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On Position Sensorless Control for Permanent Magnet Synchronous Motor Based on a New Sliding Mode Observer

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Abstract: For the problems of buffeting and phase delay in traditional rotor detection in sensorless vector control of permanent magnet synchronous motor (PMSM), the Sigmoid function is proposed to replace sign function and the approach of piecewise linearization is proposed to compensate phase delay. To the problem that the output of traditional low pass filter contains high-order harmonic, two-stage filter including traditional low-pass filter and Kalman filter is proposed in this paper. Based on the output of traditional first-order low-pass filter, the Kalman filter is used to get modified back-EMF. The phase-locked loop control of rotor position is adopted to estimate motor position and speed. A Matlab/Simulink simulation model of PMSM position servo control system is established. The simulation analysis of the new sliding mode observer's back-EMF detection, position and speed estimation, load disturbance and dynamic process are carried out respectively. Simulation results verify feasibility of the new sliding mode observer algorithm. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Permanent magnet synchronous motor, Sliding mode observer, Phase compensation, Two-stage filter, Phase-locked loop control.

1. Introduction

To obtain the exact rotor position and speed information in the PMSM vector control system, position and speed sensor should be installed on the motor shaft, but the using of position and speed sensor not only increase the system cost, but also reduce the system robustness.

Therefore, in recent years, the application of sensorless control technology in PMSM speed control system becomes especially important [1, 2]. Currently, position and speed sensorless control techniques usually have stator flux estimation method [3], model reference adaptive method [4], state observer estimation method [5, 6] and artificial intelligence estimation method [7], etc. Observer methods become the most popular and sliding mode observer [8, 9] method is one of them. However, conventional sliding mode observer exists many problems, so it need to be studied and improved, since the conventional sliding mode observer just use a simple first-order low-pass filter to obtain motor back-EMF estimated value. According to the relationship between back-EMF and the motor rotor position, the rotor position and speed information can be obtained. As the sliding mode make system serious buffeting, back-EMF after filtering has a large phase lag. Currently, in the position and speed sensorless PMSM vector control system, many ways have been proposed to estimate the motor rotor position and velocity. Literature [10] uses the electromagnetic correlativity of PMSM to estimate the rotor position and speed. This method has simple calculation and fast dynamic response, but it is very sensitive to the motor parameters, and when motor speed is low, estimate will not very accurate. Literature [11] has proposed a method of trickling high frequency voltage to the motor, and detected the current to obtain rotor speed and position information simultaneously. Although this method can be applied to a relatively wide speed range, there are still deficient that noise problems would be brought about after high frequency signal has been injected, and there are many strict requirements to the hardware circuit. Switching function in literature is replaced by saturation function [12, 13], buffeting can be weakened by choosing a reasonable boundary layer thickness. But only its rotor position estimation method has been verified according to theory, the motor speed estimation and closed-loop control have not been researched in depth [14]. These points limit the further applications of sliding mode observer in sensorless PMSM control system to some extent.

Based on sliding mode control theory, a new type of sliding mode observer is proposed in this paper. Instead of the traditional sign function, sigmoid function [15, 16] has effectively eliminated chattering [17]. In some high performance applications, back-EMF is obtained merely by conventional first-order low-pass filter, which can not be directly used to calculate the rotor position, because it contains more disturbances. Therefore, two stage filter is proposed in this paper. This two stage filter contains a first-order low-pass filter and a conventional Kalman filter. Firstly, the back-EMF is obtained through a first-order low-pass filter. Then, the conventional Kalman filter can be used to eliminate the high frequency ripple in back-EMF. Specific to a first-order low-pass filtering, the motor rotor position estimation has a lag, so a piecewise linear phase compensation method is proposed. In addition, as the accuracy of rotor position estimated from the traditional approach is not satisfied, the phase-locked loop technique is adopted to estimate the rotor position, which greatly improves the accuracy of the rotor position.

Based on a new sensorless PMSM vector control system with a three-ring structure, namely the position loop, velocity loop and current loop, PMSM position sensorless servo control system simulation model is established on Matlab / Simulink platform. The back-EMF, estimation of position and velocity, load disturbance and dynamic process of the new sliding mode observer is analyzed respectively. The simulation results show that the new sliding mode observer algorithm is feasible and effective.

2. Mathematical Model of PMSM

In the two-phase stationary $\alpha-\beta$ reference frame, the mathematical model of PMSM is as shown in equation (1-1) to equation (1-4).

$$\frac{di_a}{dt}=-\frac{R}{L}i_a+\frac{1}{L}\left(u_a-e_a\right), \tag{1-1}$$

$$\frac{di_\beta}{dt}=-\frac{R}{L}i_\beta+\frac{1}{L}\left(u_\beta-e_\beta\right) \tag{1-2}$$

$$e_a=-\frac{\psi_f}{L}\omega_e\sin\theta_e \tag{1-3}$$

$$e_\beta=\frac{\psi_f}{L}\omega_e\cos\theta_e \tag{1-4}$$

where i_α, i_β are the currents of α axis and β axis respectively, u_a, u_β are the stator voltages of α axis and β axis respectively, e_α, e_β are the motor back-EMF of α axis and β axis respectively, ψ_f is the rotor flux, ω_e is the rotor speed, θ_e is the rotor angle, L is the stator inductance, R is the stator resistance.

3. The Design of Improved Sliding Mode Observer

3.1. The Design of New Observer

The structure of improved sliding mode observer is shown in Fig. 1.

Improved sliding mode observer mainly includes five parts that are current observer, Sigmoid function, Kalman filter, rotor position phase-locked loop and piecewise linear compensation.

The current observation model is as shown in equation (2-1) and equation (2-2).

$$\frac{di_a^*}{dt}=-\frac{R}{L}i_a^*+\frac{1}{L}u_a-\frac{k_1}{L}H\left(i_a^*-i_a\right), \tag{2-1}$$

$$\frac{di_\beta^*}{dt}=-\frac{R}{L}i_\beta^*+\frac{1}{L}u_\beta-\frac{k_1}{L}H\left(i_\beta^*-i_\beta\right), \tag{2-2}$$

where i_a^*, i_β^* are the new sliding mode observer's observing currents of $\alpha-\beta$ axis, k_1 is the gain of a sliding mode observer, H is Sigmoid function. Equation (3) is the definition of H function.

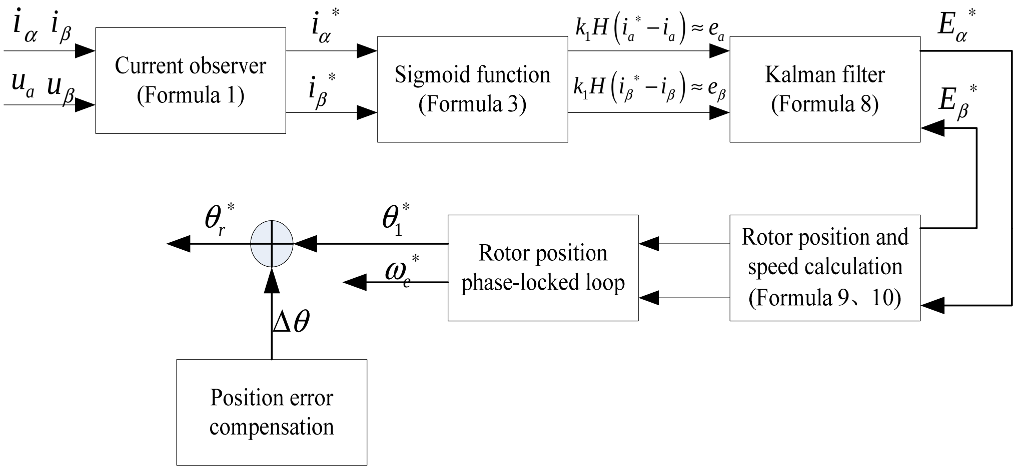

Fig. 1. The structure of new sliding mode observer.

$$\begin{bmatrix} H\left(i_a^* - i_a\right) \\ H\left(i_\beta^* - i_\beta\right) \end{bmatrix} = \begin{bmatrix} \dfrac{2}{1+e^{-a\left(i_a^* - i_a\right)}} - 1 \\ \dfrac{2}{1+e^{-a\left(i_\beta^* - i_\beta\right)}} - 1 \end{bmatrix}, \quad (3)$$

where constant a is the slope of the Sigmoid function.

Equation (2-1), (2-2) respectively substracts equation (1-1), (1-2), the current error equation (4-1), (4-2) can be obtained.

$$\frac{d\left(i_a^* - i_a\right)}{dt} = -\frac{R}{L}\left(i_a^* - i_a\right) + \frac{1}{L}\left[e_a - k_1 H\left(i_a^* - i_a\right)\right], \quad (4\text{-}1)$$

$$\frac{d\left(i_\beta^* - i_\beta\right)}{dt} = -\frac{R}{L}\left(i_\beta^* - i_\beta\right) + \frac{1}{L}\left[e_\beta - k_1 H\left(i_\beta^* - i_\beta\right)\right], \quad (4\text{-}2)$$

Define the sliding surface,

$$S = \left[\bar{i}_a \ \bar{i}_\beta\right]^T, \quad (5\text{-}1)$$

$$\bar{i}_a = i_a^* - i_a, \quad (5\text{-}2)$$

$$\bar{i}_\beta = i_\beta^* - i_\beta, \quad (5\text{-}3)$$

Therefore, system state equation (6-1), (6-2) can be obtained.

$$\frac{d\bar{i}_a}{dt} = -\frac{R}{L}\bar{i}_a + \frac{1}{L}\left[e_a - k_1 H\left(\bar{i}_a\right)\right], \quad (6\text{-}1)$$

$$\frac{d\bar{i}_\beta}{dt} = -\frac{R}{L}\bar{i}_\beta + \frac{1}{L}\left[e_\beta - k_1 H\left(\bar{i}_\beta\right)\right], \quad (6\text{-}2)$$

When the trajectory of estimation error reaches the switching surface, S = 0. In other words, the observed value of the current eventually converges to the actual current value, that is to say,

$$i_a^* = i_a, \quad (7\text{-}1)$$

$$i_\beta^* = i_\beta, \quad (7\text{-}2)$$

So equation (8-1), (8-2) can be derived by equation (6-1), (7-1) and equation (6-2), (7-2) receptively.

$$e_a = k_1 H\left(\bar{i}_a\right), \quad (8\text{-}1)$$

$$e_\beta = k_1 H\left(\bar{i}_\beta\right), \quad (8\text{-}2)$$

3.2. The Design of Kalman Filter[18]

In equation (8-1) and (8-2) the e_a and e_β contains back-EMF information. A relatively smooth back-EMF can be obtained after the traditional first-order low-pass filter, assuming that e_a^* and e_β^* are the relatively smooth back-EMF signal. And equation (9-1), (9-2) can be derived.

$$e_a^* = \frac{\omega_c}{s+\omega_c} e_a = \frac{\omega_c}{s+\omega_c} * \left(k_1 H\left(\bar{i}_a\right)\right), \qquad (9\text{-}1)$$

$$e_\beta^* = \frac{\omega_c}{s+\omega_c} e_\beta = \frac{\omega_c}{s+\omega_c} * \left(k_1 H\left(\bar{i}_\beta\right)\right), \qquad (9\text{-}2)$$

In some high performance applications, the back-EMF e_a^*, e_β^* which are estimated by equation (9-1), (9-2) contain more disturbance, thus can not be directly used to estimate rotor position and speed. So it is necessary to carry out the second filtering. When the Kalman filter is introduced, state equations of back-EMF are shown in equation (10-1), (10-2), (10-3).

$$\frac{dE_a^*}{dt} = -\omega_e^* E_\beta^* - k_1\left(E_a^* - e_a^*\right), \qquad (10\text{-}1)$$

$$\frac{dE_\beta^*}{dt} = -\omega_e^* E_\alpha^* - k_1\left(E_\beta^* - e_\beta^*\right), \qquad (10\text{-}2)$$

$$\frac{d\omega_e^*}{dt} = \left(E_a^* - e_a^*\right)E_\beta^* - \left(E_\beta^* - e_\beta^*\right)E_a^*, \qquad (10\text{-}3)$$

where E_a^*, E_β^* are the back-EMF estimated values of the improved sliding mode observer; ω_e^* is the rotor angle estimated value; k_1 is the sliding coefficient of the improved sliding mode observer.

By arctangent conventional method and back-EMF estimated value in equation (10-1), (10-2), (10-3), estimated value of rotor angle and rotor speed can be obtained, as shown in equation (11) and equation (12).

$$\theta_1^* = \arctan\left(-\frac{E_a^*}{E_\beta^*}\right), \qquad (11)$$

$$\omega_e^* = \frac{d\theta_1^*}{dt}, \qquad (12)$$

3.3. Estimating the Rotor Position and Speed by Phase-locked Loop

Rotor position's calculation always adopts arctangent traditional method which is shown in equation (11). Actually, rotor position and speed accuracy is not satisfied when equation (11) and (12) are used. In order to further improve the precision of rotor position and speed estimated value, a phase-locked loop technique is introduced and its structure is shown in Fig. 2.

E_a^* and E_β^* are the improved estimated value of sliding mode observer's back-EMF, they can be obtained by the Kalman filter.

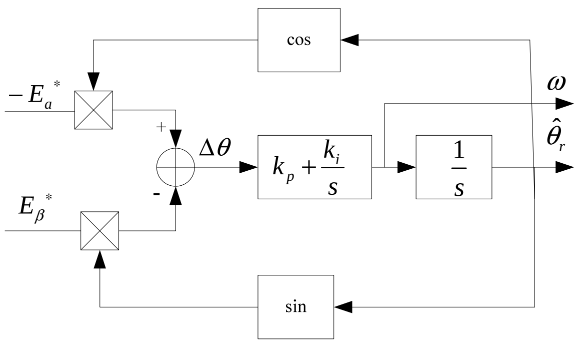

Fig. 2. The structure of rotor position phase-locked loop.

From equation (11), equation (13) can get,

$$\tan\theta_1^* = -\frac{E_a^*}{E_\beta^*} = \frac{\sin\theta_1^*}{\cos\theta_1^*}, \qquad (13)$$

Then angle can also be calculated as follows.

$$\theta_1^* = \tan^{-1}\frac{\sin\theta_1^*}{\cos\theta_1^*}, \qquad (14)$$

From the structure of rotor phase-locked loop, the estimated value of rotor position θ_1^* is obtained, from Fig. 1 can get equation (15).

$$\Delta\theta = -E_a^*\cos\hat{\theta}_r - E_\beta^*\sin\hat{\theta}_r, \qquad (15)$$

Regulated by the PI controller continually, the complete tracking of $\hat{\theta}_r$ to θ_1^* be achieved when θ_1^* equals to $\hat{\theta}_r$.

3.4. Phase Compensation of Estimated Rotor Angle

The estimated value of back-EMF after through the conventional first-order low-pass filter has a phase lag, and phase lag will increase as the motor's operating frequency increases. So the estimated value of rotor position compared to actual value will have a large phase lag, which will result in instability of motor operation, and therefore the estimated value of rotor position should have phase compensation accordingly. The traditional compensation approach of phase angle is that using lag phase angle compensates for the estimated value of rotor position. $\Delta\theta^*$ is the lag phase angle,

$$\Delta\theta^* = \tan^{-1}\left(\omega / \omega_c\right), \quad (16)$$

θ is the final rotor position:

$$\theta = \Delta\theta^* + \theta_1^*, \quad (17)$$

Furthermore, this traditional method relates to the divider and the arctangent calculation, so that actual programming will still face many difficulties. Therefore, this article adopt a piecewise linear compensation method to compensate the position estimated value correspondingly.

That is to say, the motor rotor angle compensation is divided into different segments which are all adopted line approximation method, and different segments are limited by motor angular frequency value. Then each segment motor angular frequency has its own slope and constant phase compensation value.

Simulation results show that rotor position estimation error caused by a first-order low-pass filter can be calculated by a first-order transfer function whose cut-off frequency is 150 HZ. In this paper, the phase angle compensation value under typical speed can be obtained by the Bode diagram of a first-order filter. The compensation value of phase angle under typical speed is shown in Table 1.

According to the compensation value of phase angle in Table 1, four segmented estimated value of position compensation can be obtained, which is shown in Table 2. ω is the motor speed.

Table 1. The compensation value of phase angle under typical speed.

Motor speed/(rad/s)	Compensation angle $\Delta\theta^\circ$
100	39.66
200	60.26
400	77.01
600	85.69
800	86.9

Table 2. The estimated value of compensation angle.

Motor speed/(rad/s)	Compensation angle $\Delta\theta^\circ$
100~200	0.206ω+19.09
200~400	0.0837ω+43.51
400~600	0.0434ω+59.65
600~800	0.0061ω+82.06

4. Simulations and Analysis

The simulation model of PMSM sensorless control system is established based on the sliding mode observer. Simulation system adopts $i_d = 0$ current control strategy, the control system is consisted of an external position loop, a velocity loop and an inner current loop.

PMSM sensorless algorithm simulation model based on the new sliding mode observer is shown in Fig. 3.

The parameters in simulation are selected as follows: R=0.62 Ω, L_d =2.075 mH, L_q =2.075 mH, ψ_f =0.08627 Wb, J=0.0003617 kg m^2, motor pole logarithmic P=4, DC bus voltage of the inverter U_{dc} =300 V, carrier frequency is 5 kHz. For the position given value range from 10*pi(rad) to 85*pi(rad), the simulation model has better tracking performance.

4.1. Simulation Analysis of the Back-EMF

The estimated value of rotor position can be obtained after back-EMF pass through phase-locked loop, so the quality of the back-EMF will directly affect the estimated value of rotor position and velocity. The two stage filtering is used to get the improved back-EMF signal. In simulations, the position given value is 20*pi(rad), slip coefficient of the improved sliding mode observer is 50, a first-order low-pass filter's cutoff frequency is 150 HZ. The waveform of the back-EMF is shown in Fig. 4, the back-EMF pass through the first low-pass filter is not smooth which contains more harmonic components, so the back-EMF is not suitable for calculation of the rotor position. While Figure 5 shows the waveform of the back-EMF which has pass through the second filter, the back-EMF is relatively smooth and has less harmonic components which is suitable for calculation of the rotor position.

4.2. Simulation Analysis of the Position and Velocity Estimation

The estimated values of position and velocity are obtained by back-EMF pass through phase-locked loop. Compared to the conventional arctangent method, rotor position and velocity estimated values' accuracy will be higher. In addition, a first-order low-pass filter will result in the estimated value of rotor position have a large error. So the estimated value of rotor position should be compensated. As shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9, the accuracy of the speed and position estimated values which pass through the phase-locked loop are higher.

According to the compensation value of phase angle in Table 1, four segmented estimated value of position compensation can be obtained, which is shown in Table 2. ω is the motor speed.

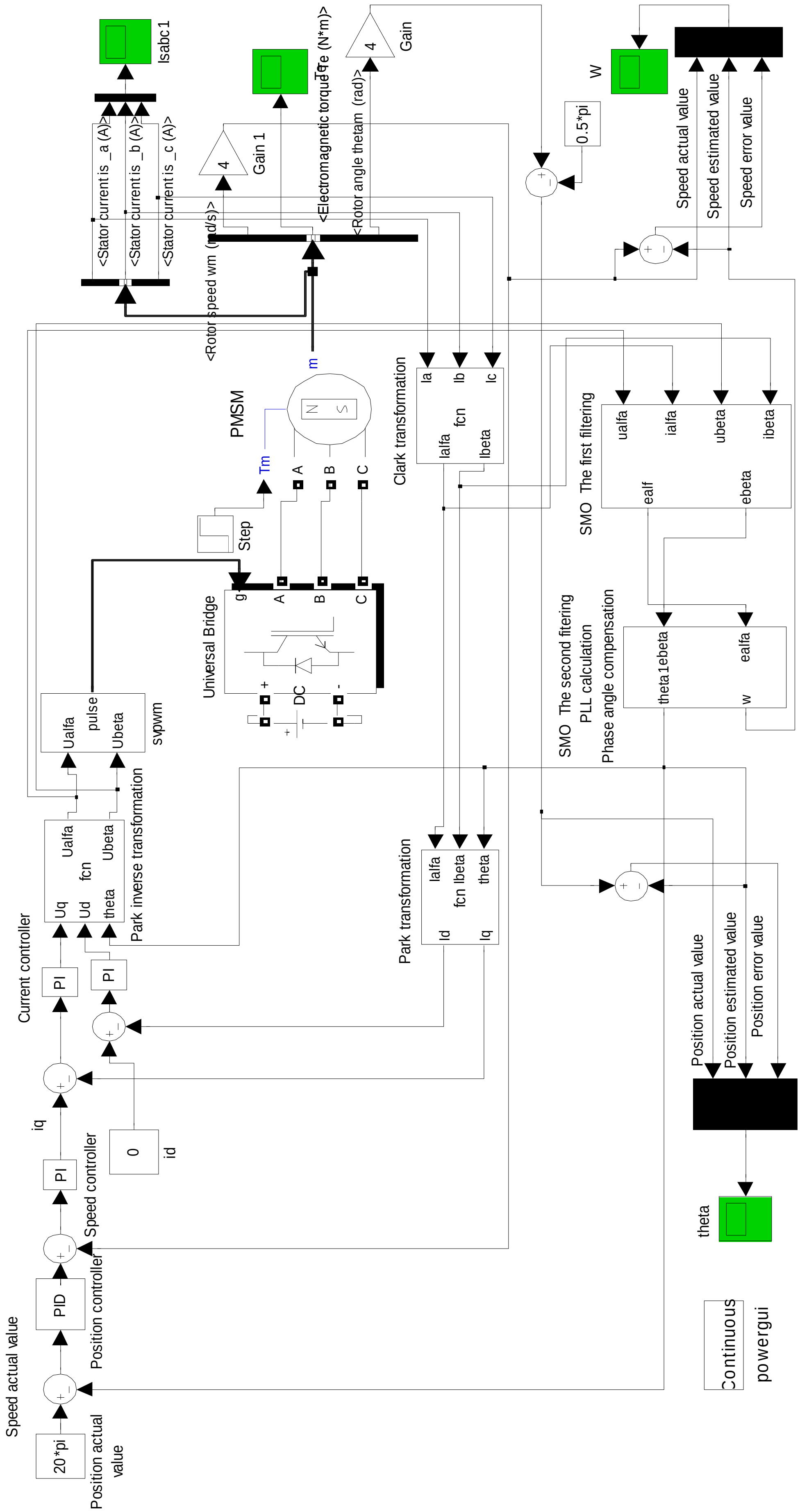

Fig. 3. The simulation model of PMSM control system based on the new sliding mode observer.

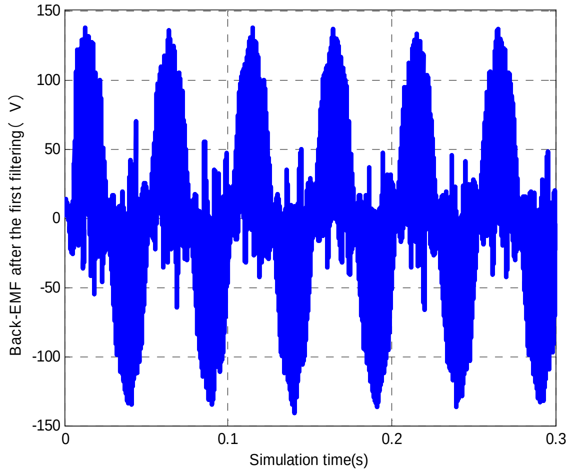

Fig. 4. The waveform of back-EMF after the first filtering.

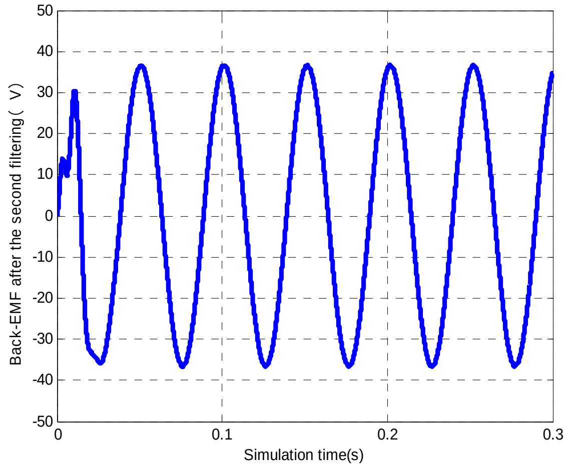

Fig. 5. The waveform of back-EMF after the second filtering.

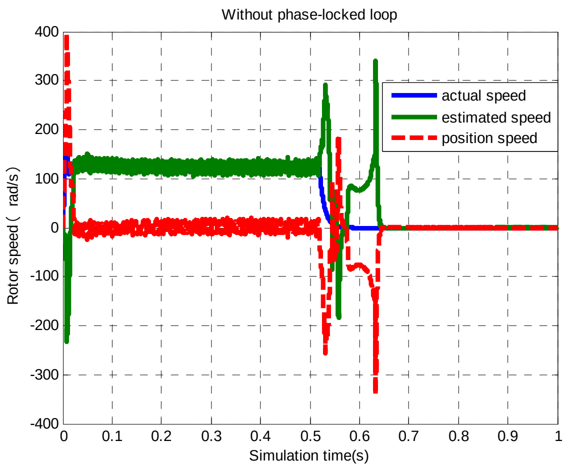

Fig. 6. The waveform of the estimated speed using the new sliding mode observer without phase-locked loop.

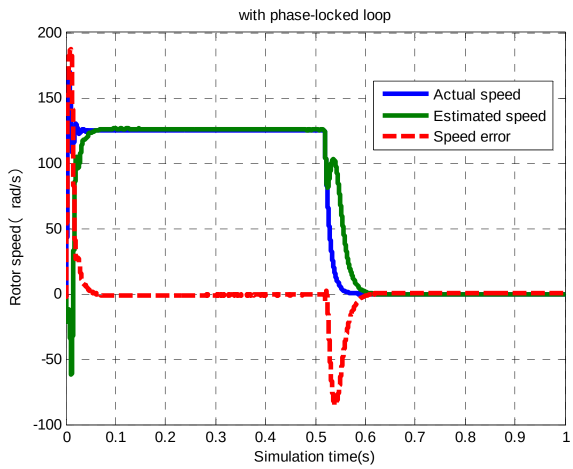

Fig. 7. The waveform of estimated speed using new sliding mode observer with phase-locked loop.

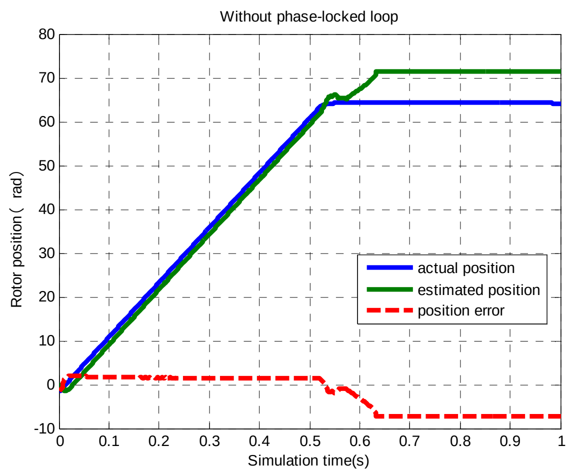

Fig. 8. The waveform of the estimated position using the new sliding mode observer without phase-locked loop.

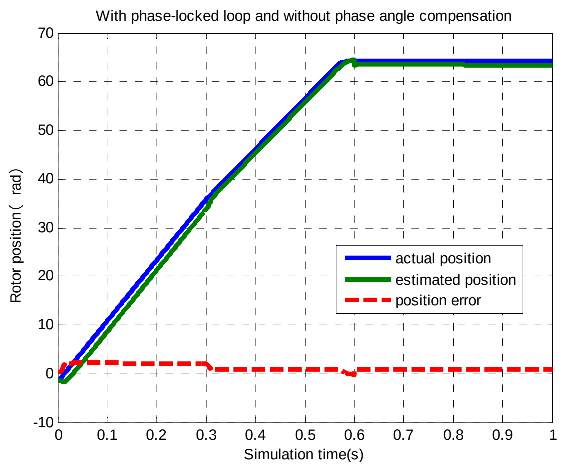

Fig. 9. The waveform of the estimated position using new sliding mode observer with phase-locked loop and without phase angle compensation.

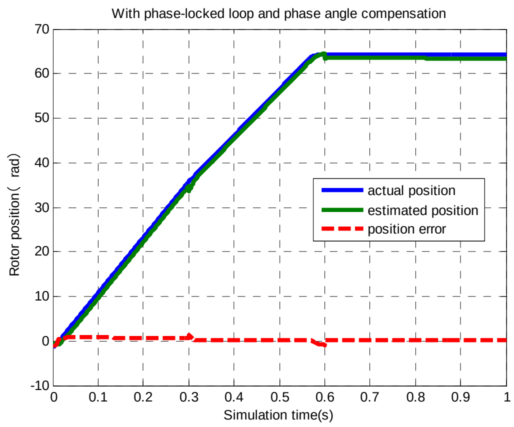

Fig. 10. The waveform of estimated position using new sliding mode observer with phase-locked loop and phase angle compensation.

4.3. Simulation Analysis of System Dynamic

In order to study the dynamic performance, the simulation results of the estimated values of position and speed are presented when the position given value has a sudden change. Fig. 11(a) and Fig. 11(b) are respectively the simulation results of the waveform of the estimated speed without phase-locked loop and with phase-locked loop. Fig. 11(c) is the simulation result of the waveform of the estimated position with phase-locked loop and without phase angle compensation, however, Fig. 11(d) is the simulation result of the waveform of the estimated position with phase-locked loop and phase angle compensation.

At the beginning, the given objective position is 20*pi(rad), while at 0.7 s, the given objective position changes to 40*pi(rad) suddenly. From the simulation results, we know that when the given position value changes suddenly, the sliding mode observer can still be quickly and accurately track the actual rotor speed and position with a very short period of adjustment time.

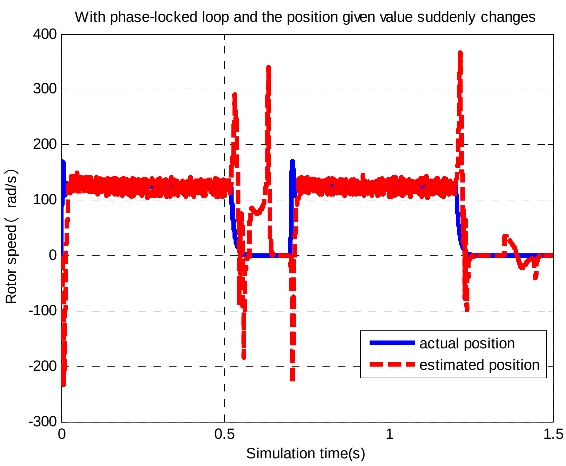

Fig. 11 (a). The waveform of the estimated speed using sliding mode observer without phase-locked loop.

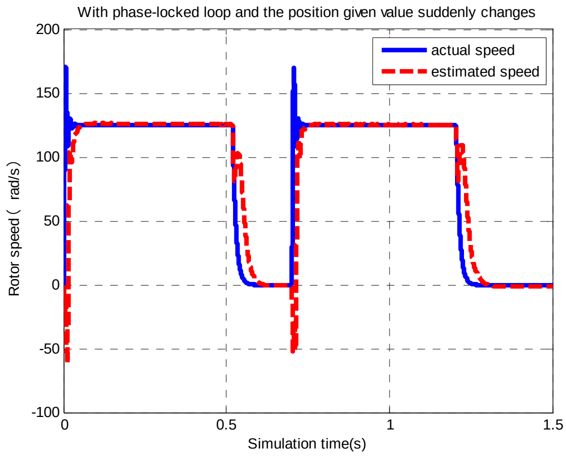

Fig. 11 (b). The waveform of the estimated speed using sliding mode observer with phase-locked loop.

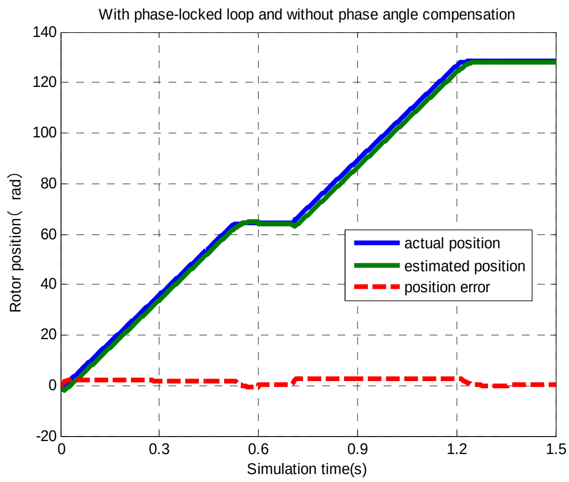

Fig. 11 (c). The waveform of the estimated position using new sliding mode observer without phase-locked loop and without phase angle compensation.

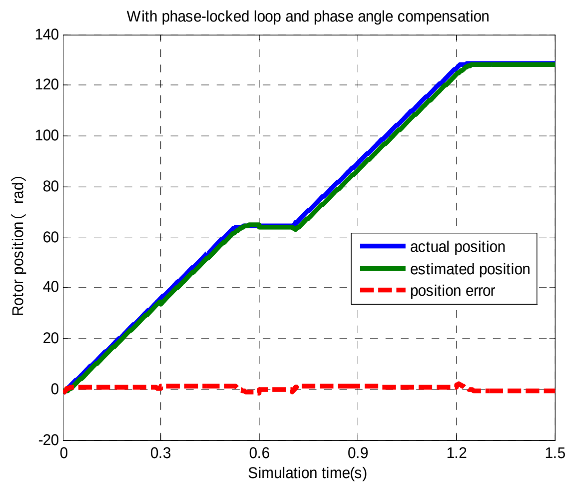

Fig. 11 (d). The waveform of the estimated position using new sliding mode observer without phase-locked loop and phase angle compensation.

4.4. Simulation Analysis of Load Disturbance

In order to study the speed and position tracking performance of new sliding mode observer and response velocity of the system when the load change suddenly, the corresponding simulations are given. Motor's given position value is 20*pi (rad), load rating is 1 (N·m) starting from 0 s, the load is mutated to 2.5 (N·m) at 0.3 s. The motor's stator current, the electromagnetic torque and speed estimation waveforms in the whole dynamic process are given in the Fig. 12, Fig. 13 and Fig. 14.

As can be seen from the simulation results, when the load changes suddenly, the motor stator current, the electromagnetic torque and speed will be adjusted to normal only after a small fluctuation. The results show that the new sliding mode observer can work properly when the load changes suddenly. The system has a good robustness to sudden load change, and an ability to respond quickly.

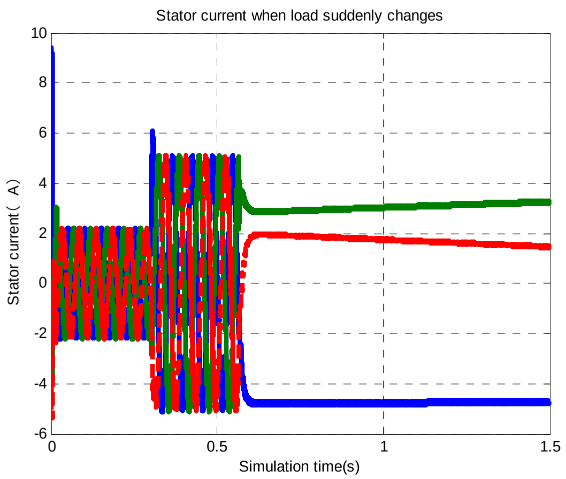

Fig. 12. The response of stator current when load changes suddenly.

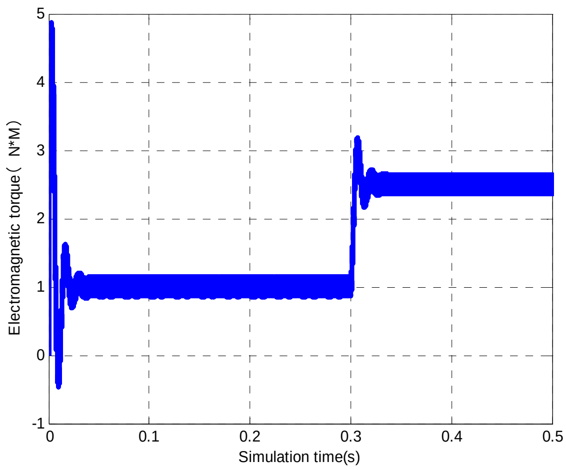

Fig. 13. The waveforms of electromagnetic torque.

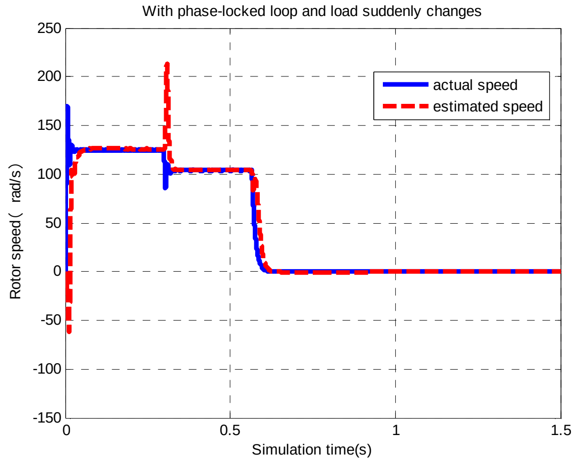

Fig. 14. The waveforms of actual speed and estimated speed when load changes suddenly.

5. Conclusions

Based on sliding mode variable structure control theory, a new type of sliding mode observer which is used to estimate rotor position and speed of PMSM is proposed in this paper. Sigmoid function is introduced to the new sliding mode observer which can reduce frequency chattering problem. Improved back-EMF is obtained by two filtering, a phase-locked loop structure is introduced to estimate the rotor position and speed, and a piecewise linear compensation method is adopted to compensate for the rotor position estimation. The simulation model of PMSM position sensorless servo control system is set up by Matlab/Simulink. The simulation results show that back-EMF harmonics are much less and more smooth after two filtering, the back-EMF is suitable to estimate position and speed. The accuracy of PMSM's rotor position and speed estimated value will be higher after through position phase-locked loop structure. And via phase compensation, the estimated value of rotor position can track the actual value well. When the load changes suddenly, the new sliding mode observer is able to track the rotor position and velocity accurately and quickly.

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