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Sensorless Vector Control of AC Servo System with Artificial Neural Network Observer and Fuzzy Speed Controller

***Abstract**. The intelligent sensorless control for the permanent magnet synchronous motor (PMSM) based AC servo system is introduced in this paper. The determination of rotor position and thereby speed are realized by estimating back electromotive force (EMF) using two artificial neural network (ANN) observers. In addition, the Fuzzy-sliding model control (FSMC) was employed to track the servo speed at the speed loop. The control experiments using the dSPACE simulation platform has validated the efficiency of the newly proposed control method.*

***Streszczenie.** Przedstawiono metodę inteligentnego bezczujnikowego sterowania maszyną synchroniczną z magnesami trwałymi. Użyto obserwatora bazującego na sieciach neuronowych. Dodatkowo wykorzystano kontroler bazujący na logice rozmytej do śledzenia prędkości. (**Bezczujnikowe sterowanie maszyną synchroniczną z wykorzystaniem sieci neuronowych i logiki rozmytej**)*

Keywords: AC servo system, sensorless, intelligent observer, Fuzzy sliding model control.
Słowa kluczowe: serwomechanizm AC, sterowanie bezczujnikowe, logika rozmyta, sterowanie ślizgopwe.

Introduction

The permanent magnet synchronous motor (PMSM) became a very popular choice in driving technology due to some inherent advantages [1], such as high torque to current ratio, lager power to weight ratio, higher efficiency and robustness. Therefore, it has been used in the AC servo system to enhance the processing ability and processing quality of the machine tools. However, due to the complex nature of the PMSM, it is difficult to establish its precise mathematical model. Hence, high control performance is hard to achieve. Some advanced control methodologies have been proposed to control the PMSM based AC servo system. These new control techniques include artificial neural network (ANN) control [2], fuzzy control [3], sliding model control (SMC) [4], H∞ control [5], etc. The SMC is among the most used approach in practice. Nevertheless, the buffeting problem limits the applications of the SMC. How to depress the buffeting of the sliding surface is still the hot topical in the field of SMC.

On the other hand, most of the existing vector controllers need extra electromechanical sensors such as tachogenerators and encoders mounted on the PMSM rotor to acquire accurate speed and rotor position. However, the complexity and cost of the driver system are correspondingly increased [6-8]. The extra sensors can be eliminated if a mathematic method is adopted to estimate the speed and position of the motor rotor. This processing is the so called sensorless control technique [9].

In order to optimize the control of the PMSM based AC servo system, a new intelligent sensorless vector control scheme is proposed in the present work. The $i_d = 0$ vector control scheme was adopted for the servo control. The ANN has been employed to estimate the position and hence speed. There were two radial basis function neural network (RBF NN) observers to estimate the PMSM's back EMF in the α-β reference frame. Then the information on the flywheel position was extracted from the estimated back EMF components by means of inverse trigonometric functions [7, 8]. Moreover, the Fuzzy-sliding model control (FSMC) was adopted to track the servo speed at the speed loop. The Fuzzy logic hereby was used to eliminate the buffeting problem of the sliding model. The advantage of the proposed AC servo system is that it not only adopts the sensorless vector control strategy but also employs the FSMC to enhance the system speed control. Hence, it possesses more powerful control ability compared with the approaches in [9, 10]. The experiments using the dSPACE simulation platform has been conducted to evaluate and validate the proposed control method.

The vector control of PMSM

The voltage equation of PMSM at the *d-q* axis reference frame can be described as [9]

$$\begin{cases} u_q = Ri_q + p\psi_q + \omega_r \psi_d \\ u_d = Ri_d + p\psi_d - \omega_r \psi_q \end{cases} \tag{1}$$

where: u_d , u_q – direct and quadrature components of stator voltage, i_d , i_q – direct and quadrature components of stator current, ψ_d , ψ_q – direct and quadrature components of flux linkage, R – stator resistance, p – differential operator, ω_r – rotor electrical angular speed.

The *d-q* flux linkage equation is

$$\begin{cases} \psi_q = L_q i_q \\ \psi_d = L_d i_d + \psi_f \end{cases} \tag{2}$$

where: ψ_f – flux linkage due to permanent magnet.

The electromagnetic torque of motor is [9]

$$T_e = 3p_n[\psi_f i_q + (L_d - L_q)i_d i_q]/2 \tag{3}$$

where: L_d , L_q – direct and quadrature components of stator inductances, p_n – pole number of the machine.

The relation of moment and motor speed is

$$Jp\omega_r = p_n[T_e - B\omega_r / p_n - T_L] \tag{4}$$

where: J –moment of inertia, T_L – external load torque, *B* – viscous friction coefficient.

Notice that $p\psi_f = 0$, so for the surface mounted PMSM (SPMSM), $L_d = L_q = L$.

As usual in control strategy, the direct reference current is set to zero and then the motor torque is controlled by the quadrature current referring to Eqs. (3) and (4). Fig. 1 illustrates the proposed field-oriented sensorless vector control scheme, and the RBF NN observer based rotor speed/position estimation and the FSMC speed regulator have been proposed in the control system.

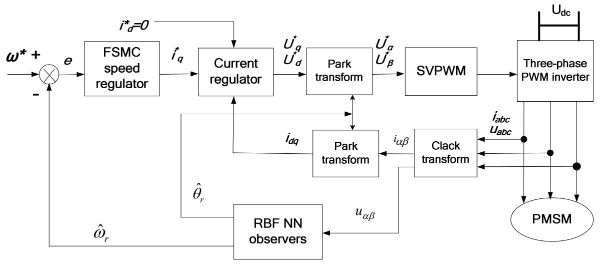

Fig. 1. The proposed control scheme.

Design of RBF NN observer

Since the RBF NN has better performance than BP NN due to its precise and fast optimal approximation property, it has been adopted in the sensorless vector control of PMSM based AC servo system. Fig. 2 shows the diagram of the proposed RBF NN observers for position/speed estimation.

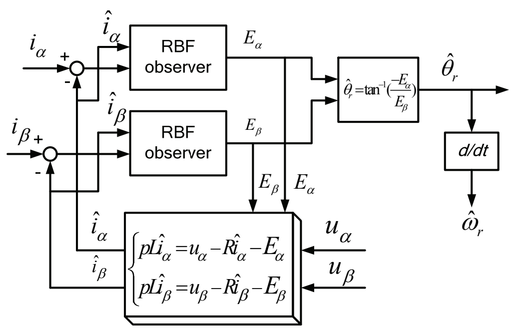

Fig. 2. The diagram of the proposed ANN based position estimator

Two RBF observers are used to estimate the two components of back EMF, E_α and E_β in the *α-β* reference frame. Each observer has two inputs and one output. The two inputs are the estimated current component and the error of the estimated and measured currents. The output is the estimated back EMF. Then, the rotor position information can be calculated from the back EMF terms. The mathematical derivation is given below.

Replace *L* with L_d and L_q in Eq. (1), the voltage equation of SPMSM at the *α-β* axis reference frame is obtained as

$$\begin{cases} u_\alpha = Ri_\alpha + pLi_\alpha - \omega_r\psi_f(\sin\theta_r) \\ u_\beta = Ri_\beta + pLi_\beta + \omega_r\psi_f(\cos\theta_r) \end{cases} \tag{5}$$

where: u_α, u_β – stator voltage components at the *α-β* axis, θ_r – rotor position, $\omega_r\psi_f(\sin\theta_r)$, $\omega_r\psi_f(\cos\theta_r)$ – back EMF component terms.

It can be seen from the Eq. (5) that the rotor position can be obtained by using the antitangent of the back EMF component terms, $\omega_r\psi_f(\sin\theta_r)$ and $\omega_r\psi_f(\cos\theta_r)$. However, the back EMF component terms are unknown, we use the RBF NN to approximate them. From Fig. 2 one can note that the RBF NN observers need the estimated currents, $\hat{i}_\alpha$, $\hat{i}_\beta$ to calculate the back EMF component terms. The relationships between u_α, u_β, the estimated currents, $\hat{i}_\alpha$, $\hat{i}_\beta$ and the estimated back EMFs can be defined as

$$\begin{cases} pL\hat{i}_\alpha = u_\alpha - R_a\hat{i}_\alpha - E_\alpha \\ pL\hat{i}_\beta = u_\beta - R_a\hat{i}_\beta - E_\beta \end{cases} \tag{6}$$

where: E_α, E_β – estimated back EMFs.

Then the rotor position can be derived by

$$\hat{\theta}_r = \tan^{-1}(-\frac{E_\alpha}{E_\beta}) \tag{7}$$

where: $\hat{\theta}_r$ – estimated rotor position.

Then the estimated speed $\hat{\omega}_r$ can be obtained by differentiating $\hat{\theta}_r$.

Design of FSMC speed regulator

Choose the below Equation as the sliding model states:

$$\begin{cases} x_1 = \hat{\omega}_r - \omega_r \\ x_2 = \dot{x}_1 = -\dot{\omega}_r \end{cases} \tag{8}$$

where: x_1, x_2 – sliding model states.

Combine Eqs. (1)~(3) and (8) yields:

$$\begin{cases} \dot{x}_1 = -\dot{\omega}_r = -(1.5P\psi_f i_q - T_L)/J \\ \dot{x}_2 = \ddot{x}_1 = -\ddot{\omega}_r = -1.5P\psi_f \dot{i}_q / J \end{cases} \tag{9}$$

where: $\dot{i}_q$ – differential of i_q, $\dot{x}_1$, $\dot{x}_2$ – differential of the sliding model states.

Then, the state space of the system is:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -A \end{bmatrix} u \tag{10}$$

where: *A* – $1.5P\psi_f / J$, u – $\dot{i}_q$.

Select the switching function as follows:

$$s = \alpha x_1 + x_2 \tag{11}$$

where: α – coefficient.

Calculate the partial differentiation of *s* by

$$\dot{s} = \alpha\dot{x}_1 + \dot{x}_2 = \alpha x_2 + \dot{x}_2 = \alpha x_2 - A\dot{i}_q \tag{12}$$

Set $\dot{s} = 0$, then get the equivalent controller as:

$$u_e = \int \dot{i}_q = \frac{1}{A}\int \alpha x_2 dt \tag{13}$$

Design the following switching controller:

$$u_s = \eta\,\mathrm{sgn}(s) \tag{14}$$

where: $\mathrm{sgn}(\cdot)$ – sign function, η – coefficient.

Thus, the SMC controller is obtained by

$$u = u_e + u_s \tag{15}$$

According to Liapunov stability law, the SMC controller is stable by the following proof:

$$s\dot{s} = s \cdot (-\eta \cdot \mathrm{sgn}(s)) = -\eta |s| \le 0 \tag{16}$$

The above SMC controller is readily to buffeting on the sliding surface. Severe buffeting may make the system unstable. Hence, the fuzzy control is adopted to eliminate the buffeting. The fuzzy SMC controller is designed as:

$$u_f = u_e + \gamma u_s \tag{17}$$

where: γ – fuzzy control output.

The input of the fuzzy control is switching function s. The domains of discourse of the fuzzy input and output are [-50，50] and [-24，24], respectively.

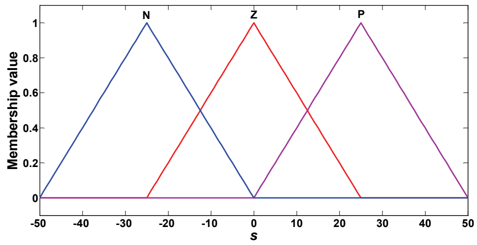

Fig. 3. The membership function of the fuzzy input

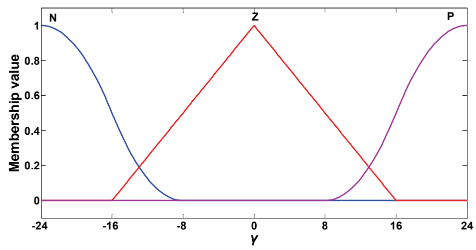

Fig. 4. The membership function of the fuzzy output

The fuzzy variables choose {N, Z, P}, and their membership functions are shown in Figs. 3 and 4. The fuzzy inference rules adopt follows: (1) if *s* is N, then β is P, (2) if *s* is Z, then β is Z, and (3) if *s* is P, then β is P. The defuzzification uses centroid method.

Experiments and results

The simulation test for the control model shown in Fig. 1 is implemented in the dSPACE platform. The dSPACE platform adopted the DS1103 controller board. The control algotithm codes were compiled accoding to the designed method. The tested PMSM parameters are as follows:

R = 1.75 Ω, L_q = L_d = 0.0045H, ψ_f = 0.115 Wb, P_n = 2, B = 0, J = 5.3e-4 kg·m^2.

The performance of the proposed sensorless control technique has been validated by several speed references. In the experiment 1, the speed reference is 1000 rpm, and the sliding model parameter is α = 3.8. The experiment results are shown in Figs. 5-7. Fig. 5 shows the speed tracking performance using different methods. The performance of the traditional PID, SMC and FSMC have been compared in the experiment. Fig. 6 shows their speed tracking errors. It can be seen that under constant speed reference, the speed tracking performance is satisfactory for the three control approach. Each method can achieve high precision control result with little speed tracking error.

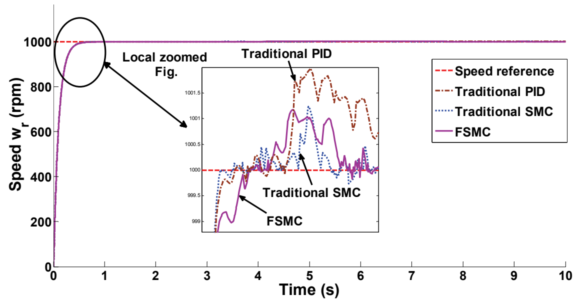

Fig. 5. The speed tracking performance

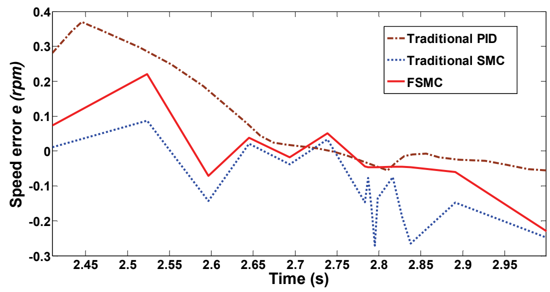

Fig. 6. The speed tracking error

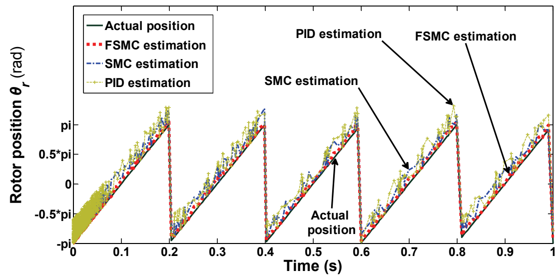

Fig. 7. The rotor position estimation performacne

Fig. 7 shows the rotor position estimation performance using the RBF observer. The FSMC has been compared with the traditional PID and SMC. One can be noticed that the RBF observer can estimate the rotor position accurately, and the FSMC has smoother position curve than the traditional PID and SMC.

In the experiment 2, a sinusoidal reference speed of 5.0 Hz was given to evaluate the proposed control method. Fig. 8 shows the speed tracking performance using the traditional PID, SMC and FSMC. Fig. 9 shows their speed tracking errors. It can be seen from Figs, 8 and 9 that when the speed reference varies, the the traditional PID fails to follow the speed reference and the control system can not work normally. And the SMC can track the speed reference by a long regulation time. In contrast to the PID and SMC, the FSMC can control the time varying speed reference adaptively and perfectly. The adjusted control time is smaller than the SMC and the steady-state error is much better than the PID and SMC. This is because the fuzzy control can eliminate the SMC buffering so that the FSMC can provide more robust and adaptive control ability. Since the PID parameters are fixed in the control processing it can not deal with the system parameter change.

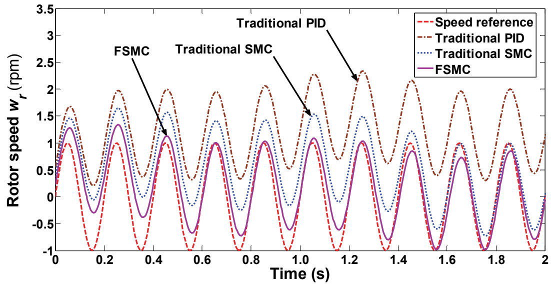

Fig. 8. The speed tracking performance

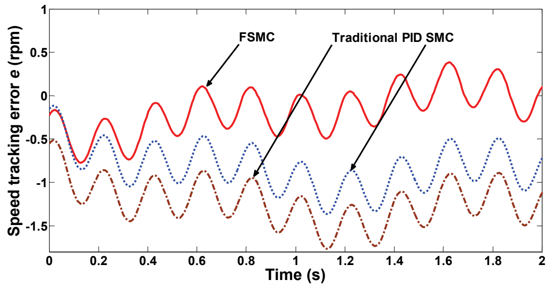

Fig. 9. The speed tracking error

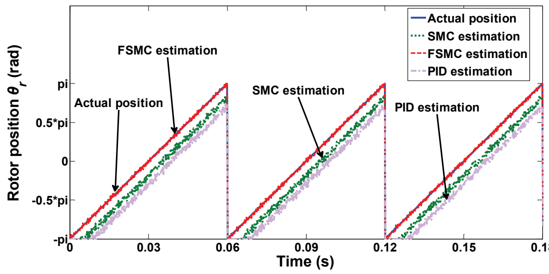

Fig. 10. The rotor position estimation performacne

Fig. 10 shows the rotor position estimation performance using the RBF observer. It can be seen from Fig. 10 that the RBF observer can estimate the rotor position accurately, and the position estimation performance of the FSMC is superior to the traditional PID and SMC.

Conclusions

A new sensorless vector control system for the permanent magnet synchronous motor (PMSM) based AC servo system is presented in this paper. The rotor position/speed are estimated by means of two RBF NN observers. Moreover, the Fuzzy sliding model control has been introduced to enhance the system speed tracking ability. The porposed control system has been tested in the dSPACE platform for the purpose of investigating the system dynamic respond. The testing results show that the performance of the system is satisfactory using the proposed control scheme. The speed conrol is fast and precise, and the rotor position estimation is acceptable. The RBF NN observers can achieve little error in the estimation of position even the speed reference is tiem varying. In addition, thanks to the fuzzy control, the FSMC can respond the system parameter change quickly and the control performance outperforms the the PID and SMC. Hence, the proposed sensorless control strategy provides an effective method for the control of PMSM based AC servo system.

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