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Sensorless Control of PMSM Based on Sliding Mode Observer

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Abstract：A novel sliding mode observer(SMO) of PMSM(permanent magnetic synchronous motor) was presented, which estimated the rotor position and angular velocity accurately.The proposed SMO substitutes a sigmoid function for the conventional signum function with a variable boundary layer which is changed according to the rotational velocity.The dependence to motor parameters and chattering effects that is commonly found in signum function using for the switching function were overcome.By combining the model of PMSM under $d-q$ coordinate,the convergence condition of observer was deduced.The convergence was verified by the Lyapunov theory.Simulation results show that the rotor position and velocity can be observed accurately,and also has good dynamic performance and robustness.

Introduction

Permanent magnetic synchronous motors have widely been used in AC driving system due to the high efficiency,high power density and good controllability.Generally,the rotor position and velocity can be detected by speed sensors.However,sensors are expensive and very sensitive to environment[1].So the research interest on PMSM sensorless control is still lively[2-5].

Recently,much research has been focused on investigating and testing various sensorless position and speed detection methods.The approach of flux linkage observation was reported in [6].In this observer,the change of stator resistance will cause flux linkage estimation inaccurate.Furthermore,the performance deteriorates drastically at low speeds.The extended Kalman filter approach was introduced into flux linkage observation in [7].This method overcomes effects of parameters variation and perturbation,but the algorithm is complex and the amount of calculation is large.An estimation based on high-frenquency(HF) signal injection was reported in[8-9].HF signal injection offers a solution at standstill and low speeds,but as the speed increase,its performance deteriorates drastically.The rotor position and velocity can be estimated using SMO[10-13].SMO is a promising approach an effective technique due to its outstanding robustness properties against system parameter uncertainties and external disturbances.However,a low-pass filter(LPF) and an additional position compensation are used to reduce the chattering problem commonly found in SMO using a signum function.This will cause a time delay.

This paper propose a new sensorless control algorithm for a PMSM based on SMO which uses a sigmoid function as a switching function with variable boundary layers.This new SMO requires neither the LPF nor the extra compensator for the rotor position,and can eliminate chattering effectively.The position and velocity of the rotor can be calculated from the estimated back EMF.To overcome the sensitivity of the parameter variations in the sensorless control and to improve the steady-state performance,the method of stator resistance estimation has been proposed in this paper.Simulation results show that proposed SMO is correct and effective.

PMSM Modeling

The state equations of the PMSM in $\alpha-\beta$ reference frame are:

$$\begin{cases} \dot{\psi}_\alpha = -\dfrac{R}{L_s}\psi_\alpha + \dfrac{R}{L_s}\psi_{f\alpha} + u_\alpha \\ \dot{\psi}_\beta = -\dfrac{R}{L_s}\psi_\beta + \dfrac{R}{L_s}\psi_{f\beta} + u_\beta \\ \dot{\psi}_{f\alpha} = -\omega\psi_{f\beta} \\ \dot{\psi}_{f\beta} = \omega\psi_{f\alpha} \end{cases} \tag{1}$$

The output equations are:

$$\begin{cases} i_\alpha = \dfrac{1}{L_s}\psi_\alpha - \dfrac{1}{L_s}\psi_{f\alpha} \\ i_\beta = \dfrac{1}{L_s}\psi_\beta - \dfrac{1}{L_s}\psi_{f\beta} \end{cases} \tag{2}$$

where ψ_α, ψ_β are the α-axis and β-axis stator flux respectively. $\psi_{f\alpha}, \psi_{f\beta}$ are the α-axis and β-axis permanent magnet flux respectively. u_α , u_β are the α-axis and β-axis voltage respectively. i_α, i_β are the α-axis and β-axis current respectively. R is the stator resistance. ω is the electrical rotor speed. L_s is stator inductance.

Permanent magnet flux vector on the stationary reference frame are shown in Fig. 1,according to this, the PM fluxes are:

$$\begin{cases} \psi_{f\alpha} = \psi_f \cos\theta \\ \psi_{f\beta} = \psi_f \sin\theta \end{cases} \tag{3}$$

where $\theta = \omega t$.

According to equations (1) and (2),the state equation of stator flux and current are:

$$\begin{cases} \dot{\psi}_\alpha = -Ri_\alpha + u_\alpha \\ \dot{\psi}_\beta = -Ri_\beta + u_\beta \\ \dot{i}_\alpha = \dfrac{1}{L_s}\omega\psi_\beta - \dfrac{R}{L_s}i_\alpha - \omega i_\beta + \dfrac{1}{L_s}u_\alpha \\ \dot{i}_\beta = -\dfrac{1}{L_s}\omega\psi_\alpha + \omega i_\alpha - \dfrac{R}{L_s}i_\beta + \dfrac{1}{L_s}u_\beta \end{cases} \tag{4}$$

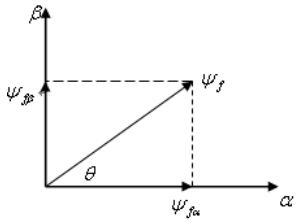


Fig.1 Rotor flux linkage in $\alpha-\beta$ reference frame

The motor EMFs e_α, e_β are defined as:

$$\begin{cases} e_\alpha = \dot{\psi}_{f\alpha} = -\psi_f \omega \sin\theta \\ e_\beta = \dot{\psi}_{f\beta} = \psi_f \omega \cos\theta \end{cases} \tag{5}$$

So the equations of the PMSM with respect to the current are:

$$\begin{cases} \dot{i}_\alpha = -\dfrac{R}{L_s} i_\alpha - \dfrac{1}{L_s} e_\alpha + \dfrac{1}{L_s} u_\alpha \\ \dot{i}_\beta = -\dfrac{R}{L_s} i_\beta - \dfrac{1}{L_s} e_\beta + \dfrac{1}{L_s} u_\beta \end{cases} \tag{6}$$

SMO Design of PMSM

SMO Model. Based on the machine model in (6),the structure of the SMO is expressd as

$$\begin{cases} \dot{\hat{i}}_\alpha = -\dfrac{\hat{R}}{L_s} i_\alpha + \dfrac{1}{L_s} u_\alpha - \dfrac{1}{L_s} kH(\bar{i}_\alpha) \\ \dot{\hat{i}}_\beta = -\dfrac{\hat{R}}{L_s} i_\beta + \dfrac{1}{L_s} u_\beta - \dfrac{1}{L_s} kH(\bar{i}_\beta) \end{cases} \tag{7}$$

where k is SMO gain, $\bar{i}_\alpha, \bar{i}_\beta$ are the estimation errors between the estimated current $\hat{i}_\alpha, \hat{i}_\beta$ and actual current i_α, i_β.The estimation errors are defined as $\bar{i}_\alpha = \hat{i}_\alpha - i_\alpha, \bar{i}_\beta = \hat{i}_\beta - i_\beta$.The new SMO uses a sigmoid function as the switching function.The sigmoid function is represented as

$$\begin{bmatrix} H(\bar{i}_\alpha) \\ H(\bar{i}_\beta) \end{bmatrix} = \begin{bmatrix} (\dfrac{2}{1+\exp(-a\bar{i}_\alpha)}) - 1 \\ (\dfrac{2}{1+\exp(-a\bar{i}_\beta)}) - 1 \end{bmatrix} \tag{8}$$

where a is a positive constant used to regulate the slope of the sigmoid function.

Stability Analysis. According to current error,the sliding surface S can be defined as $S = [s_\alpha, s_\beta]^T = [\bar{i}_\alpha, \bar{i}_\beta]^T = [\hat{i}_\alpha - i_\alpha, \hat{i}_\beta - i_\beta]^T = 0$ When the estimation errors are on the sliding surface, $\hat{i}_\alpha = i_\alpha, \hat{i}_\beta = i_\beta$. At that moment,the observer becomes robust against the systerm parameters and disturbances.In order to determine the stability of the designated observer,the Lyapunov function can be defined as

$$V = \frac{1}{2} S^T S + \frac{1}{2} \bar{R}^2 \tag{9}$$

where $\bar{R} = \hat{R} - R$ is the error of stator resistance.

The condition of global asymptotic stability is $V > 0,\ \dot{V} < 0$.Taking the derivative of (9),we find

$$\dot{V} = S^T \dot{S} + \bar{R}\dot{\hat{R}} \tag{10}$$

According to the current equations (6) and estimation model (7),the current estimation error dynamics is given by

$$\dot{s}_\alpha = \dot{\bar{i}}_\alpha = \dot{\hat{i}}_\alpha - \dot{i}_\alpha = (\hat{A} - A)\hat{i}_\alpha + A(\hat{i}_\alpha - i_\alpha) + \frac{1}{L_s} e_\alpha - \frac{1}{L_s} kH(\hat{i}_\alpha - i_\alpha) \tag{11}$$

$$\dot{s}_\beta = \dot{\bar{i}}_\beta = \dot{\hat{i}}_\beta - \dot{i}_\beta = (\hat{A} - A)\hat{i}_\beta + A(\hat{i}_\beta - i_\beta) + \frac{1}{L_s} e_\beta - \frac{1}{L_s} kH(\hat{i}_\beta - i_\beta) \tag{12}$$

where $A=-\frac{R}{L_s}, \hat{A}=-\frac{\hat{R}}{L_s}$.

By substituting (11) (12) into (10),the sliding condition can be represented as

$$\dot{V}=[\bar{i}_\alpha,\bar{i}_\beta]\cdot\begin{bmatrix}(\hat{A}-A)\hat{i}_\alpha+A(\hat{i}_\alpha-i_\alpha)+\frac{1}{L_s}[e_\alpha-kH(\hat{i}_\alpha-i_\alpha)]\\(\hat{A}-A)\hat{i}_\beta+A(\hat{i}_\beta-i_\beta)+\frac{1}{L_s}[e_\beta-kH(\hat{i}_\beta-i_\beta)]\end{bmatrix}+\bar{R}\cdot\dot{\hat{R}}<0 \tag{13}$$

To satisfy the condition $\dot{V}<0$,(13) is decomposed into two equations as follows:

$$[\bar{i}_\alpha,\bar{i}_\beta]\cdot\begin{bmatrix}(\hat{A}-A)\hat{i}_\alpha\\(\hat{A}-A)\hat{i}_\beta\end{bmatrix}+\bar{R}\cdot\dot{\hat{R}}=0 \tag{14}$$

$$[\bar{i}_\alpha,\bar{i}_\beta]\cdot\begin{bmatrix}A\bar{i}_\alpha+\frac{1}{L_s}[e_\alpha-kH(\hat{i}_\alpha-i_\alpha)]\\A\bar{i}_\beta+\frac{1}{L_s}[e_\beta-kH(\hat{i}_\beta-i_\beta)]\end{bmatrix}<0 \tag{15}$$

According to (14),the estimation of the stator resistance can be obtained as

$$\hat{R}=\frac{1}{L_s}\int(\bar{i}_\alpha\cdot\hat{i}_\alpha+\bar{i}_\beta\cdot\hat{i}_\beta)dt \tag{16}$$

According to (15),the inequality can be described as follows:

$$-A((\bar{i}_\alpha)^2+(\bar{i}_\beta)^2)+\frac{1}{L_s}\bar{i}_\alpha[e_\alpha-kH(\bar{i}_\alpha)]+\frac{1}{L_s}\bar{i}_\beta[e_\beta-kH(\bar{i}_\beta)]<0 \tag{17}$$

where the observer gain can be derived to satisfy the inequality condition as

$$k>\max(|e_\alpha|,|e_\beta|) \tag{18}$$

The chattering will become serious with k increasing.So the stability and chattering should be comprehensive considerate in the value of k.

Position and Velocity Estimation of the Rotor. When the system reaches sliding surface,the equation are as follow

$$[\dot{s}_\alpha,\dot{s}_\beta]^T=[s_\alpha,s_\beta]^T=[0,0]^T \tag{19}$$

From the equation (19),the back EMF can be expressed in the form

$$\begin{aligned}e_\alpha&\approx kH(\bar{i}_\alpha)\\e_\beta&\approx kH(\bar{i}_\beta)\end{aligned} \tag{20}$$

the position and velocity of the rotor are calculated from

$$\theta=-\tan^{-1}(\frac{e_\alpha}{e_\beta}) \tag{21}$$

$$\omega=\frac{d}{dt}\theta \tag{22}$$

Experiment Rrsults

Fig.2 is the block diagram of the sensorless controller.The parameters of the PMSM is listed in Table 1.

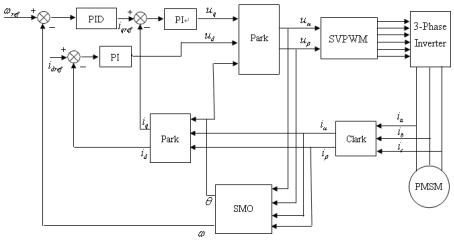
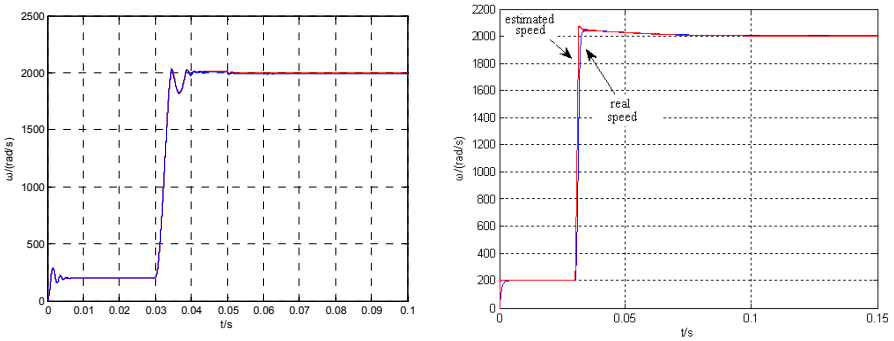


Fig.2 Block diagram of the sensorless controller

Tab.1 Parameters of PMSM

Parameter	Value
Stator Resistance	$0.7\,\Omega$
Stator Inductor	$0.00484\,H$
Flux	$0.0556\,Wb$
Rotor Inertia	$0.74\text{e-}4\,kg\cdot m^2$
poles	4

The control system is simulated based on Matlab/Simulink facility.Fig.3 shows the step responses form 200r/min to 2000r/min using the sigmum function SMO and using the sigmoid function SMO.As it is shown by Fig.3(a) the fluctuation is obvious using sigmum function SMO.From the Fig3(b) we can see that the dynamic performances of speed is better.In addition,the chattering can be overcome effectively .



(a) (b)

Fig.3 Responses of velocity. (a) using the sigmum function (b) using the sigmoid function.

Fig.4 shows the speed respone when the load torque changes at time 0.05s.It can be seen that the speed tracing response will appear fluctuation in the case of load torque disturbance when use the sigmum function as switching function.But the proposed SMO is robust to load disturbances. Fig.5 shows actual and estimated rotor position.From these figures,the proposed SMO can estimate current and rotor position effectively.

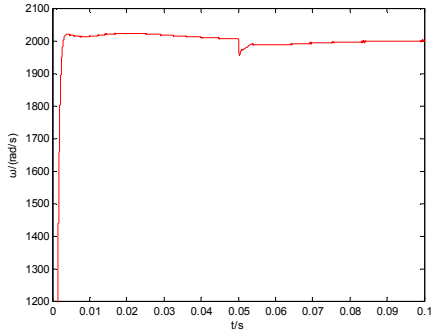


Fig.4 Speed response to load torque changes

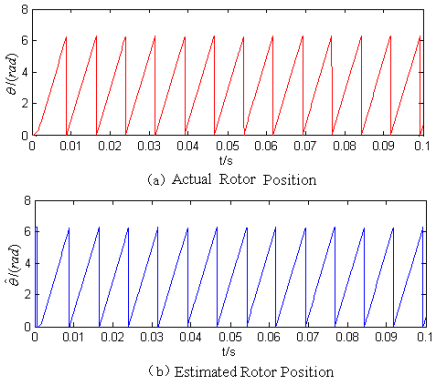


Fig.5 Real and estimated rotor position

Conclusion

This paper has proposed a new SMO which adopts sigmoid function with variable boundary layer as the switching function for PMSM.The boundary layer changes according to the rotational velocity.The stabilities of proposed control system are guaranteed by Lyapunov stability

analysis.This new SMO overcomes dependence of motor parameters in conventional SMO,and the chattering problem is resolved effectively.The experimenal results shows that this control systerm can estimate rotor position and velocity accurately,and it also has good dynamic and static performances.

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