking control performance under load variations, the PI controller parameters are modified during operation by adaptive fuzzy method. This method based on optimal fuzzy logic system has simple structure and computational simplicity. It needs only sample data which is obtained by optimal controller off-line. As the sample data implemented in the adaptive fuzzy system can be modified or extended, a flexible control system can be obtained. Simulation results show the usefulness of the proposed controller.

Keywords: adaptive fuzzy, PMSM, speed control, current control

1. INTRODUCTION

The PMSM has been widely used in many industry applications because of high power density , low electric noise, high torque and high efficiency. In variable speed operations of PMSM, the PI control is still the most used control. This is because of its simplicity and ease of design. However, it has disadvantages that the performance depends to proportional, integral and derivative gains. Therefore, when the operating condition changes such as disturbances and load changes, the re-tuning process of control gains is necessary. Controllers using artificial intelligent tools, such as fuzzy logic and neural networks can be applied to overcome this problem [1]. In a simple way, an expert's experience is normally utilized to tune the controller parameters to achieve desirable control requirements. Tuning a coefficient is a continuously smooth process of adjusting its value. Fuzzy logic can be used for this purpose [2-5].

In order to overcome this problem, the fuzzy logic based control (FLC) has been increased. The FLC has an ability to control unknown system with linguistic variables determined by experts. But, because membership function of linguistic variables and fuzzy rules are determined by operator, the control performance can be deteriorated.

In this paper, an adaptive fuzzy speed controller for PMSM drives which keeps simple structure is proposed for the robust control performance against parameter and load variations. PI controller parameters are modified on-line by adaptive fuzzy tuning method. This method has advantages that the structure is simple as shown in Fig. 2 and computational task is inexpensive[6]. And an improved feedback current control method for three phase pulse width modulated power inverters is used. To achieve fast dynamical response a three level hysteresis sliding mode controller is used.

2. MODELLING OF PMSM

The PMSM studied here is a surface mounted PM motor which have three balanced phase connected in wye configuration. By means of vector control, it is possible to make i_{ds} become zero. Therefore, the system equations of PMSM model can be describes as

$$\dot{w_r} = \frac{3}{2}\frac{1}{J}\left(\frac{P}{2}\right)^2 \lambda_m i_{qs} - \frac{B}{J}w_r - \frac{p}{2J}T_L \quad (1)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\lambda_m i_{qs} = k_t i_{qs} \quad (2)$$

$$k_t = \frac{3}{2}\left(\frac{P}{2}\right)\lambda_m \quad (3)$$

where w_r is the angular rotor speed, λ_m is the flux linkage of permanent magnet, k_t is the torque constant, P is the number of poles, T_e is the developed motor torque, T_L is the load torque, J and B are the motor inertia and damping coefficient, respectively. i_{qs} is the q axis stator current.

3. PROPOSED CONTROLLER

The PI controller is widely adopted in the speed control of PMSM drive due to its simple structure, as shown Fig.1. Its control signal is easily computed by combining proportional and integral terms

$$u(t) = K_P e(t) + K_I \int e(t)dt \quad (4)$$

where k_P, k_I are the controller parameters. Its discritized and incremental form is expressed by

$$\triangle u(k) = u(k) - u(k-1) = K_P[e(k) - e(k-1)] + K_I T e(k) \quad (5)$$

where T is the sampling time.

To improve the system robustness about load variations, adaptive fuzzy tuner is introduced to continuously change the control parameters K_P and K_I , depending on the control error and its rate of change. The basic structure of the proposed on-line tuning is illustrated by the structure in Fig. 2.

$$\triangle u(k) = u(k) - u(k)$$
$$= K_P^\star \triangle u_P(k) + K_I^\star \triangle u_I Te(k) \quad (6)$$

where $\triangle u_P(k)$ and $\triangle u_I(k)$ are the output of the incremental fuzzy logic tuner, and $K_P^\star$ and $K_I^\star$ are proportional and integral coefficient each. They are equal K_P and K_I in this paper [7].

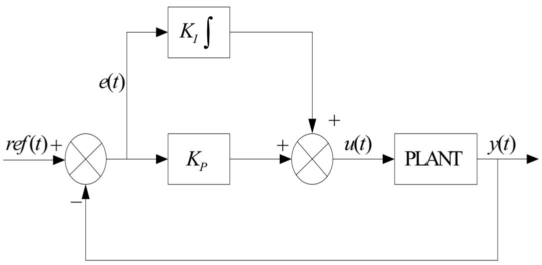

Fig. 1 Control schemes of PI type controller

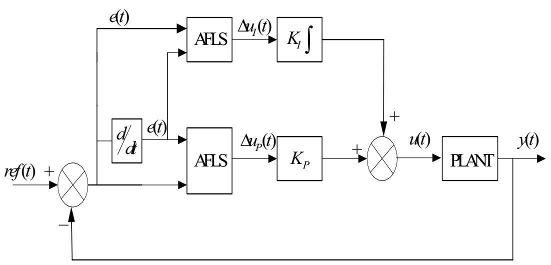

Fig. 2 Control schemes of proposed controller

4. ADAPTIVE FUZZY TUNING METHOD

A block diagram of the proposed system is shown in Fig. 3. Fig. 4 shows the flow chart of adaptive fuzzy tuner. As shown in Fig. 4, window is selected first. This window is a memory windowing system which allows different sets of clusters to be used depending on actual speed. This allows the clusters to more closely position themselves according to system dynamics and desired control action. Therefore this adaptive fuzzy system is suitable for systems where few input/output sets are known a priori. In this system the input sets consist of a set of n consecutive speed error samples. The output is a change in control input which alters the proportional and integral gains so as to optimally correct the dynamic response. The system initially starts with a small number of input/output sets which are the initial clusters. As input is provided to a given window's clusters, the input is compared with the clusters and the norm (distance) from the input is determined for each cluster. The distances from each of the clusters is

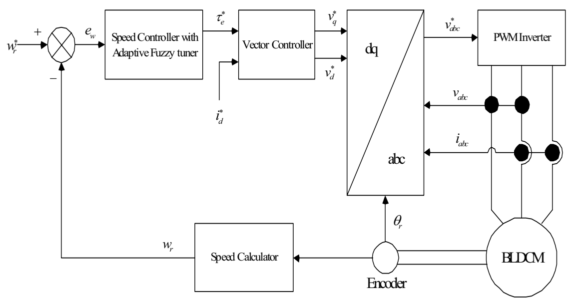

Fig. 3 Control schemes of proposed controller

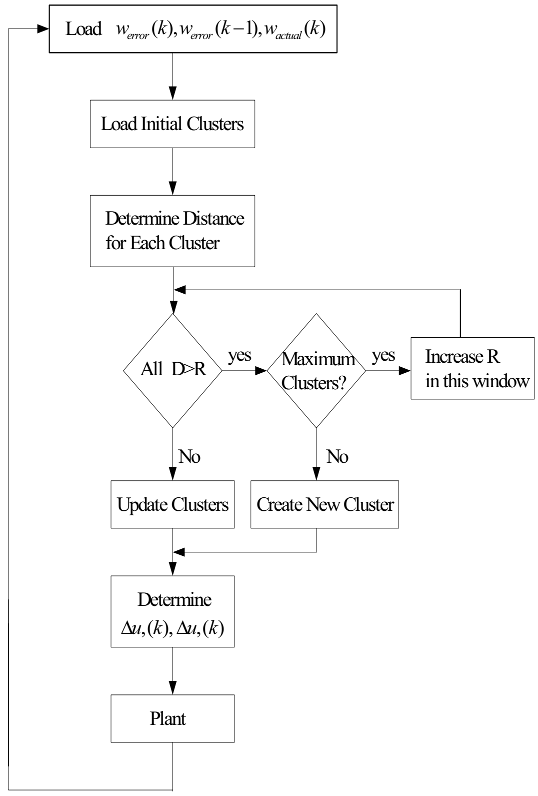

Fig. 4 Flow-Chart of adaptive fuzzy controller

compared to a specified radius. If all distances are updates its output coefficients while all other clusters remain unchanged. A defuzzification of the input provides a crisp output. Given the following definitions, the adaptive fuzzy system follows in equation form :

Definitions :

$\underline{x}^k, y^k$: input and output after sample k

$\underline{x}_0^M$: center of Mth cluster

$\underline{x}_0^{lk}$: the nearest cluster to kth input $\underline{x}^k$

D : distances of input to M cluster centers

M : number of clusters

a) If $|\underline{x}^k - x_0^{l_k}| > r$,

· stablish $\underline{x}^k$ as a new cluster center $x_0^{M+1} = x^k$

· et $A^{M+1}(k) = y^k$, $B^{M+1}(k) = 1$

keep $A^l(k) = A^l(k-1)$, $B^l(k) = B^l(k-1)$

l = 1, 2, ... , M

b) If $|\underline{x}^k - x_0^{l_k}| \le r$, do the following;

· $A^{l_k}(k) = A^{l_k}(k-1) + y^k$, $B^{l_k}(k) = B^{l_k}(k-1) + 1$

· et $A^l(k) = A^l(k-1)$, $B^l(k) = B^l(k-1)$

l = 1, 2, ... , M, $l \neq l_k$

and then the adaptive fuzzy system at the kth step is computed as

$$f_k(\underline{x}) = \frac{\sum_{l=1}^{M} A^l(k) \exp\left(-\frac{|\underline{x} - \underline{x}_0^l|^2}{\sigma^2}\right)}{\sum_{l=1}^{M} B^l(k) \exp\left(-\frac{|\underline{x} - \underline{x}_0^l|^2}{\sigma^2}\right)} \quad (7)$$

which is the adaptive fuzzy system at the kth step with center average defuzzifer, product-inference rule, singleton fuzzifier, and Gaussian membership function.

if $\underline{x}^k$ does not establish a new cluster; and, if $\underline{x}^k$ establishes a new cluster, change the M in Eq. (7) to

M+1.

The initial clusters for the windows are constructed by utilizing a system model based on the manufacturer's specifications. A natural adaptiveness of this tuner is in the ability to cluster new inputs around a given number of cluster centers. Optimal values of radius and σ were chosen off-line. For the proposed system all clusters are of equal size, with a 3 element input vector consisting of 2 consecutive speed error values and the command speed. The size of the clusters and maximum number of clusters are arbitrary, limited only by system storage resources. As mentioned above, the radius R may be varied as cluster limits are met. The smaller the R, the greater the granularity of the clusters and the greater the possibility new clusters will be formed. The parameter σ in Eq. (7) is used to enhance the accuracy of the solution of the adaptive fuzzy logic system. Larger σ tends to allow the adaptive fuzzy logic system to generalize and tends to smooth the recalled output for a given input/output data set, while a smaller σ tends to provide more accurate output, but has less generalizing capability to new input.

5. CURRENT CONTROLLER BASED ON THREE LEVEL COMPARATOR

In this paper, an improved current control method based on three level comparator is proposed. To achieve fast dynamical response a three level hysteresis sliding mode controller is used. The voltage vectors applied to the load are accurately selected in order to minimize the current error. The current command is assumed to be a d-q type in this controller [8]. When two level comparator is used, voltage utilization ratio is low because it tused the max voltage of neither V_d nor V_q. This disadvantage is overcome by using three level comparator. These comparators can be defined as,

$$\delta_{\alpha_t} = \frac{1+sgn\left(\epsilon_{i\alpha d_t} + H_{\alpha 1} sgn \epsilon_{i\alpha_{t-1}}\right)}{2} + \frac{-1+sgn\left(\epsilon_{i\alpha_t} + H_{\alpha 2} sgn \epsilon_{i\alpha_{t-1}}\right)}{2}$$

$$\delta_{\beta_t} = \frac{1+sgn\left(\epsilon_{i\beta_t} + H_{\beta 1} sgn \epsilon_{i\beta_{t-1}}\right)}{2} + \frac{-1+sgn\left(\epsilon_{i\beta_t} + H_{\beta 2} sgn \epsilon_{i\beta_{t-1}}\right)}{2} \quad (8)$$

where $H_{\alpha 1}$ and $H_{\alpha 2}$ are the two hysteresis levels for the α current, $H_{\beta 1}$과 $H_{\beta 2}$ are the two hysteresis levels for the β current. $\epsilon_{i\alpha}$ and $\epsilon_{i\beta}$ are the current errors on α-β axis, δ_α and δ_β are the results of the comparators. When the Eq. (8) is used, an ambiguous situation may occur in which selected are two or three ones to satisfy the output of three level comparator. This situation is solved with additional condition using magnitude of the b, c current errors [see Fig. 5]. Table 1 is the look-up-table in which contains three level comparators results and corresponding output voltage vectors.

6. SIMULATION RESULTS

Matlab/Simulink is used to confirm the proposed control system performance, and motor parameters are given in Table 2. Figs. 6~7 show the output voltage vectors and α-β axis current of the proposed current controller respectively. As shown, all voltage vectors are used. Current response is fast and error is a little.

Figs. 8~11 show the speed responses with different

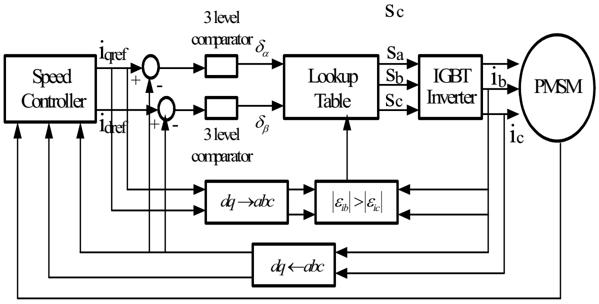

Fig. 5 Proposed current controller block diagram

Table 1. Three level comparators results and corresponding output voltage vectors

δ α	δ β	V_α	V_β	V_k
0	0	x	x	V_0
0	+1	x	+	V_3 V_2 (i)
0	−1	x	−	V_5 V_6 (ii)
+1	0	+	x	V_1 V_6 V_2 (iii)
+1	+1	+	+	V_2
+1	−1	+	−	V_6
−1	0	−	x	V_5 V_3 V_4 (iv)
−1	+1	−	+	V_3
1−	−1	−	−	V_5

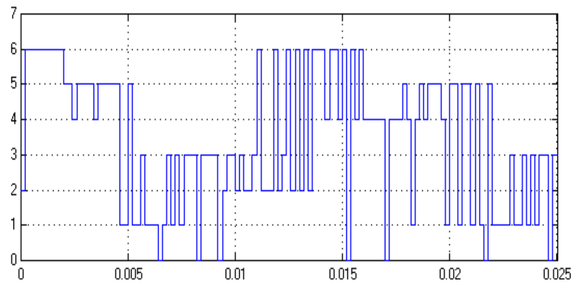

Fig. 6 Output voltage vector of proposed current controller

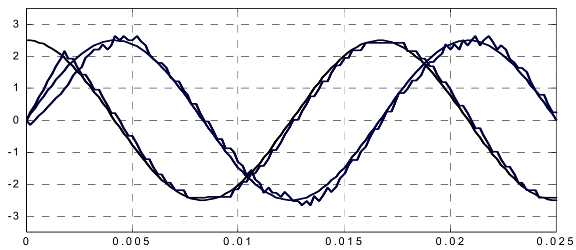

Fig. 7 α−β axis currents

conditions. The speed and torque response is depicted with rated speed and half load in Figs. 8~9. Figs. 10~11 are speed response with 100[rpm], half load and 1250[rpm], no load respectively. Fig. 12 shows dynamic response with half load. The load disturbance mainly affects the steady-state speed error, sudden load speed drop or overshoot, recovery time, and dynamic rise time. With the motor running at half rated speed, rated load torque is suddenly applied to the motor as shown in Fig. 13. The proposed controller has superb performance with respect to speed overshoot, speed rise time, and recovery time. To test the parameter variations, the proposed system was tested with two different

parameter sets :
Set 1 : J -> 1.5 J, Ls -> 1.5 Ls
Set 2 : Ls -> 1.5 Ls, Rs -> 1.5 Rs
Fig. 14 shows the speed response of the proposed system with parameter Set 1 for a 100[rpm] speed setpoint. Fig. 15 is in case of parameter Set 2.

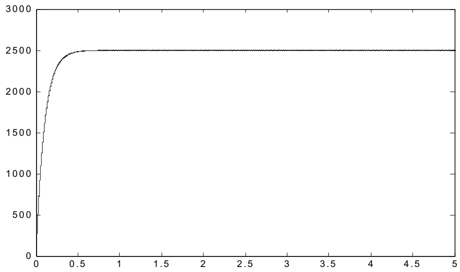

Fig. 8 Speed response with 0.5[p.u] load

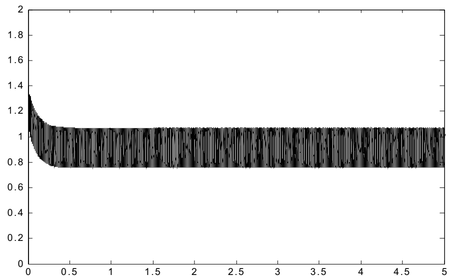

Fig. 9 Torque response [Nm]

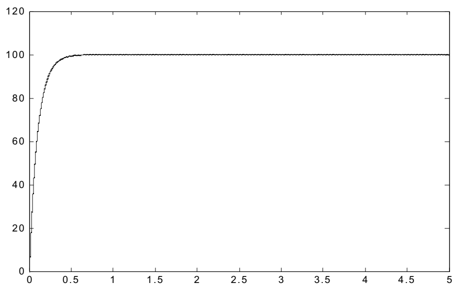

Fig. 10 speed response with 0.5[p.u] load

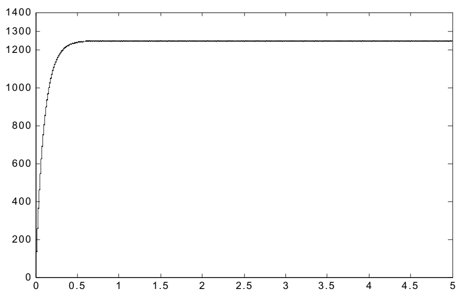

Fig. 11 Speed response with no load 1250 [rpm]

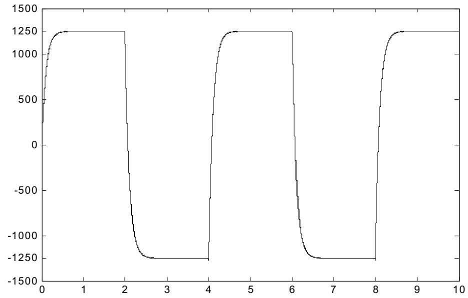

Fig. 12 Dynamic response with 0.5 [p.u] load 1250[rpm]

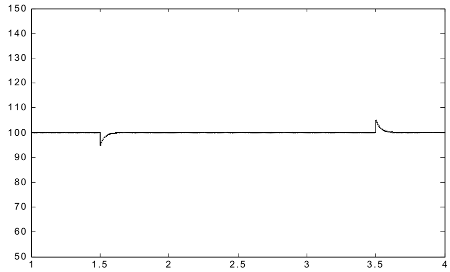

Fig. 13 Speed response during sudden full load 100 [rpm]

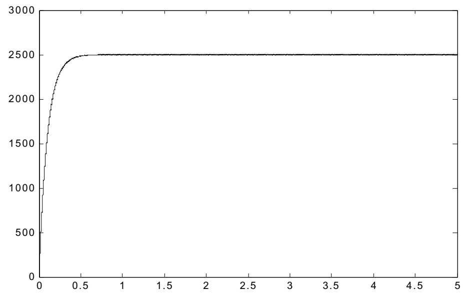

Fig. 14 Speed response with varied parameters 2500 [rpm] (J->1.5J, L_s->1.5L_s)

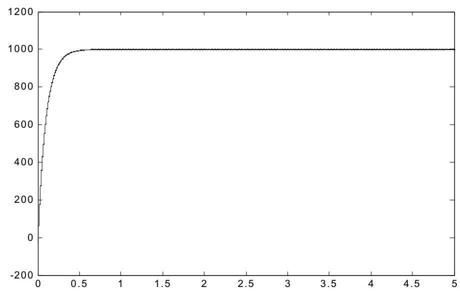

Fig. 15 Speed response with varied parameters 1250 [rpm] (L_s->1.5L_s,R_s->1.5R_s)

7. CONCLUSION

This paper has proposed a speed controller with adaptive fuzzy tuning method for the PMSM drives. Proposed controller has tuned the PI controller parameters to track the speed command. And an improved current control method based on three level comparator is proposed.

To raise the voltage utilization ratio, three level comparator is used. The simulation results have confirmed the good speed response and the efficiency of the proposed adaptive fuzzy logic scheme for varying motor parameters and load.

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Table 2. PMSM parameters

Rotor Inertia (J)	0.35 e-4	$kg\,m^2$
Stator Inductance (L)	10.9	mH
Stator Resistance (R)	4	Ω
Pole Pairs (P)	4	Nm/A
Mechanical Time constant	1.96	ms
Electrical Time constant	1.08	ms
Torque Constant (K_T)	0.53	Nm/A