# A Vector-control System Based on Fuzzy Self-tuning PID controller for PMSM

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*Abstract*—**The permanent magnet synchronous motor (PMSM) is increasingly playing an important role in alternating current(AC) transmission system. Recently, lots of researches have been investigated for the PMSM system without speed and position sensors. The Vector-control system based on fuzzy self-tuning PID is proposed in this paper. The new algorithm based on fuzzy self-tuning PID can improve the performance of the system. The speed and torque fluctuations are reduced. Simulation results show that the validity of the proposed strategy.**

***Keywords: Fuzzy; PID control; PMSM; Simulink;***

## I. INTRODUCTION

Permanent magnet synchronous motors have been widely used due to its high power density, efficiency, high torque-to-inertia ratio and reliable operation. In general, most of the PMSM control systems use the conventional PID regulator as it is non-linear， time-varying and big lag. However, the conventional PID for this non-linear system is difficult to achieve the desired effect of control. In addition, the parameters of PID regulator need make the corresponding adjustment when the characteristic of controlled object changes.

Various strategies have been applied on the PMSM control system, such as PID [2], Fuzzy [2], Artificial Intelligence [2], Fuzzy Self-tuning PID, etc. The Fuzzy Self-tuning PID algorithm [3], which is easy to implement and effective, has been widely used in the PMSM control system.

This paper mainly focuses on designing the new fuzzy self-tuning PID algorithm in order to control temperature. The purpose is to decrease the speed and torque fluctuations of the control system and improve the performance of the system.

The outline of the paper is as follows: the model of the PMSM is presented in Section II. The self-tuning PID controller design is provided in Section III. Simulation results on analysis of the algorithms are presented in Section IV. Finally, concluding remarks are made in Section V. Simulation results illustrate the effectiveness of the proposed method.

## II. PRELIMINARY AND BACKGROUND

### A. *Mathematic Model of PMSM System*

The mathematic model of PMSM can be expressed by such equations in the rotating reference frame ( $d-q$ reference frame).

The stator voltage equation in the d-q axes can be expressed as

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -L_d\omega_r \\ -L_d\omega_r & R_s + pL_q \end{bmatrix} \begin{bmatrix} I_d \\ Iq \end{bmatrix} + \omega_r\psi_r \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

(1)

where $U_d, U_q, I_d, I_q$ are stator voltage and current in $d-q$ axes. $L_d, L_q$ are equivalent inductance in $d-q$ axes.

The stator current equation is

$$\begin{bmatrix} \frac{dI_d}{dt} \\ \frac{dI_q}{dt} \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -L_d\omega_r \\ -L_d\omega_r & R_s + pL_q \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_d} \end{bmatrix} \begin{bmatrix} U_d \\ U_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\omega_r\psi_r}{L_q} \end{bmatrix} \quad (2)$$

The stator Flux linkage equation is as follows

$$\begin{cases} \psi_q = L_q I_q \\ \psi_d = L_d I_d + \psi_r \end{cases}$$

(3)

The electromagnetic torque equation is as follows

$$Te = \frac{3}{2} n_p (\varphi_d I_q - \varphi_q I_d) = \frac{3}{2} n_p (\psi_\alpha I_\beta - \psi_\beta I_\alpha)$$

(4)

The mechanical equation of the PMSM can be described as

$$Te - T_L - B\omega_r = \frac{J}{n_p}\frac{d\omega_r}{dt}$$

(5)

where $J$ is the inertia coefficient and $B$ is the friction coefficient, $\omega_r$ is the mechanical speed of the rotor and $T_L$ is the load torque.

The speed equations are given by:

$$\frac{d\omega_r}{dt} = -\frac{3n_p^2\varphi_r}{2J}I_q - \frac{B}{L}\omega_r - \frac{n_p}{J}T_L \tag{6}$$

$$\frac{d\theta}{dt} = \omega_r \tag{7}$$

There are many various control strategies for PMSM system. If $I_d = 0$ , $T_e$ is only relevant to $I_q$ .The control strategy of $I_d = 0$ is proposed in the paper.

*B. Space Vector Pulse Width Modulation*

The SVPWM technique is widely used in inverter. Compared to the sinusoidal pulse width modulation (SPWM), SVPWM is more suitable for digital implementation. Also, the SVPWM algorithm [4] can increases the obtainable maximum output voltage with peak line voltage approaching 70.7% of the dc-link voltage compared to 61.2% of the SPWM in the linear modulation range. Moreover, it can acquire a better voltage total harmonic distortion factor.

The relationship between line voltage vectors $[U_{ab}, U_{bc}, U_{ca}]^T$ and on-off state $S_{abc}{}^T$ is

$$\begin{bmatrix} U_{ab} \\ U_{bc} \\ U_{ca} \end{bmatrix} = U_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{8}$$

The phase voltage vectors $[U_a, U_b, U_c]^T$ and the on-off state $S_{abc}{}^T$ is as followed equation

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \frac{1}{3}U_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{9}$$

The flux linkage vector's path is a hexagon (Fig.1) when inverter generates a space voltage vector each period. Multilateral polygons are made to approach the circular flux linkage, what must be done is to generate more space voltage vectors in a period. All these vectors can be compounded by two basic vectors from the six valid vectors [5].

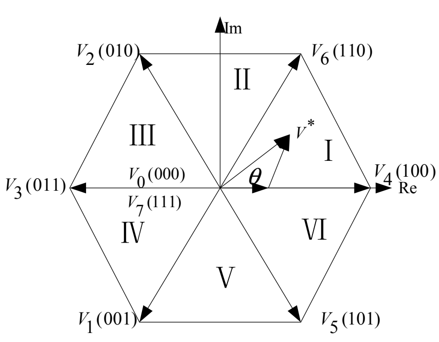


Figure 1. Space vector hexagon diagram

For example, $V_{ref}$ can be compounded by $V_4$ and $V_6$ .The equation can be expressed as

$$V4 * T4 + V6 * T6 = V_{ref} * T \tag{10}$$

where $T$ is switch period. $T4$ , $T6$ are operating times corresponding to $V_4$ and $V_6$ . Also, $T4 + T6 \le T$ .The voltage vector $V_\alpha$ , $V_\beta$ in α-β reference frame is

$$\begin{cases} V_\alpha T = T6\left|V6\right|\sin\frac{\pi}{3} \\ V_\beta = T4\left|V4\right|\sin\frac{\pi}{3} + T6\left|V6\right|\cos\frac{\pi}{3} \end{cases}$$

(11)

The amplitude of each basic space vector is $2U_{dc}/3$ , so we can get

$$\begin{cases} T6 = V_\beta \cdot \sqrt{3}T / U_{dc} \\ T4 = \frac{1}{2}(\sqrt{3}V_\alpha - V_\beta) \cdot \sqrt{3}T / U_{dc} \end{cases}$$

(12)

Then, operating time $T_K$ , $T_{K+1}$ corresponding to $V_K$ , $V_{K+1}$ can be calculated in the same way.

## III. FUZZY SELF-TUNING PID CONTROLLER DESIGN

*A. The structure of Fuzzy self-tuning PID controller*

The new fuzzy-PID controller takes conventional PID as the foundation, which uses the theory of fuzzy reason and variable discourse of universe to on-line regulate the parameters of PID automatically. The structure of fuzzy self-tuning PID controller is shown in Fig.2.

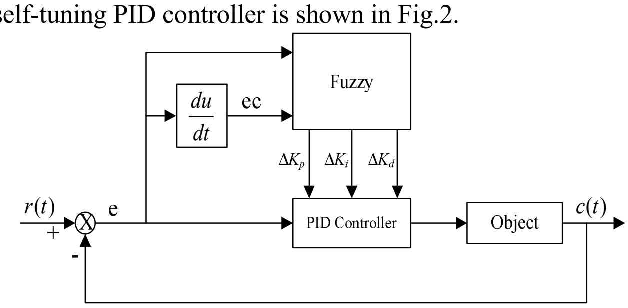


Figure 2. Fuzzy self-tuning PID controller

The error and error changing rate are used as the input variables in control system, and the output variables are the parameters of PID control, those are $\Delta Kp$ , $\Delta Ki$ and $\Delta Kd$ . Here, $e$ denotes the system error, $ec$ denotes the system error changing rate.

The fuzzy sets of $e$ , $ec$ , $\Delta Kp$ , $\Delta Ki$ , $\Delta Kd$ is { NB, NM, NS, 0, PS, PM, PB }, the region of $e$ , $ec$ are{ $-3, -2, -1, 0, 1, 2, 3$ }, and the region of $\Delta Kp$ , $\Delta Ki$ , $\Delta Kd$ are { $-3, -2, -1, 0, 1, 2, 3$ } respectively. Where NB, NM, NS, 0, PS, PM and PB are linguistic values. They respectively represent "negative big", "negative medium", "negative small", "0", "positive small", "positive medium" "positive big" [4].

### *B. Forming And Reasoning Of Fuzzy Control Rules*

The essential part of the fuzzy logic controller is a set of linguistic rules. In many cases it is easy to translate an expert's experience into such rules [5]. Any number of rules can be created to define the actions of the fuzzy controller. In this paper, the fuzzy control rules design is based on the medical robot can approach the target quick and stable. The application of conventional fuzzy conditions and fuzzy relations "If $e$ is A and $ec$ is B then $\Delta Kp$ is C, $\Delta Ki$ is D, $\Delta Kd$ is E" [6] can establish fuzzy rules, the finally determined fuzzy rules are shown in the following table .

TABLE I. FUZZY RULE FOR $\Delta Kp$

| ec \ e | ***NB*** | ***NM*** | ***NS*** | ***ZO*** | ***PS*** | ***PM*** | ***PB*** |
|---|---|---|---|---|---|---|---|
| NB | PB | PB | PM | PM | PS | ZO | ZO |
| NM | PB | PB | PM | PS | PS | ZO | NS |
| NS | PM | PM | PM | PS | ZO | NS | NS |
| ZO | PM | PM | PS | ZO | NS | NM | NM |
| PS | PS | PS | ZO | NS | NS | NM | NM |
| PM | PS | ZO | NS | NM | NM | NM | NB |
| PB | ZO | ZO | NM | NM | NM | NB | NB |

TABLE II. FUZZY RULE FOR $\Delta Ki$

| ec \ e | ***NB*** | ***NM*** | ***NS*** | ***ZO*** | ***PS*** | ***PM*** | ***PB*** |
|---|---|---|---|---|---|---|---|
| NB | NB | NB | NM | NM | NS | ZO | ZO |
| NM | NB | NB | NM | NS | NS | ZO | ZO |
| NS | NB | NM | NS | NS | ZO | PS | PS |
| ZO | NM | NM | NS | ZO | PS | PM | PM |
| PS | NM | NS | ZO | PS | PS | PM | PB |
| PM | ZO | ZO | PS | PS | PM | PB | PB |
| PB | ZO | ZO | PS | PM | PM | PB | PB |

TABLE III. FUZZY RULE FOR $\Delta Kd$

| ec \ e | ***NB*** | ***NM*** | ***NS*** | ***ZO*** | ***PS*** | ***PM*** | ***PB*** |
|---|---|---|---|---|---|---|---|
| NB | PS | NS | NB | NB | NB | NM | PS |
| NM | PS | NS | NB | NM | NM | NS | ZO |
| NS | ZO | NS | NM | NM | NS | NS | ZO |
| ZO | ZO | NS | NS | NS | NS | NS | ZO |
| PS | ZO | ZO | ZO | ZO | ZO | ZO | ZO |
| PM | PB | NS | PS | PS | PS | PS | PB |
| PB | PB | PM | PM | PM | PS | PS | PB |

After constructing the table of fuzzy control rule ( $\Delta Kp$ 、 $\Delta Ki$ , $\Delta Kd$ ), we can make adaptive correction by the following method [7] [8] ：

$$Kp = Kp' + \Delta Kp$$
$$Ki = Ki' + \Delta Ki$$
$$Kd = Kd' + \Delta Kd$$
(13)

Based on the above analysis, according to the principle of self-tuning parameters of PID, the model of fuzzy self-tuning PID is presented in Fig.3

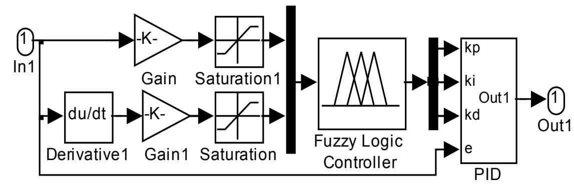


Figure 3. The model of fuzzy self-tuning PID

## IV. SIMULATION RESULTS

A control system based on Fuzzy-PID controller for PMSM is simulated in Matlab Simulink platform. The control block diagram of the whole system is shown in Fig. 4.

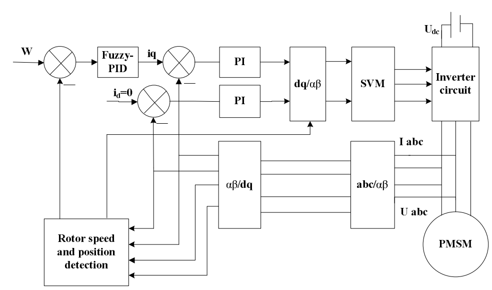


Figure 4. Structure diagram of the system

The parameters of the PMSM are shown in Table Ⅳ. The reference rotor speed is set to $100 rad/s$ , load torque is $2N \cdot m$ , The simulation period is set to $0.5s$ .

TABLE IV. MOTOR SPECIFICATION

| | | | |
|---|---|---|---|
| $P$ | 4 | $J$ | $0.0008 Kg \cdot m^2$ |
| $R$ | $0.975 \Omega$ | $B$ | $0.0002 N \cdot m \cdot s / rad$ |
| $L$ | $0.006 H$ | $P0$ | $380 W$ |
| $M$ | $-0.067 H$ | $U_{DC}$ | $220 V$ |

Simulation results are as follows. Speed response curve based on the PID controller is illustrated in the Fig.5. Speed response curve based on the Fuzzy-PID controller is illustrated in the Fig.6.

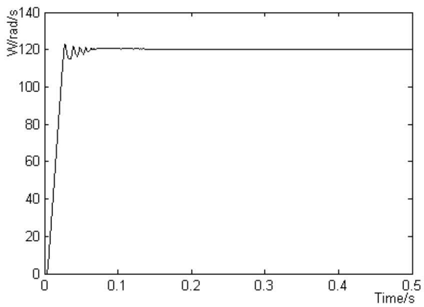


Figure 5. Speed response based on PID controller

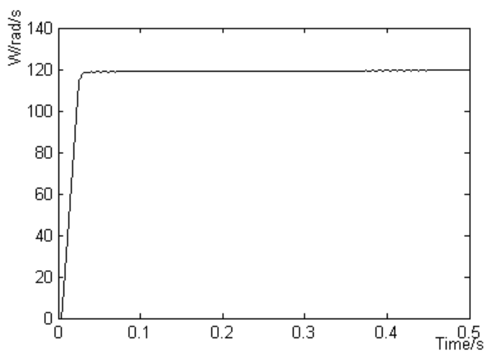


Figure 6. Speed response based on the Fuzzy-PID controller

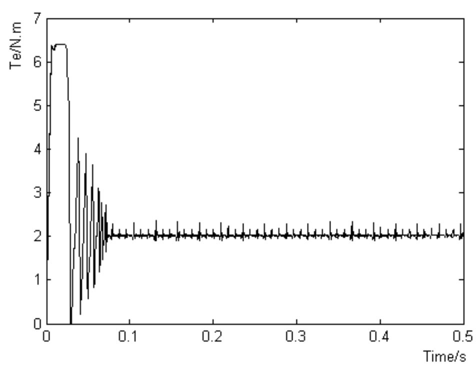


Figure 7. Torque response based on PID controller

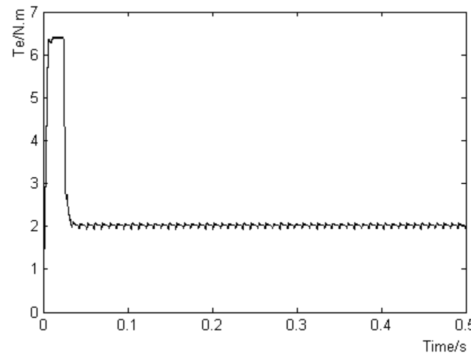


Figure 8. Torque response based on the Fuzzy-PID controller

Fig. 7 and Fig. 8 show the waveforms of the torque response. Torque response curve based on the PID controller is illustrated in the Fig.7. Torque response curve based on the Fuzzy-PID controller is illustrated in the Fig.8.

There exists speed overshoot in the Fig.5. However, there is no overshoot in the Fig.6. The performance of system is improved by using Fuzzy-PID controller. Using the improved algorithm, the torque ripple is reduced abruptly. Simulation results indicate that the proposed method is effective for the PMSM system.

## V. CONCLUSIONS

For the PMSM system, in order to decrease the speed and torque fluctuations, the new method based on Fuzzy-PID is proposed. According to the simulation results, the proposed algorithm is reasonable and feasible for the PMSM system.

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