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Sensorless Control of Doubly Salient Permanent Magnet Motor Based on a New Sliding Mode Observer

Dongxiao Zhao

Shanghai Maritime University, Shanghai 201306, China.

Abstract

For doubly salient permanent magnet motor overload conditions in propeller, two-phase static coordinate system in the Sliding Mode Observer (SMO) traditional extension counter electromotive force amplitude size problem of the influence of the propeller load, under the two phase rotating coordinate system design a new sliding mode observer is used to realize the doubly salient permanent magnet motor speed and rotor position observation. In order to improve the robustness of the observer and reduce the error caused by jitter in the traditional SMO, a second order sliding mode observer based on Super-Twisting Algorithm (STA) is proposed. The model is built in Matlab, and the simulation results show that the designed control scheme not only satisfies the control precision, but also reduces the chattering of the system.

Keywords

DSPM Motor; Sensorless Control; Synchronous Rotation Coordinate System; Sliding Mode Observer; Super-twisting Control.

1. Introduction

Doubly Salient Machine (DSM), as a variable reluctance motor, has no permanent magnet magnetic steel and excitation windings on the rotor, and the rotor is made of silicon steel sheets. It produces electromagnetic torque in accordance with the principle of "minimum reluctance path", and has the advantages of simple and reliable, large torque/current ratio, and good speed regulation performance [1]. Motor according to different excitation mode can be divided into three types of permanent magnet, the electric field and hybrid excitation, the earliest three-phase 6/4 pole is the concept of the doubly salient permanent magnet motor by the United States in the 1990 s, a professor at the university of Wisconsin T.A.L ipo, the motor stator core design as close to the square, to broaden area to improve the air gap magnetic induction intensity of magnetization direction. Professor T.A.L ipo on ontology structure design of Doubly Salient Motor made great contributions to the design of Doubly Salient Permanent Magnet Motor (DSPM) on the rotor adopts convex tooth structure, Permanent Magnet embedded in the stator yoke, stator pole arc coefficient satisfies a certain function proportion, mechanical positioning is zero, when respectively within the range of Motor flux decline, rising into the negative and positive electric current when the Motor electromagnetic torque, the magnetic resistance torque in an electrical cycle average is zero,The starting torque of the motor is greatly improved [2]. At the same time, the team used the finite element method to study and analyze the internal nonlinear, high saturation and strong coupling magnetic field of the double-salient pole motor, and summarized the torque formula of DSPM and the corresponding system control model.

Professor Cheng Ming from Southeast University conducted an in-depth study on the double salient pole by using electric control technology and finite element calculation analysis method, and proposed the 8/6 permanent magnet structure double salient pole motor, and reached the conclusion that the power density of this type of motor is greater than that of the 6/4 structure motor [3]. The new 64/48 pole DSPM motor studied in this paper has a large output torque and good low-speed

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performance, and makes a great contribution to ocean current power generation. In particular, as a ship propulsion motor, it can provide strong power for ships, save cabin space and reduce costs.

At the same time, with the continuous expansion of the use range of motor and the harsh requirements of special working environment, the speed (position) sensorless starting technology of motor is the inevitable trend of further research on motor control technology in the future.Sensorless starting control technology is the basic idea is through the acquisition of three-phase motor runtime armature current and voltage of electricity information, after a certain calculate indirectly get the self inductance, mutual inductance of the motor, incremental self inductance, magnetic chain as well as the potential electromagnetic parameters, based on the electromagnetic parameters and the nonlinear relationship between the motor rotor position estimate the rotor position Angle, thus for motor operation control [4]. In the aspect of speed-less (position) sensing technology, many scholars at home and abroad have put forward many theories and methods, but most of them are aimed at brushless DC motor (BLDOC) or permanent magnet synchronous motor (PMSM).Although there are similarities in control methods, these methods are not fully applicable to DSPM motor due to its complex nonlinear characteristics [5].In recent years, with the development of modern control theory, the nonlinear control methods represented by sliding mode variable structure control (SMVC) have attracted more and more attention because of their unique advantages.

Sliding mode variable structure control is essentially a special kind of nonlinear control, to control the nonlinear performance of discontinuity, the control strategy differs with other control system of "structure" is not fixed, but can according to the current state of the system in dynamic process (such as deviation and its derivative, etc.) have the destination changing, forcing system according to the book "sliding mode" of the state trajectory [6]. Because the sliding mode can be designed and independent of object parameters and disturbances, the variable structure control has the advantages of fast response, insensitivity to parameter changes and disturbances, no need of on-line identification of the system, and simple physical implementation.The disadvantage of this method is that when the state trajectory reaches the sliding mode surface, it is difficult to slide strictly along the sliding mode facing the equilibrium point, but to cross back and forth on both sides of the sliding mode surface, resulting in vibration.Although the sliding mode variable structure has some shortcomings, its strong robustness and rapidity are unmatched by other controls.

The conventional observation method based on linear system cannot guarantee accurate observation results when the working point of nonlinear system changes. At the same time, the uncertainty of the parameters will affect the accuracy of the observer, and the rotor velocity and position cannot be accurately estimated.Many speed estimation methods are troubled by this problem, so some scholars proposed to use sliding mode observer to observe motor speed.This method is based on the error between the observed current and the actual current to reconstruct the back electromotive force of the motor and estimate the rotor velocity [7,8]. The key point of the sliding mode control speed observation algorithm is the selection of the sliding mode surface and the sliding mode gain, which not only ensures the convergence of the algorithm and the convergence speed, but also avoids the excessive pulsation caused by the excessive gain of the motor.When the electric motor is running for a long time, the resistance value of the stator resistance will increase due to heat. Literature [9] presents a method to estimate rotor speed and identify stator resistance simultaneously by using sliding mode observer, and the validity of this method is verified by experiments.

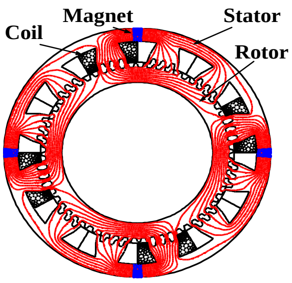

Fig. 1 DSPM structure

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Taking 64/48 pole DSPM motor as an example, a sliding mode observer based on synchronous rotating coordinate system is designed to estimate the rotor position and speed of the motor.In order to improve the robustness of the observer and reduce the error caused by jitter in traditional SMO, a second order sliding mode observer based on superhelix algorithm was proposed.

2. Mathematical model and closed -loop control of DSPM

2.1 Mathematical model of DSPM

As shown in Figure.1, DSPM is a three-phase variable reluctance device with permanent magnets. It adopts centralized stator windings, and the motor excitation is provided by non-rotating permanent magnets (PM) located on the stator. The rotor has 64 teeth, and the stator has 48 teeth evenly distributed on 12 slots.

The mathematical model of DSPM is composed of flux equation, voltage equation, torque equation and mechanical equation, etc. According to the results of finite element analysis, FFT (Fast Fourier Transform) is adopted and the Fourier term above the second order is ignored to obtain the self-inductance, mutual inductance and flux linkage equations respectively as follows:

$$\begin{cases} L_a = L_0 + L_1\, cos\theta_e \\ L_b = L_0 + L_1\, cos(\,\theta_e - \frac{2}{3}\pi) \\ L_C = L_0 + L_1\, cos(\,\theta_e - \frac{4}{3}\pi) \end{cases} \tag{1}$$

$$\begin{cases} M_{ab} = M_{ba} = M_0 + M_1\, cos(\,\theta_e - \frac{4}{3}\pi) \\ M_{ac} = M_{ca} = M_0 + M_1\, cos(\,\theta_e - \frac{2}{3}\pi) \\ M_{bc} = M_{cb} = M_0 + M_1\, cos\theta_e \end{cases} \tag{2}$$

$$\begin{cases} \psi_{ma} = \psi_0 + \psi_1\, cos\theta_e \\ \psi_{mb} = \psi_0 + \psi_1\, cos(\,\theta_e - \frac{2}{3}\pi) \\ \psi_{mc} = \psi_0 + \psi_1\, cos(\,\theta_e - \frac{4}{3}\pi) \end{cases} \tag{3}$$

The electromagnetic torque equation is:

$$\Gamma_{em} = \frac{p}{2}[i_s]^t[\frac{\partial L_s}{\partial L_s}][i_s] + p[i_s]^t[\frac{\partial \phi_m}{\partial \theta_e}] \tag{4}$$

The first term of the electromagnetic torque equation is the reluctance torque, and its magnitude is related to the geometric size of the rotor.The second term, the mixed torque, is caused by the interaction between the stator current and the permanent magnet flux. Through Clark and Park transformation of the mathematical model of the motor, the mathematical model of DSPM in the 0-D-Q coordinate system can be deduced as follows:

$$\begin{bmatrix} \psi_0 \\ \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_o & M_{od} & M_{oq} \\ M_{od} & L_d & M_{dq} \\ M_{oq} & M_{dq} & L_q \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} + \sqrt{3} \begin{bmatrix} \psi_0 \\ \frac{1}{\sqrt{2}}\psi_1 \\ 0 \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \end{bmatrix} = \begin{bmatrix} e_{mo} \\ e_{md} \\ e_{mq} \end{bmatrix} + [\alpha] \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} + [\beta]\frac{d}{dt} \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} e_{mo} \\ e_{md} \\ e_{md} \end{bmatrix} = \sqrt{\frac{3}{2}}\psi_1 \omega_e \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{7}$$

Where:

$$L_o = L_0 + 2M_0\,.\,L_d = L_0 - M_0 + \left(\frac{L_1}{2} + M_1\right) cos\,3\,\theta\,, L_q = L_0 - M_0 - \left(\frac{L_1}{2} + M_1\right) cos\,3\,\theta,$$

$$M_{od} = \frac{1}{\sqrt{2}}(L_1 - M_1)\,, M_{dq} = -\,(\frac{L_1}{2} + M_1)\, sin\,3\,\theta \tag{8}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202106_7(6).0046

$$[\alpha]=\begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s+2\omega M_{dq} & -\omega(\frac{3L_d}{2}-\frac{L_q}{2}) \\ 0 & \omega\ (\frac{3L_d}{2}-\frac{L_q}{2}) & R_s-2\omega M_{dq} \end{bmatrix},[\beta]=\begin{bmatrix} L_o & M_{od} & M_{oq} \\ M_{od} & L_d & M_{dq} \\ M_{oq} & M_{dq} & L_q \end{bmatrix} \quad (9\text{-}10)$$

The electromagnetic torque formula is as follows:

$$\Gamma_{em}=\Gamma_{PM}-\frac{\Gamma_L}{2}+\Gamma_M, \Gamma_{PM}=e_{mq}i_q=\sqrt{\frac{3}{2}}N_r\psi_1 i_q, \Gamma_L=N_r(L_d-L_q)i_d i_q$$

$$\Gamma_M=\frac{N_r}{2}M_{dq}(i_d^2-i_q^2)+N_r M_{dq} i_0 i_q \quad (11\text{-}14)$$

DSPM has different inductance and mutual inductance from traditional motor in dq coordinate system. For traditional motors, self-inductance and mutual inductance are constant, while for DSPM, they are 3 times the sinusoidal component of the electromotive force frequency. According to the electromagnetic torque equation, the electromagnetic torque of DSPM is not only related to PM and reluctance, but also to mutual inductance Mdq of dq axis.

2.2 Current controller based on SMC

Sliding mode control is a control strategy of variable structure control system, which is suitable for both linear system and nonlinear system. The fundamental difference between this control strategy and conventional control is the discontinuity of control, that is, a switching characteristic that makes the system structure change with time. This feature allows the system to move up and down in small, high frequency motions under certain conditions, which is known as "sliding mode." The sliding mode surface can be designed independent of the system parameters and disturbances, which makes the sliding mode variable structure have many essential advantages such as fast response, insensitivity to parameters and disturbances, simple physical implementation and so on.

Taking current as the state variable, the state equation of the system is as follows:

$$\dot{X}=-[\beta]^{-1}[\alpha]X+[\beta]^{-1}U-[\beta]^{-1}E \quad (15)$$

Where $X=[i_0 \quad i_d \quad i_q]^t$, $U=[u_0 \quad u_d \quad u_q]^t$, $E=\left[e_{mo} \quad e_{md} \quad e_{mq}\right]^t$

Select the sliding surface:

$$s=I^*-I \quad (16)$$

The expected current and the feedback current are respectively:

$$I^*, I_d, I^*=[i_0^* \quad i_d^* \quad i_q^*], I=[i_0 \quad i_d \quad i_q] \quad (17)$$

Select index approach rate:

$$\dot{s}=\dot{I}^*-\dot{I}=-ks-\varepsilon\, sgn(s) \quad (18)$$

Where k and ε are sliding mode control parameters, and the symbol function is defined as:

$$sng(s)=\begin{cases}+1, & s\geq 0\\ -1, & s\leq 0\end{cases} \quad (19)$$

Then, the mathematical model of current loop sliding mode control is as follows:

$$U=[\beta]\times(\dot{s}-\dot{I}^*)-[\alpha]\times I-E \quad (20)$$

Current loop SMC control structure block diagram is shown as follows:

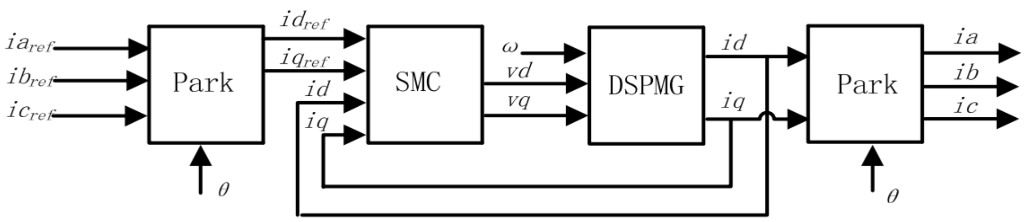

Fig. 2 SMC control structure block diagram

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3. Analysis and Research of Ship Propulsion DSPM Sliding Mode Observer in Rotating Coordinate System

3.1 Concept and design of a new sliding mode observer

Different from traditional motors, it can be seen from Equation (1-2) that self-induction and mutual induction of DSPM are functions of position Angle, so its current is also a function of position Angle. If the two-phase static coordinate system is selected to construct the sliding mode observer model, the extended back potential V is not only a sinusoidal waveform similar to the change law of permanent magnet synchronous motor, and the amplitude change is related to the current I and its differential value Pi and other parameters, but also a function of the rotor position angle θ_e. The block diagram of the sliding mode observer is shown in Figure.3.

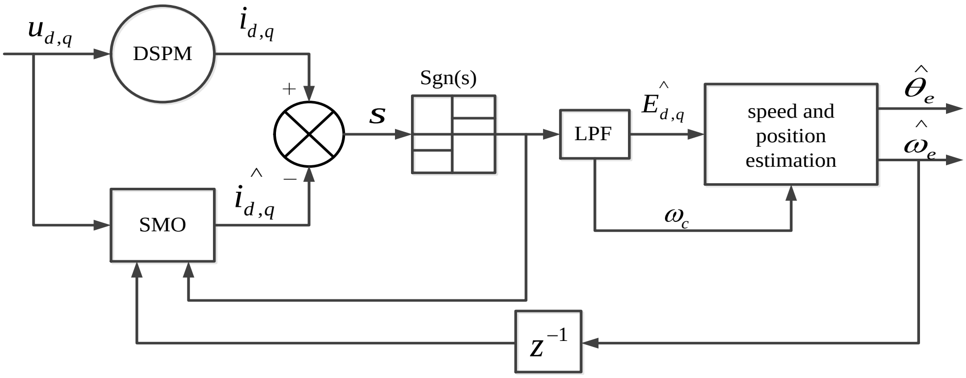

Fig. 3 Block diagram of SMO system based on DSPM

At the same time, the amplitude of the extended back electromotive force will be affected by the change of the motor load. Especially under heavy load conditions such as ship propeller, when the load of the propulsion motor changes suddenly, the motor current will change greatly, and the differential value of the current will become larger, resulting in a larger error value of the extended back electromotive force. The selection of switching gain parameters in the observer is relatively complex, and the improper selection will not satisfy the Lyapunov stability condition, thus making the dynamic equation of current error not asymptotically stable, and ultimately affecting the accuracy of the Angle estimation of the propulsion motor [10].

According to Equation (6-7), the current state equation of DSPM in the D-Q rotation coordinate system can be obtained as follows:

$$\begin{cases} \dfrac{di_d}{dt} = \dfrac{u_d-(R_s+2\omega_e M_{dq})i_d+\omega_e(1.5L_d-0.5L_q)i_q+M_{dq}\frac{di_q}{dt}}{L_d} \\ \dfrac{di_q}{dt} = \dfrac{u_q-(R_s+2\omega_e M_{dq})i_q+\omega_e(1.5L_d-0.5L_q)i_d+M_{dq}\frac{di_d}{dt}-\sqrt{\frac{3}{2}}\omega_e\phi_1}{L_q} \end{cases} \tag{21}$$

Where, u_d, u_q are the dq axis voltage component of DSPM in the D-Q rotation coordinate system, ω_e, ϕ_1 are the electromechanical angular velocity and permanent magnetic flux, respectively. dq axis back potential $V_d = 0, V_q = \sqrt{\frac{3}{2}}\phi_1\omega_e$. According to Equation (21), the state equation of sliding mode observer with dq axis current as state variable in two-phase rotation coordinates can be designed:

$$\begin{cases} \dfrac{d\hat{i}_d}{dt} = \dfrac{u_d-(R_s+2\hat{\omega}_e M_{dq})\hat{i}_d+\hat{\omega}_e(1.5L_d-0.5L_q)\hat{i}_q+M_{dq}\frac{d\hat{i}_q}{dt}-K\,sgn[\hat{i}_d-i_d]}{L_d} \\ \dfrac{d\hat{i}_q}{dt} = \dfrac{u_q-(R_s+2\hat{\omega}_e M_{dq})\hat{i}_q+\hat{\omega}_e(1.5L_q-0.5L_d)\hat{i}_d+M_{dq}\frac{d\hat{i}_d}{dt}-K\,sgn[\hat{i}_q-i_q]}{L_q} \end{cases} \tag{22}$$

ISSN: 2414-1895 DOI: 10.6919/ICJE.202106_7(6).0046

Where $\hat{i}_d, \hat{i}_q, \hat{\omega}_e$ are the estimated values of D-axis current, Q-axis current and electric angular velocity, respectively. k is the sliding mode gain, sgn is the switching function, the sliding surface is $s = \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} = \begin{bmatrix} \hat{i}_d - i_d \\ \hat{i}_q - i_q \end{bmatrix}$.

3.2 Proof of SMO stability

By making the difference between Equations (21) and (22), the matrix state equation of system current error can be obtained as follows:

$$\begin{pmatrix} \dot{\tilde{i}}_d \\ \dot{\tilde{i}}_q \end{pmatrix} = \begin{bmatrix} -\frac{R_s + 2\widetilde{\omega}_e M_{dq}}{L_d} & \frac{1.5L_d - 0.5L_q}{L_d} \\ \frac{1.5L_d - 0.5L_q}{L_q} & -\frac{R_s + 2\widetilde{\omega}_e M_{dq}}{L_q} \end{bmatrix} \begin{pmatrix} \tilde{i}_d \\ \tilde{i}_q \end{pmatrix} + M_{dq} \begin{pmatrix} \dot{\tilde{i}}_q \\ \dot{\tilde{i}}_d \end{pmatrix} + \begin{bmatrix} \frac{V_d - k\, sgn(\hat{i}_d - i_d)}{L_d} \\ \frac{V_q - k\, sgn(\hat{i}_q - i_q)}{L_q} \end{bmatrix} \tag{23}$$

Where $\dot{i} = \frac{di}{dt}, \tilde{i}_d = \hat{i}_d - i_d, \tilde{i}_q = \hat{i}_q - i_q, \widetilde{\omega}_e = \hat{\omega}_e - \omega_e$ are current error and speed estimation error respectively. According to sliding mode surface function $s = [\tilde{i}_d \quad \tilde{i}_q]^T = 0$ and Lyapunov stability theorem [11], when the selection of sliding mode gain k meets condition $S^T \cdot \dot{S} \leq 0$, the error equation enters the steady state and the system enters the sliding mode. The equivalent control can be defined as:

$$E_{eq} = \begin{pmatrix} \hat{V}_d \\ \hat{V}_q \end{pmatrix} = \begin{pmatrix} [k\, sgn(\hat{i}_d - i_d)]_{eq} \\ [k\, sgn(\hat{i}_q - i_q)]_{eq} \end{pmatrix} = \begin{pmatrix} 0 \\ \sqrt{\frac{3}{2}}\hat{\omega}_e \phi_1 \end{pmatrix} \tag{24}$$

It can be seen from Equation (2.4) that the estimated EMF equivalent control $\hat{V}_q = \sqrt{\frac{3}{2}}\hat{\omega}_e \phi_1$ of the Q axis contains the rotor speed information, so the estimated rotor speed can be obtained as:

$$\hat{\omega}_e = \frac{\hat{V}_q}{\sqrt{\frac{3}{2}}\omega_e \phi_1} \tag{25}$$

3.3 SMO based on STA control

Although the sliding mode observer has strong robustness and good observation effect on the nonlinear system, due to the existence of its switching function, the observed quantities switch at high frequency on the sliding mode surface and below, thus causing chattering phenomenon [12]. The second order sliding mode control can reduce chattering to some extent, and the super helical control algorithm is better.

The STA control generally contains two parts: one is the discontinuous function of the sliding mode variable; The second is a continuous function of the partial derivative with respect to time.The super helix control algorithm can be written as follows:

$$\begin{cases} u = \beta |s|^{\frac{1}{2}} sgn(s) + u_1 \\ \frac{du_1}{dt} = \alpha K_b\, sgn(s) \end{cases} \tag{26}$$

Where α, β are the control gain.

The sufficient condition for the stability of the control system is:

$$\begin{cases} \beta \geq \frac{A_M}{B_M} \\ \alpha \geq \frac{4A_M}{B_m} \cdot \frac{B_M(\beta + A_M)}{B_M(\beta - A_M)} \end{cases} \tag{27}$$

Where $B_m \leq B \leq B_M, A \leq A_M$, A_M, B_M, B_m are both positive gain coefficients, and A, B satisfies:

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$$\frac{d^2y}{dt^2}=A(x,t)+B(x,t)\frac{du}{dt} \tag{28}$$

According to Equation (26)-(28), the state equation of the sliding mode observer based on the superhelix control rate can be written:

$$\begin{cases}\frac{d\hat{i}_d}{dt}=\frac{u_d-(R_s+2\omega_e M_{dq})\hat{i}_d+\omega_e(1.5L_d-0.5L_q)\hat{i}_q+M_{dq}\frac{d\hat{i}_q}{dt}-\left[\int\alpha\, sgn(s_d)dt+\beta|s|^{\frac{1}{2}}sgn(s_d)\right]}{L_d}\\ \frac{d\hat{i}_q}{dt}=\frac{u_q-(R_s+2\omega_e M_{dq})\hat{i}_q+\omega_e(1.5L_d-0.5L_q)\hat{i}_d+M_{dq}\frac{d\hat{i}_d}{dt}-\left[\int\alpha\, sgn(s_q)dt+\beta|s|^{\frac{1}{2}}sgn(s_q)\right]}{L_q}\end{cases} \tag{29}$$

4. Simulation of DSPM speed regulation system based on new sliding mode observer

4.1 Structure of control system

The DSPM double closed-loop speed regulation system studied in this paper adopts proper amount control, PI control for speed loop and SMC sliding mode control for current loop. At the same time, a new sliding mode observer is constructed to estimate the actual speed of the motor in the rotating coordinate system.The control structure block diagram of the system is shown in Figure. 4.

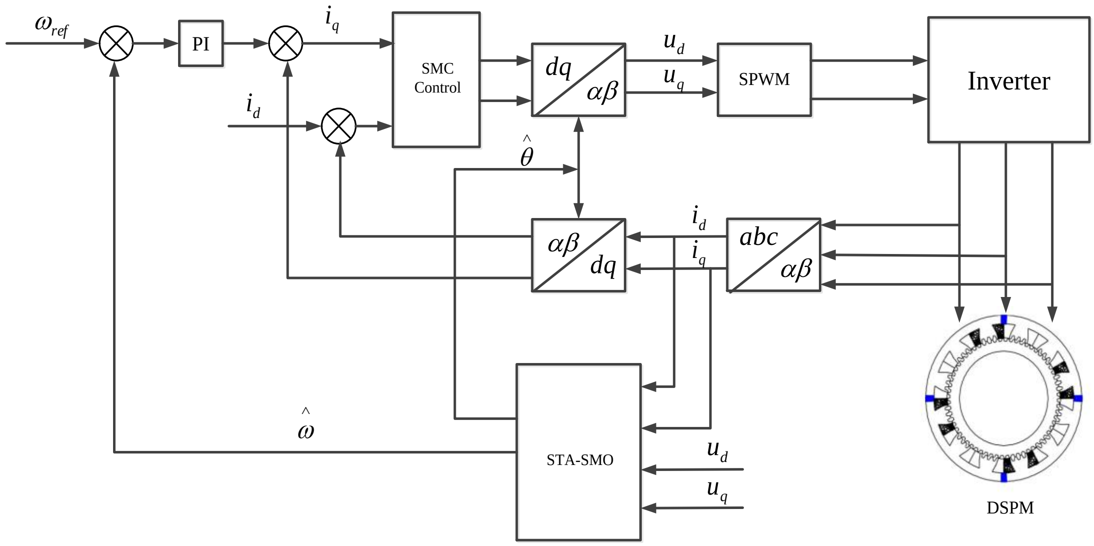

Fig. 4 Block diagram of DSPM control system based on STA-SMO

4.2 Simulation parameters and result analysis

In order to verify the effectiveness of the control strategy used in this paper, the MATLAB/ Simulink toolbox is used to establish a 64/48 pole DSPM vector control system according to the mathematical model of the motor, and the motor speed and torque are simulated. The main parameters of simulation are shown in Table 1.

Table 1. Main parameters of DSPM motor simulation

Parameter	Symbol	Value
Flux	ψ_0/ψ_1	1.455/0.4805 Wb
Self-inductance	L_0/L_1	25.5/2.5 mH
Mutual-inductance	M_0/M_1	-12.4/2.5 mH
Stator resistance	R_s	88.37 mΩ
Rotor tooth number	N_s	64

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Fig.5 and Fig.6 respectively present the actual and estimated values of rotor position angle and the actual and estimated simulation results of rotational speed. Fig.6 contains the comparison results of the traditional SMO control and the STA-SMO control. The reference speed of DSPM is 60r/min, the simulation time is 5s, and the torque of 0.5s sudden load is 2000N.

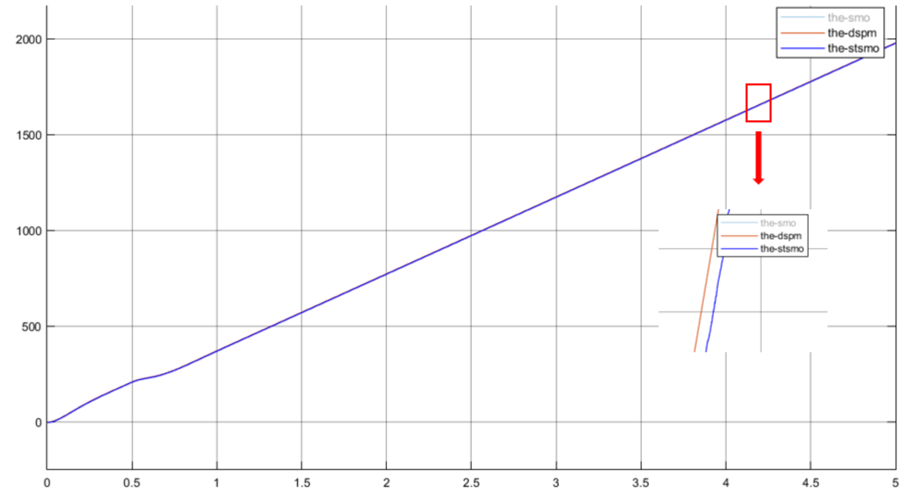

Fig. 5 Actual position and estimated position of rotor position angle

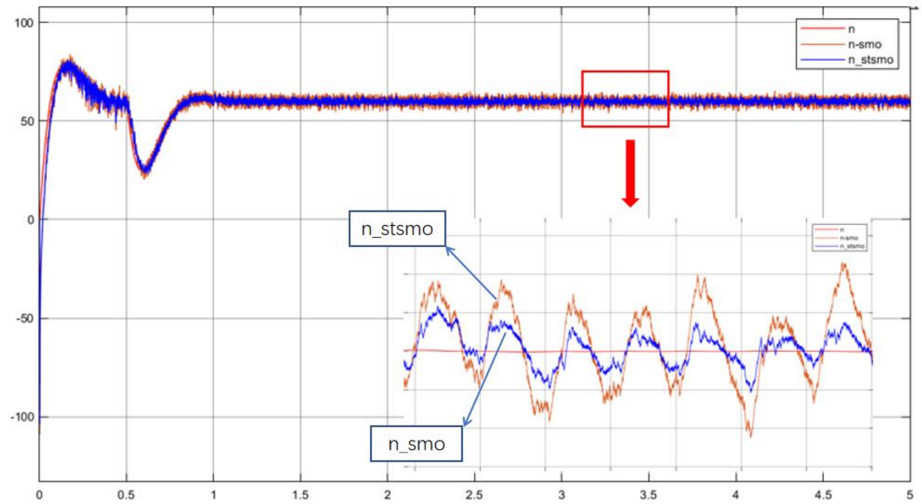

Fig. 6 Actual and estimated values of motor speed

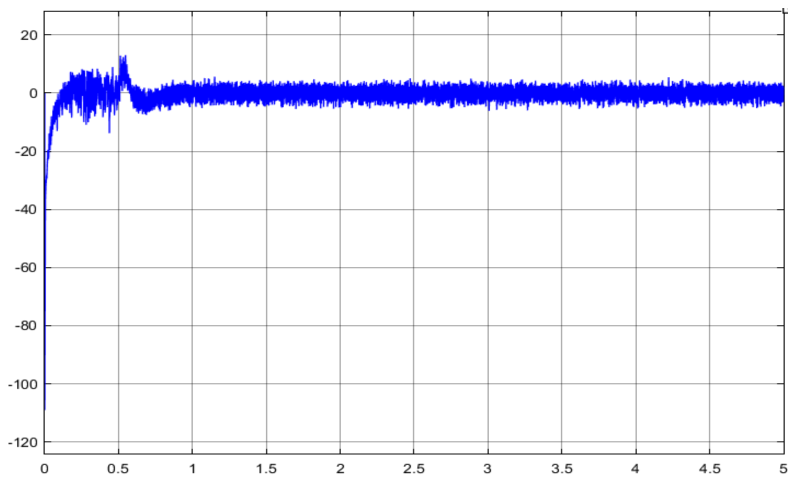

Fig. 7 Speed error

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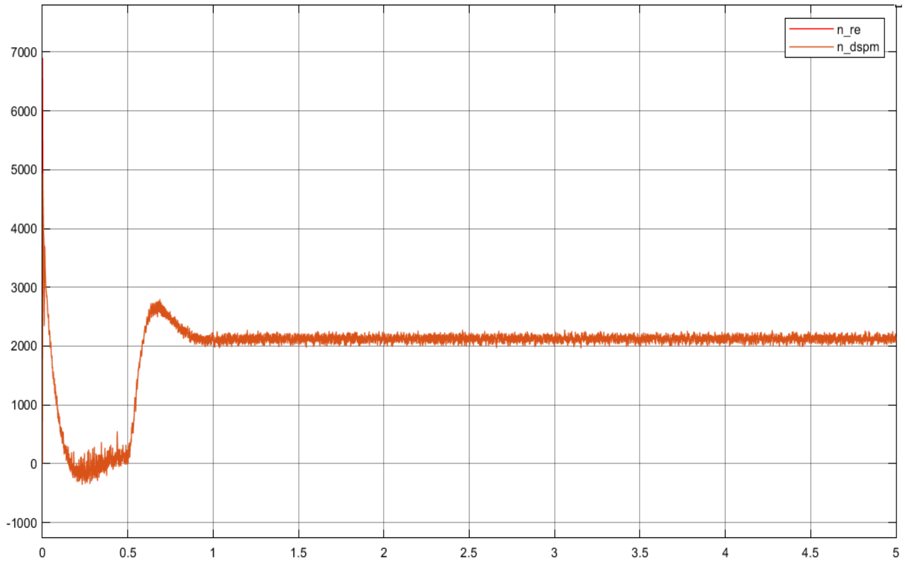

Fig. 8 Electromagnetic torque

As can be seen from fig. 5 to fig.7, after the sudden loading of 2000N in 0.5s, the errors of the actual and estimated values of the position angle and speed of the motor rotor are stable around 0. Compared with the traditional SMO, the error caused by chattering of the STA-SMO is smaller, and the estimated value is closer to the rated speed of DSPM. And the torque ripple is small, the system robustness is stronger, for the strong nonlinear DSPM motor has a better observation effect.

5. Conclusions

DSPM motor has strong nonlinear and large torque ripple characteristics.Based on the equation of state of dq axis current as state variable, a new type of sliding mode observer is designed in the two-phase rotating coordinate system to realize the sensorless control of Marine propulsion motor. In this paper, a super helical sliding mode observer based on phase-locked loop technology is used to estimate the speed and rotor position of DSPM. The chattering error in the sliding mode control is improved by using the continuity of serial high order sliding mode in the STA. The experimental results show that the dynamic response of the system is fast, the overshoot time caused by sudden loading of the original system variable is greatly reduced, the sliding mode chattering is greatly weakened, and the system has strong adaptability to external disturbance.

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