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Robust High Order Sliding Mode Control of Permanent Magnet Synchronous Motors

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1. Introduction

Nonlinear system control has been widely concern of the research. At present, the nonlinear system decoupling control and static feedback linearization that based on the theory of differential geometry brought the research getting rid of limitation for local linearization and small scale motion. However, differential geometry control must depend on precise mathematical model. As a matter of fact, the control system usually is with parameters uncertainties and output disturbance. Considering sliding mode variable structure control with good robust, which was not sensitive for parameters perturbation and external disturbance, the combination idea of nonlinear system and sliding mode controls was obtained by reference to the large number of documents. Thus, it not only can improve system robustness but solve the difficulties problem of nonlinear sliding mode surface structure. As known to all, traditional sliding mode had a defect that is chattering phenomenon. A plenty of research papers focus on elimination/avoidance chattering by using different methods. By comparing, the chapter is concerned with novel design method for high order sliding mode control, which can eliminate chattering fundamentally. Especially, the approach and realization of nonlinear system high order sliding mode control is presented.

High order sliding mode technique is the latest study. This chapter from the theory analysis to the simulation and experiment deeply study high order sliding mode control principle and its applications. The arbitrary order sliding mode controller is employed, whose relative degree can equal any values instead of one.

In addition, the control systems design is very often to differentiate the variables. Through the derivation of sliding mode, the expression of sliding mode differential value is obtained. At the same time, the differentiator for arbitrary sliding mode is given to avoiding complex numerical calculation. It not only remains the precision of variables differential value, but also obtains the robustness.

Due to its inherent advantages, the permanent magnet synchronous motor (PMSM) deserves attention and is the most used drive in machine tool servos and modern speed control applications. For improving performance, this chapter will apply nonlinear high order sliding mode research achievement to MIMO permanent magnet synchronous motor. It changes the coupling nonlinear PMSM to single input single output (SISO) linear

subsystem control problem instead of near equilibrium point linearization. Thereby, the problem of nonlinear and coupling for PMSM has been solved. In addition, Uncertainty nonlinear robust control system has been well-received study of attention. Because the robust control theory is essentially at the expense of certain performance. This kind of robust control strategy often limits bandwidth of closed loop, so that system tracking performance and robustness will be decreased. So, sliding mode control is an effective approach for improving system robust. This chapter first proposed a robust high order sliding mode controller for PMSM. The system has good position servo tracking precision in spite of parameters uncertainties and external torque disturbance.

On this basis, according to the principle of high order sliding mode, as well as differentiator, the state variables of PMSM are identified online firstly and successfully. The results of simulation indicate observe value has high precision when sliding mode variable and its differentials are convergent into zero. The same theory is used in external unknown torque disturbance estimation online for PMSM. As if, load torque will no longer be unknown disturbance. System performance can be improved greatly. It establishes theoretical foundation for the future applications.

At the end of chapter, using advanced half-physical platform controller dSPACE to drive a PMSM, hardware experiment implement is structured completely. The experiment results illustrate that PMSM adopting precious feedback linearization decoupling and high order sliding mode controller can realize system servo tracking control with good dynamic and steady character.

2. Robust high order sliding mode control

As known to all, the sliding mode control with the strong robustness for the internal parameters and external disturbances. In addition, the appropriate sliding surface can be selected to reduce order for control system. However, due to the chattering phenomena of sliding mode control, the high frequency oscillation of control system brings challenge for the application of sliding mode control. On the other hand, the choice of sliding surface strictly requires system relative degree to equal to 1, which limits the choice of sliding surface.

In order to solve the above problems, this chapter focuses on a new type of sliding mode control, that is, higher order sliding mode control. The technology not only retains advantage of strong robustness in the traditional sliding mode control, but also enables discontinuous items transmit into the first order or higher order sliding mode derivative to eliminate the chattering. Besides, the design of the controller no longer must require relative degree to be 1. Therefore, it is greatly simplified to design parameters of sliding mode surface.

Emelyanov and others first time propose the concept of high order differentiation of sliding mode variable, but also provide a second order sliding mode twisting algorithm, and prove its convergence (Emelyanov et al., 1996). Another algorithm is super twisting, which can completely eliminate chattering (Emelyanov et al., 1990), although the relative degree of sliding mode variable is required to equal to 1. In the second order sliding mode control, Levant proved sliding mode accuracy is proportional to $o(\tau^2)$ the square of the switching delay time. It has also become one of the merits of high order sliding mode control (Levant, 1993). Since then, the high order sliding mode controller has been developed and applied rapidly. For example, Bartolini and others propose a second order sliding mode control

applied the sub-optimal algorithm (Bartolini et al., 1997, 1999). After the concept of high order sliding mode control was applied to bound operator in (Bartolini et al., 2000). Levant used high order sliding mode control in aircraft pitch control (Levant, 2000) as well as the exact robust differentiator (Levant, 1998). About the summary of high order sliding mode control is also described in the literature (Fridman & Levant, 2002).

2.1 Review of high order sliding mode control

In recent years, because arbitrary order sliding mode control technique not only retains the traditional sliding mode control simple structure with strong robustness, but also eliminates the chattering phenomenon in the traditional sliding mode, at the same time, gets rid of the constraints of system relative degree. Therefore theoretical research and engineering applications has caused widespread concern and has been constant development.
Without losing generality, considering a state equation of single input nonlinear system as

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= s(x,t) \end{aligned} \tag{1}$$

Where, $x \in R^n$ is system state variable, t is time, y is output, u is control input. Here, $f(x)$, $g(x)$ and $s(x)$ are smooth functions. The control objective is making output function $s \equiv 0$.
Differentiate the output variables continuously, we can get every order derivative of s. According to the conception of system relative degree, there are two conditions.

i. Relative degree $r = 1$, if and only if $\partial \dot{s} / \partial u \neq 0$

ii. Relative degree $r \geq 2$, if $\partial s^{(i)} / \partial u = 0 \ \ (i = 1,2,\cdots r-1)$, and $\partial s^{(r)} / \partial u \neq 0$

In arbitrary order sliding mode control, its core idea is the discrete function acts on a higher order sliding mode surface, making

$$s(x,t) = \dot{s}(x,t) = \ddot{s}(x,t) = \cdots s^{(r-1)}(x,t) = 0 \tag{2}$$

Suppose the relative degree of system (1) equals to r, generally speaking, when the control input u first time appears in r-order derivative of s, that is $ds^{(r)} / du \neq 0$, then we take r-order derivative of s for the output of system (1), $s, \dot{s}, \ddot{s}, \cdots s^{(r-1)}$ can be obtained. They are continuous function for all the x and t. However, corresponding discrete control law u acts on $s^{(r)}$. Selecting a new local coordinate, then

$$y = (y_1, y_2, \cdots y_r) = (s, \dot{s}, \cdots s^{(r-1)}) \tag{3}$$

So, the following expression can be obtained

$$s^{(r)} = a(y,t) + b(y,t)u, \quad b(y,t) \neq 0 \tag{4}$$

Therefore, high order sliding mode control is transformed to stability of r order dynamic system (2), (4). Through the Lie derivative calculation, it is very easy to verify that

$$\begin{aligned} b &= L_g L_f^{r-1} s = ds^{(r)} / du \\ a &= L_f^r s \end{aligned} \tag{5}$$

Suppose $\eta = (y_{r+1}, y_{r+2}, \cdots y_n)$, then

$$\eta = \xi(t, s, \dot{s}, \cdots, s^{(r-1)}, \eta) + \chi(t, s, \dot{s}, \cdots, s^{(r-1)}, \eta)u \tag{6}$$

Now, equation (3), (4) and (6) are transformed to Isidori-Brunowsky canonical form. The sliding mode equivalent control is $u_{eq} = -a(y,t)/b(y,t)$ (Utkin,1992). At present, the aim of control is to design a discrete feedback control $u = U(x,t)$, so that new system converge into origin on the r order sliding mode surface within limited time. Therefore, in equation (4), both $a(y,t)$ and $b(y,t)$ are bounded function. There are positive constants K_m, K_M and C so that

$$\begin{aligned} &0 < K_m \le b(y,t) \le K_M \\ &|\, a(y,t) \,| \le C \end{aligned} \tag{7}$$

Theorem 1: (Levant, 1998, 2003) Suppose the relative degree of nonlinear system (1) to output function $s(x,t)$ is r, and satisfying the condition (7), the arbitrary order sliding mode controller has following expression

$$u = -\alpha \ \mathrm{sgn}(\psi_{r-1,r}(s, \dot{s}, \cdots, s^{(r-1)})) \tag{8}$$

Where,

$$\begin{aligned} \psi_{0,r} &= s \\ \psi_{1,r} &= \dot{s} + \beta_1 N_{1,r} \,\mathrm{sgn}(s) \\ \psi_{i,r} &= s^{(r)} + \beta_i N_{i,r} \,\mathrm{sgn}(\psi_{i-1,r}), \qquad i = 1, \cdots, r-1 \\ N_{1,r} &= \ |\, s \,|^{(r-1)/r} \\ N_{i,r} &= (|\, s \,|^{p/r} + |\, \dot{s} \,|^{p/(r-1)} \cdots + |\, s^{(i-1)} \,|^{p/(r-i+1)})^{(r-i)/p} \qquad i = 1, \cdots, r-1 \\ N_{r-1,r} &= (|\, s \,|^{p/r} + |\, \dot{s} \,|^{p/(r-1)} \cdots + |\, s^{(r-2)} \,|^{p/2})^{1/p} \end{aligned} \tag{9}$$

Properly choose positive parameters $\beta_1, \beta_2, \cdots \beta_{r-1}$, the system converge into origin on the r order sliding mode surface within limited time. Finally, when $s \equiv 0$, it achieves control object. The choice of positive parameters $\beta_1, \beta_2, \cdots \beta_{r-1}$ is not unique. Here, $r \le 4$ order sliding mode controller is given, which is also tested.

$$\begin{aligned} &1.\ u = -\alpha \ \mathrm{sgn}(s) \\ &2.\ u = -\alpha \ \mathrm{sgn}(\dot{s} + |\, s \,|^{1/2} \,\mathrm{sgn}(s)) \\ &3.\ u = -\alpha \ \mathrm{sgn}(\ddot{s} + 2(|\, \dot{s} \,|^3 + |\, s \,|^2)^{1/6} \,\mathrm{sgn}(\dot{s} + |\, s \,|^{2/3} \,\mathrm{sgn}(s))) \\ &4.\ u = -\alpha \ \mathrm{sgn}\{\dddot{s} + 3[(\ddot{s})^6 + (\dot{s})^4 + |\, s \,|^3]^{1/12} \,\mathrm{sgn}[\ddot{s} + ((\dot{s})^4 \\ &\quad + |\, s \,|^3)^{1/6} \,\mathrm{sgn}(\dot{s} + 0.5 |\, s \,|^{3/4} \,\mathrm{sgn}(s))]\} \\ &\quad \vdots \end{aligned} \tag{10}$$

From the above equation (10) we can also see that, when $r = 1$, the controller is traditional relay sliding mode control; when $r = 2$, in fact, the controller is super twisting algorithm of second order sliding mode.

To get the differentiation of a given signal is always essential in automatic control systems. We often need derivative a variable or function. So there are a lot of numerical algorithms for this issue. The same situation also appears in the design of high order sliding mode controller (10) that needs to calculate the derivative values of sliding mode variable. In order to be able to accurately calculate, at the same time simplifying the algorithm, this chapter directly uses own advantages of high order sliding mode control due to high accuracy and robustness. We can design a high order sliding mode differentiator used to calculate the numerical derivative of the variables.

Presentation above in the previous has been explained in detail the principles of high order sliding mode control and sliding mode controller design method. This part focuses on how to take use of high order sliding mode technique to solve the differentiation of a given signal or variable function. And their simulation results are verified

Suppose given signal is $f(t)$, now set a dynamic system as

$$\dot{x} = u \tag{11}$$

The control object is to make the variable x follow given signal $f(t)$, that is

$$x = f(t) \tag{12}$$

Therefore, sliding mode surface is selected as

$$s = x - f(t) \tag{13}$$

At this moment, according to the principle of sliding mode control, a proper controller is designed. When the system enter into sliding mode, $s = x - f(t) = 0$. Derivative of sliding mode surface (13),

$$\dot{s} = \dot{x} - \dot{f}(t) = u - \dot{f}(t) \tag{14}$$

Because control input u first time appears in the derivative of sliding mode surface s, the relative degree of system is $r = 1$. It satisfies the requirement about relative degree of second order sliding mode. So the super twisting algorithm (Fridman & Levant, 2002) is adopted. Thus,

$$\begin{aligned} u &= -\lambda \,|\, x - f(t) \,|^{1/2} \,\mathrm{sgn}(x - f(t)) + u_1 \\ \dot{u}_1 &= -\alpha \,\mathrm{sgn}(x - f(t)) \end{aligned} \tag{15}$$

Where, $\lambda > 0$, $\alpha > 0$ are positive constant. Definite a function as $\Theta(\alpha, \lambda, C) = |\, \Psi(t) \,|$, C is Lipschitz constant about derivative of $f(x)$. $(\Sigma(t), \Psi(t))$ is the solution of equation of (16), the initial value are $\Sigma(0) = 0$, $\Psi(0) = 1$

$$\begin{aligned} \dot{\Sigma} &= -|\,\Sigma\,|^{1/2} + \Psi \\ \dot{\Psi} &= \begin{cases} -\dfrac{1}{\lambda^2}(\alpha - C), & -|\,\Sigma\,|^{1/2} + \Psi > 0 \\ -\dfrac{1}{\lambda^2}(\alpha + C), & -|\,\Sigma\,|^{1/2} + \Psi \le 0 \end{cases} \end{aligned} \tag{16}$$

Theorem 2: (Levant, 1998) Let $\alpha > C > 0$, $\lambda > 0$, function $\Theta(\alpha,\lambda,C) < 1$. Then, provided $f(t)$ has a derivative with Lipschitz's constant C, the equality $u = \dot{f}(t)$ is fulfilled identically after finite time transient process. And the smaller value of Θ, faster convergence; If $\Theta(\alpha,\lambda,C) > 1$, control input u will not converge into $\dot{f}(t)$. Observer parameters should meet the following sufficient condition for convergence of the second-order sliding mode control,

$$\begin{aligned} &\alpha > C \\ &\lambda^2 \geq 4C\frac{\alpha + C}{\alpha - C} \end{aligned} \tag{17}$$

According to the principle of second order sliding mode, after a finite time, the system will converge into the origin, that is,

$$s(x,t) = \dot{s}(x,t) = 0 \tag{18}$$

Then,

$$u = \dot{f}(t) \tag{19}$$

Now, observer input u is the estimation of derivative of given signal $f(t)$. Using a sliding mode controller achieve differentiation of variable function.

Let input signal be presented in the form $f(t) = f_0(t) + n(t)$, where $f_0(t)$ is a differentiable base signal, $f_0(t)$ has a derivative with Lipschitz's constant $C > 0$, and $n(t)$ is a noise, $|n(t)| < \varepsilon$. Then, there exists such a constant $b > 0$ depend on $(\alpha - C)/\lambda^2$ and $(\alpha + C)/\lambda^2$ that after a finite time, the inequality $|u(t) - \dot{f}_0(t)| < \lambda b \varepsilon^{1/2}$ holds. (Levant, 1998)

Through the first order sliding mode differentiator description of the working principle, it will naturally think, whether can design a sliding mode differentiator to obtain the arbitrary order derivative of given signal. Well, the design of high order sliding mode controller (10) needs to know all sliding mode variables and their corresponding differentiation.

Theorem 3: Design an arbitrary order sliding mode differentiator, which can be used to estimate the derivative value of sliding mode variables, so as to achieve a simplified numerical differential purposes as following.

$$\begin{aligned} \dot{z}_0 &= v_0 \\ v_0 &= -\lambda_0 |z_0 - f(t)|^{n/(n+1)} \operatorname{sgn}(z_0 - f(t)) + z_1, \\ \dot{z}_1 &= v_1 \\ v_1 &= -\lambda_1 |z_1 - v_0|^{(n-1)/n} \operatorname{sgn}(z_1 - v_0) + z_2, \\ &\vdots \\ \dot{z}_{n-1} &= v_{n-1} \\ v_{n-1} &= -\lambda_{n-1} |z_{n-1} - v_{n-2}|^{1/2} \operatorname{sgn}(z_{n-1} - v_{n-2}) + z_n, \\ \dot{z}_n &= -\lambda_n \operatorname{sgn}(z_n - v_{n-1}) \end{aligned} \tag{20}$$

The same with first order sliding mode differentiator, suppose given signal is $f(t)$, $t \in [0,\infty)$. It has been known that the n order derivative of $f(t)$ has Lipschitz constant,

recorded as $L > 0$. Now, the object of sliding mode differentiator is estimating the value of $f'(t), f''(t), \cdots, f^{(n)}(t)$ in real time.

Arbitrary order sliding mode differentiator has the following recursive form as equation (20).

It can be verified, When $n = 1$, it is first order differentiator. Suppose $f_0(t)$ is basic value of given signal $f(t)$, $\delta(t)$ is uncertain part, but bounded, satisfying $|\delta(t)| < \varepsilon$, then $f(t) = f_0(t) + \delta(t)$.

Theorem 4: (Levant, 2003) If properly choose parameter $\lambda_i (0 \le i \le n)$, the following equalities are true in the absence of input noise after a finite time of a transient process.

$$\begin{aligned} z_0 &= f_0(t) \\ z_i &= v_i = f_0^{(i)}(t), \quad i = 1, \cdots, n \end{aligned} \tag{21}$$

The theorem 4 illustrates that arbitrary order sliding mode differentiator can use differentiation $z_i (0 \le i \le n)$ to estimate any order derivative of input function $f(t)$ online within limited time.

Theorem 5: (Levant, 2003) Let the input noise satisfy the inequality $\delta(t) = |f(t) - f_0(t)| \le \varepsilon$. Then the following inequality are established in finite time for some positive constants μ_i , τ_i depending exclusively on the parameters of the differentiator.

$$\begin{aligned} |z_i - f_0^{(i)}(t)| &\le \mu_i \varepsilon^{(n-i+1)/(n+1)} \quad i = 0, \cdots, n \\ |v_i - f_0^{(i+1)}(t)| &\le \tau_i \varepsilon^{(n-i)/(n+1)} \quad i = 0, \cdots, n-1 \end{aligned} \tag{22}$$

By Theorem 5, we can see that the arbitrary order sliding mode differentiator has robustness.

The arbitrary order sliding mode differentiator can accurately estimate any order derivative of a given input. If this differentiator can be used in high order sliding mode controller (10), any order derivative of sliding mode variable s can be accurately estimated avoiding the complicated calculation, which greatly simplifies the controller design. Adopting the differentiator, consider $s(t)$ in high order sliding mode controller as given input for differentiator. Then the output of differentiator $z_i (0 \le i \le n)$ can substitute any order derivative of $s(t)$, that is

$$\begin{aligned} z_0 &= s \\ z_i &= s^{(i)} \quad i = 1, \cdots n \end{aligned} \tag{23}$$

The sliding mode controller (8) can be rewritten by

$$u = -\alpha \ \mathrm{sgn}(\psi_{r-1,r}(z_0, z_1, \cdots, z_{(r-1)})) \tag{24}$$

The expression from this controller can also be clearly seen, with high order sliding mode differentiator, the differentiation of arbitrary order sliding mode variable will not be difficult to solve, which makes the high order sliding mode controller design has been simplified greatly.

2.2 Applications for permanent magnet synchronous motor

Permanent magnet synchronous motors (PMSM) are receiving increased attention for electric drive applications due to their high power density, large torque to inertia ratio and high efficiency over other kinds of motors (Glumineau et al, 1993; Ziribi et al, 2001; Caravani et al, 1998).

But the dynamic model of a PMSM is highly nonlinear because of the coupling between the motor speed and the electrical quantities, such as the d, q axis currents. In last years, many different control algorithms have been used to improve the performance of the magnet motor. For example, as the dynamic model of the machine is nonlinear, a natural approach is the exact feedback linearization control method, by which the original nonlinear model can be transformed into a linear model through proper coordinate transformation. However, in general, the dynamics of the synchronous motors may not be fully known, since some of parameters appearing in the equations will vary. For instance, the resistance and inductance will be changed when the temperature alters. As a consequence, nonlinearities can only be partially cancelled by the feedback linearization technique, and parameters uncertainties act on the equations of the motion. Then an important aim of the control design is to develop a robust controller which ensures good dynamic performances in spite of parameters uncertainties and perturbation.

The sliding mode control is known to be a robust approach to solve the control problems of nonlinear systems. Robustness properties against various kinds of uncertainties such as parameter perturbations and external disturbances can be guaranteed. However, this control strategy has a main drawback: the well known chattering phenomenon. In order to reduce the chattering, the sign function can be replaced by a smooth approximation. However, this technique induces deterioration in accuracy and robustness. In last decade, another approach called higher order sliding mode (HOSM) has been proposed and developed. It is the generalization of classical sliding mode control and can be applied to control systems with arbitrary relative degree r respecting to the considered output. In HOSM control, the main objective is to obtain a finite time convergence in the non empty manifold $S = \{x \in X \mid s = \dot{s} = \ddot{s} = \cdots = s^{(r-1)} = 0\}$ by acting discontinuously on r order derivatives of the sliding variable s. Advantageous properties of HOSM are: the chattering effect is eliminated, higher order precision is provided whereas all the qualities of standard sliding mode are kept, and control law is not limited by relative degree of the output.

The common analysis of permanent magnet synchronous motor is d-q axis mathematical model. It can be used to analyze not only the permanent magnet synchronous motor steady state operating characteristics, but also can be used to analyze the transient performance motor. In order to establish sinusoidal PMSM d-q axis mathematical model, firstly assume:

i. Motor core saturation neglected;
ii. Excluding the eddy current and magnetic hysteresis loss of motor;
iii. The motor current is symmetrical three phase sine wave current.

Thereby, the following voltage, flux linkage, electromagnetic torque and mechanical motion equations can be obtained, where all the values in equations are transient.

The voltage equation:

$$\begin{aligned} u_d &= \frac{d\psi_d}{dt} - \omega\psi_q + Ri_d \\ u_q &= \frac{d\psi_q}{dt} + \omega\psi_d + Ri_q \end{aligned} \tag{25}$$

The flux linkage equation:

$$\begin{aligned} \psi_d &= L_d i_d + \psi_f \\ \psi_q &= L_q i_q \end{aligned} \tag{26}$$

The electromagnetic torque equation:

$$T_{em} = P(\psi_d i_q - \psi_q i_d) = P[(L_d - L_q) i_d i_q + \psi_f i_q] \tag{27}$$

The motor motion equation:

$$J\frac{d\Omega}{dt} = T_{em} - T_l - B\Omega \tag{28}$$

Where: u_d, u_q are d-q axis stator voltage; i_d, i_q are d-q axis stator current; L_d, L_q are d-q axis stator inductance, as $L_d = L_q$, motor is non-salient pole; as $L_d < L_q$, motor is salient pole; ψ_d, ψ_q are d-q axis stator flux linkage; ψ_f is magnetic potential generated by permanent magnet rotor; ω is motor's electrical angular velocity; R is stator phase resistance; P is number of motor pole pairs; T_{em} is electromagnetic torque; T_l is load torque; Ω is motor's mechanical angular velocity, with $\Omega = P\omega$; J is total inertia of rotor and load; B is viscous friction coefficient.

Set of equations (25), (26), (27) and (28), we can get the state equation expression of PMSM as following.

$$\begin{bmatrix} \frac{d\omega}{dt} \\ \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} \frac{P}{J}[(L_d - L_q) i_d + \psi_f] i_q - \frac{B}{J}\omega - \frac{T_l}{J} \\ -\frac{R}{L_d} i_d + P\frac{L_q}{L_d}\omega i_q + \frac{1}{L_d} u_d \\ -P\frac{\psi_f}{L_q}\omega - P\frac{L_d}{L_q}\omega i_d - \frac{R}{L_q} i_q + \frac{1}{L_q} u_q \end{bmatrix} \tag{29}$$

Suppose θ_e is the electrical angle between rotor axis and stator A phase axis, θ is mechanical angular position of motor, with $\theta = P\theta_e$, and following equality is set up.

$$\theta = \int \Omega dt + \theta_0 \tag{30}$$

Where, θ_0 is rotor initial angular position. Considering position control, equation (29) can be rewritten by

$$\begin{bmatrix} \frac{d\theta}{dt} \\ \frac{d\omega}{dt} \\ \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} P\omega \\ \frac{P}{J}[(L_d - L_q) i_d + \psi_f] i_q - \frac{B}{J}\omega - \frac{T_l}{J} \\ -\frac{R}{L_d} i_d + P\frac{L_q}{L_d}\omega i_q + \frac{1}{L_d} u_d \\ -P\frac{\psi_f}{L_q}\omega - P\frac{L_d}{L_q}\omega i_d - \frac{R}{L_q} i_q + \frac{1}{L_q} u_q \end{bmatrix} \tag{31}$$

From the equation (31) we can see that PMSM is a multi-variable, coupling, nonlinear time varying systems. In addition, the variables in d-q axis can be changed to three phase abc axis by coordinate transformation.

2.2.1 Robust control for PMSM

This section will use the high order sliding mode control algorithm with differentiator, in spite of system parameter uncertainties, external disturbances and other factors, to design a robust controller for nonlinear multi-input multi-output permanent magnet synchronous motor. The advantage of this controller is the elimination of the chattering in standard sliding mode. At the same time, it is still with precision and robustness of the standard sliding mode control. And its control law no longer subjects to relative degree constraints.

Firstly, let x denotes the motor state variable $x=[x_1,x_2,x_3,x_4]^T=[\theta,\Omega,i_d,i_q]^T$, and control input $u=[u_1,u_2]^T=[u_d,u_q]^T$. The parameters R, L_d, L_q and B are considered as uncertain parameters, such as R will change with the temperature rise of the synchronous motor. Therefore, use R_0, L_{d0}, L_{q0} and B_0 to express their nominal value part of R, L_d, L_q and B respectively.

$$\begin{aligned}
k_1 &= k_{01}+\delta k_1 = P(L_d-L_q)/J \\
k_2 &= k_{02}+\delta k_2 = P\psi_f/J \\
k_3 &= k_{03}+\delta k_3 = -B/J \\
k_4 &= k_{04}+\delta k_4 = -R/L_d \\
k_5 &= k_{05}+\delta k_5 = PL_q/L_d \\
k_6 &= k_{06}+\delta k_6 = 1/L_d \\
k_7 &= k_{07}+\delta k_7 = -P\psi_f/L_q \\
k_8 &= k_{08}+\delta k_8 = -PL_d/L_q \\
k_9 &= k_{09}+\delta k_9 = -R/L_q \\
k_{10} &= k_{010}+\delta k_{10} = 1/L_q
\end{aligned} \tag{32}$$

In order to facilitate the calculation, the coefficient $k_i(1\le i\le 10)$ is used to plan these variable expressions, Where, $k_{0i}(1\le i\le 10)$ is the nominal value of the concerned parameter, δk_i is the uncertainty on the concerned parameter such that $|\delta k_i|\le \delta k_{0i}\le |k_{0i}|$, with δk_{0i} a known positive bound. The state variable $x\in R^4$, such that $|x_i|\le x_{iMAX}(2\le i\le 4)$, x_{2MAX} is the maximum values of the angular velocity, x_{3MAX} and x_{4MAX} are the maximum values of the current i_d and i_q respectively. And control input $u\in R^2$ such that $|u_i|\le u_{iMAX},(1\le i\le 2)$. Where, u_{1MAX} and u_{2MAX} are the maximum values of the voltage input v_d and v_q respectively.

Then the state space model of the synchronous motor can be changed as following nonlinear system.

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \underbrace{\begin{bmatrix} x_2 \\ (k_1x_3+k_2)x_4+k_3x_2-T_l/J \\ k_4x_3+k_5x_2x_4 \\ k_7x_2+k_8x_2x_3+k_9x_4\end{bmatrix}}_{f(x,t)} + \underbrace{\begin{bmatrix}0 & 0\\ 0 & 0\\ k_6 & 0\\ 0 & k_{10}\end{bmatrix}}_{g(x,t)}\begin{bmatrix}u_1\\ u_2\end{bmatrix} \tag{33}$$

The aim is to design an appropriate control which guarantees robust performance in presence of parameters and load variations. The control objective is double aspect. First, the rotor angular position $x_1 = \theta$ must track a reference trajectory angular position x_{1ref}. Second, the nonlinear electromagnetic torque must be linearized to avoid reluctance effects and torque ripple. This objective is equivalent to constrain $x_3 = i_d$ to track a constant direct current reference $x_{3ref} = 0$.

As we known that PMSM is a multi-input multi-output nonlinear dynamic system. It is assumed that the position and current are available for measurement. A first sliding variable s for the tracking of direct current x_3 towards its equilibrium point x_{3ref} f is defined from the direct current error. So, the first sliding mode variable is

$$s_1 = h_1(x) = x_3 - x_{3ref} \tag{34}$$

Derivative of s_1, we can see that the relative degree of sliding mode variable s_1 equals 1, that is

$$\begin{aligned} \dot{s}_1 &= \dot{x}_3 - \dot{x}_{3ref} \\ &= k_4 x_3 + k_5 x_2 x_4 + k_6 u_1 - \dot{x}_{3ref} \end{aligned} \tag{35}$$

To track the angular position $x_1 = \theta$, another sliding manifold is proposed so that the error dynamics follows a desired third order dynamic. Denoting x_{1ref} the desired trajectory, following form can be obtained.

$$s_2 = h_2(x) = x_1 - x_{1ref} \tag{36}$$

Considering load torque as external disturbance, derivative of s_2 continuously until control input appears.

$$\begin{aligned} \dot{s}_2 &= \dot{x}_1 - \dot{x}_{1ref} = x_2 - \dot{x}_{1ref} \\ \ddot{s}_2 &= \dot{x}_2 - \ddot{x}_{1ref} = (k_1 x_3 + k_2) x_4 + k_3 x_2 - \ddot{x}_{1ref} \\ \dddot{s}_2 &= k_1 x_4 (k_3 x_3 + k_5 x_2 x_4) + k_1 k_6 x_4 u_1 + k_3 [(k_1 x_3 + k_2) x_4 + k_3 x_2] \\ &\quad + (k_1 x_3 + k_2)(k_7 x_2 + k_8 x_2 x_3 + k_9 x_4) + (k_1 x_3 + k_2) k_{10} u_2 - \dddot{x}_{1ref} \end{aligned} \tag{37}$$

The control input u appears in the 3 order derivative of s_2, so the relative degree of s_2 equals 3. Considering sliding mode variable $s = [\dot{s}_1, \ddot{s}_2]^T$ as a new dynamci system, the space state express can be writtern by

$$\begin{bmatrix} \dot{s}_1 \\ \dddot{s}_2 \end{bmatrix} = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} + \begin{bmatrix} B_{11} & 0 \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{38}$$

Where,

$$A_1 = k_4 x_3 + k_5 x_2 x_4 =: A_{10} + \delta A_1$$

$$A_2 = (k_1 x_3 + k_2)(k_7 x_2 + k_8 x_2 x_3 + k_9 x_4) + k_3 [(k_1 x_3 + k_2) x_4 + k_3 x_2] + k_1 x_4 (k_3 x_3 + k_5 x_2 x_4) - \dddot{x}_{1ref} =: A_{20} + \delta A_2$$

$$B_{11} = k_6 =: B_{110} + \delta B_{11}$$

$$B_{21} = k_1 k_6 x_4 =: B_{210} + \delta B_{21}$$

$$B_{22} = (k_1 x_3 + k_2) k_{10} =: B_{220} + \delta B_{22}$$

A_{10}, A_{20}, B_{110}, B_{210} and B_{220} are the known nominal expressions whereas the expressions of δA_1, δA_2, δB_{11}, δB_{21} and δB_{22} contain all the uncertainties due to parameters and load torque variations.

Next, controller should be designed so that sliding mode variable s_1 achieves to zero in finite time. Another sliding mode variable s_2 and its first and second derivative likewise achieve to zero in finite time. When the sliding mode happens, then

$$\begin{aligned} S_1 &= \{x \in X \mid s_1(x,t) = 0\} \\ S_2 &= \{x \in X \mid s_2(x,t) = \dot{s}_2(x,t) = \ddot{s}_2(x,t) = 0\} \end{aligned} \tag{39}$$

The control problem is equivalent to the finite time stabilization of the following MIMO system.

$$\begin{bmatrix} \dot{s}_1 \\ \dddot{s}_2 \end{bmatrix} = A + B \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{40}$$

Where,

$$A = \begin{bmatrix} A_{10} \\ A_{20} \end{bmatrix} + \begin{bmatrix} \delta A_1 \\ \delta A_2 \end{bmatrix} =: A_0 + \delta A \tag{41}$$

$$B = \begin{bmatrix} B_{110} & 0 \\ B_{210} & B_{220} \end{bmatrix} + \begin{bmatrix} \delta B_{11} & 0 \\ \delta B_{21} & \delta B_{22} \end{bmatrix} =: B_0 + \delta B \tag{42}$$

From the equation (37), the outputs of this MIMO system are coupled since $\dddot{s}_2$ is affected by u_1 and u_2. So an input-output feedback linearization technique can be used, here w is new control input.

$$u = B_0^{-1} \cdot [-A_0 + w] \tag{43}$$

Now, if considering influence of external disturbance and parameter uncertainties, equation (40) can be rewritten by

$$\begin{aligned} s &= A + Bu \\ &= A_0 + \delta A + (B_0 + \delta B)u \\ &= A_0 + \delta A + (B_0 + \delta B)[B_0^{-1}(-A_0 + w)] \end{aligned} \tag{44}$$

Evolution and ordinate, then

$$\Rightarrow \begin{bmatrix} \dot{s}_1 \\ \dddot{s}_2 \end{bmatrix} = \begin{bmatrix} \hat{A}_1 \\ \hat{A}_2 \end{bmatrix} + \begin{bmatrix} \hat{B}_{11} & 0 \\ \hat{B}_{21} & \hat{B}_{22} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} \tag{45}$$

Where,

$$\hat{A}_1 = \delta A_1 - \frac{\delta B_{11}}{B_{110}} A_{10}$$

$$\hat{A}_2 = \delta A_2 - [\frac{\delta B_{21}}{B_{110}} - \frac{\delta B_{22} B_{210}}{B_{110} B_{220}}] A_{10} - \frac{\delta B_{22}}{B_{220}} A_{20}$$

$$\hat{B}_{11} = 1 + \frac{\delta B_{11}}{B_{110}}$$

$$\hat{B}_{21} = \frac{\delta B_{21}}{B_{110}} - \frac{\delta B_{22} B_{210}}{B_{110} B_{220}}$$

$$\hat{B}_{22} = 1 + \frac{\delta B_{22}}{B_{220}}$$

In the new dynamic system with $w = [w_1, w_2]^T$, it leads to s_1 equals integrator of w_1 and s_2 equals three time integrators of w_2, if the part of uncertainties $\delta A = 0$ and $\delta B = 0$. Then w_1 and w_2 are designed to stabilize in this new system.

In fact, the term $-B_0^{-1} A_0$ of (43) is the so-called equivalent control in the sliding mode context. In this new system, due to state variable $x_i (2 \le x \le 4)$, there exist three positive constants C_1, C_2, K_{11m}, K_{22m}, K_{11M}, K_{22M} and K_{21}, so that

$$\begin{aligned} &| \hat{A}_1 | \le C_1, \quad 0 < K_{11m} \le \hat{B}_{11} \le K_{11M} \\ &| \hat{A}_2 | \le C_2, \quad 0 < K_{22m} \le \hat{B}_{22} \le K_{22M} \\ &| \hat{B}_{21} | \le K_{21} \end{aligned} \tag{46}$$

Then, owing to the relative degree of s_1 equals 1, the first order sliding mode algorithm previously presented with control law

$$w_1 = -\alpha_1 \operatorname{sgn}(s_1) \tag{47}$$

Where α_1 is positive constant. In the actual system, due to all the state variables have the bound, selecting parameter α_1 properly to satisfy convergence. For the motor angular position control, a 3 order sliding mode control law is used. In this case, only a single scalar parameter α_2 is to be adjusted. Actually, the control input w_2 can be chosen as following.

$$w_2 = -\alpha_2 \operatorname{sgn}(\ddot{s}_2 + 2(|\dot{s}_2|^3 + |s_2|^2)^{1/6} \operatorname{sgn}(\dot{s}_2 + |s_2|^{2/3} \operatorname{sgn}(s_2))) \tag{48}$$

According to the principle of sliding mode differentiator, the arbitrary order derivative of s_2 can be estimated by the output of differentiator z_0, z_1 and z_2.

$$\begin{aligned} &\dot{z}_0 = \nu_0, \ \nu_0 = -150 |z_0 - s|^{2/3} \operatorname{sgn}(z_0 - s) + z_1 \\ &\dot{z}_1 = \nu_1, \ \nu_1 = -160 |z_1 - \nu_0|^{1/2} \operatorname{sgn}(z_1 - \nu_0) + z_2 \\ &\dot{z}_2 = -400 |z_2 - \nu_1| \end{aligned} \tag{49}$$

Then, substituting z_0, z_1 and z_2 for s_2, $\dot{s}_2$ and $\ddot{s}_2$ respectively in equation (48), that is

$$w_2 = -\alpha_2 \operatorname{sgn}(z_2 + 2(|z_1|^3 + |z_0|^2)^{1/6} \operatorname{sgn}(z_1 + |z_0|^{2/3} \operatorname{sgn}(z_0))) \tag{50}$$

The figure 1 is the block graph of control system. The first sliding mode variable s_1 is given by the error between direct axis current reference and feedback. And the second variable s_2 is identified by the error between the motor reference position and actual feedback. According to the Theorem 4 after finite time, z_0, z_1 and z_2 can be used to estimate s_2, $\dot{s}_2$ and $\ddot{s}_2$. In system, the state variable speed of motor w_2 is obtained by differentiator of angle position signal θ. Finally, the nonlinear dynamic system must be linearized by input-output feedback linearization, then the control input u_1 and u_2 are used to drive the synchronous motor.

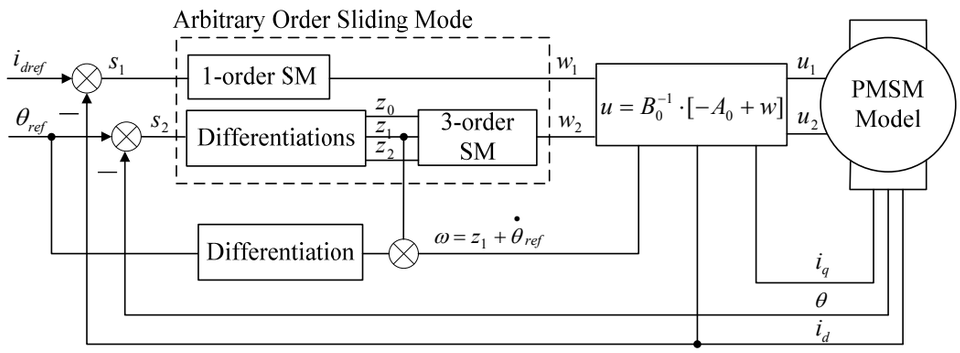


Fig. 1. The block graph of dynamic system structure.

In the simulation, The PMSM is a DutymAx 95DSC060300 (Leroy Somer Co.) drive. Two sensors give measurements of phase currents, a optical encoder is used to measure the position of the motor. The parameters of synchronous motor are $P = 3$, $R = 3.3\Omega$, $L_d = 0.027H$, $L_q = 0.0034H$, $B = 0.0034N \cdot m \cdot s$, $\psi_f = 0.341Wb$, $J = 0.00037kg \cdot m^2$. A phase current of the maximum accepted value is $6.0A$, the load torque maximum value is $6N \cdot m$, and angular velocity is $3000rpm$.To achieve the efficiency of controller, the parameter in (47) and (50) are chosen by $\alpha_1 = 5$, $\alpha_2 = 3300$. In the differentiator, the coefficient of (49) are selected by $\lambda_0 = 150$, $\lambda_1 = 160$, $\lambda_2 = 400$ in order to allow the convergence of the differentiator. The system sampling frequency is $8000Hz$. To show the system robustness of the controller, consider permanent magnet synchronous motor parameters uncertainties (with $\delta R = \pm 50\% R$, with $\delta L_{d0} = \pm 25\% L_d$ and $\delta L_{q0} = \pm 25\% L_q$ and with $\pm 20\% B$).

The trajectory of motor angular position reference and feedback are shown in figure 2 above in spit of PMSM parameters uncertainty. From this figure, we can see that the servo system track trajectory has good performance. The precision can achieve 10^{-3}. In addition, using high order sliding mode control, the chattering is eliminated in lower sliding mode surface so that the track trajectory becomes smoother.

Figure 2 below shows position tracking error, which does not exceed 0.09 rad. It means that the controller has high robust capability versus the parameters variations.

The figure 3 shows the curve of input u_d and u_q for PMSM using the high order sliding mode observer.

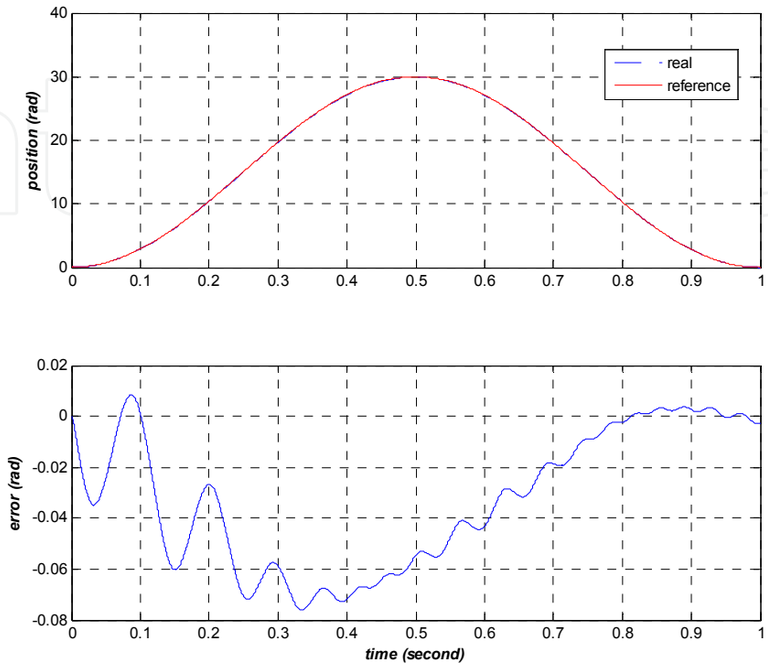


Fig. 2. Reference angle positon and actual angle position.

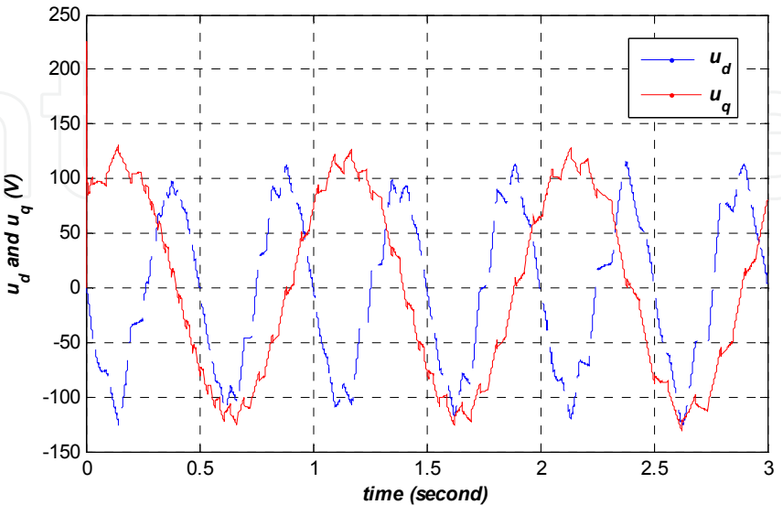


Fig. 3. The curve of input u_d and u_q.

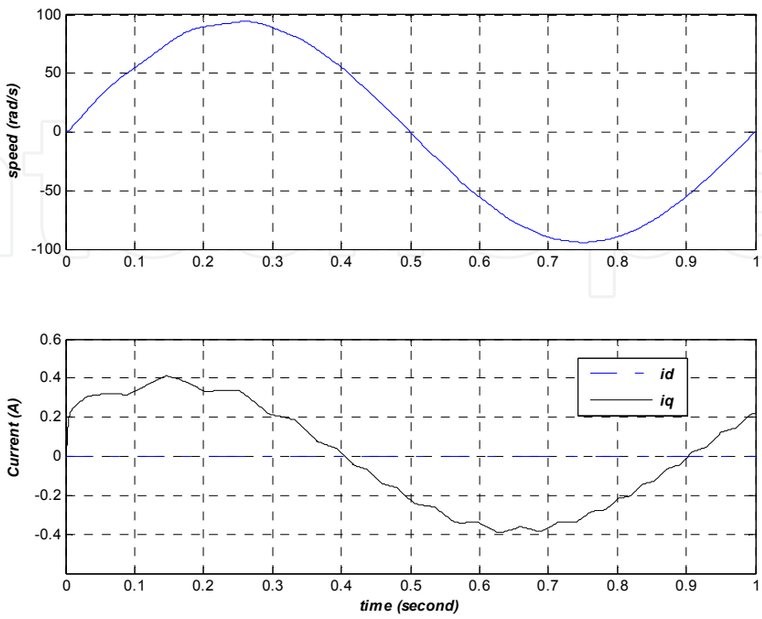


Fig. 4. Four quadrant run and quadrature/direct axis currents.

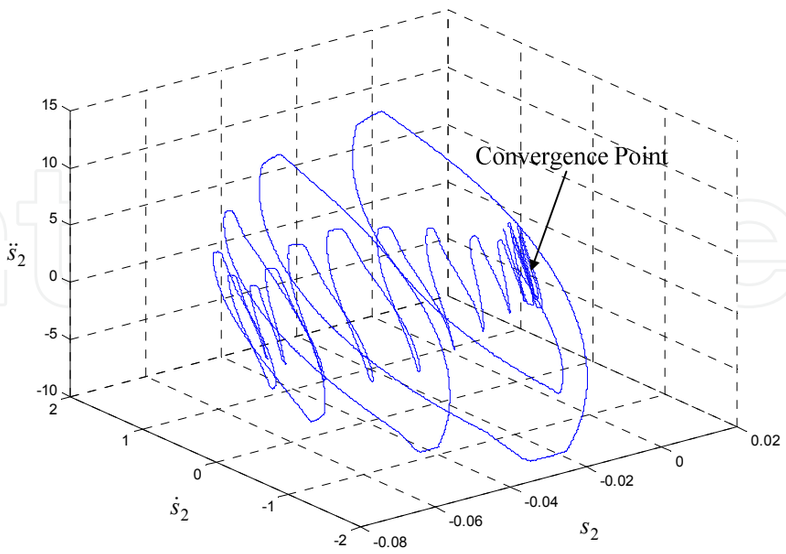


Fig. 5. Sliding mode variables s_2, $\dot{s}_2$ and $\ddot{s}_2$.

The figure 4 is the speed and d-q axis current of synchronous motor. The motor in the four-quadrant operation, with acceleration, deceleration, has good dynamic performance. In this figure, direct axis current i_d is very near reference $i_{dref} = 0$.
The figure 5 shows that sliding mode variable s_2 converge into origin in three dimensional surface within limited time.

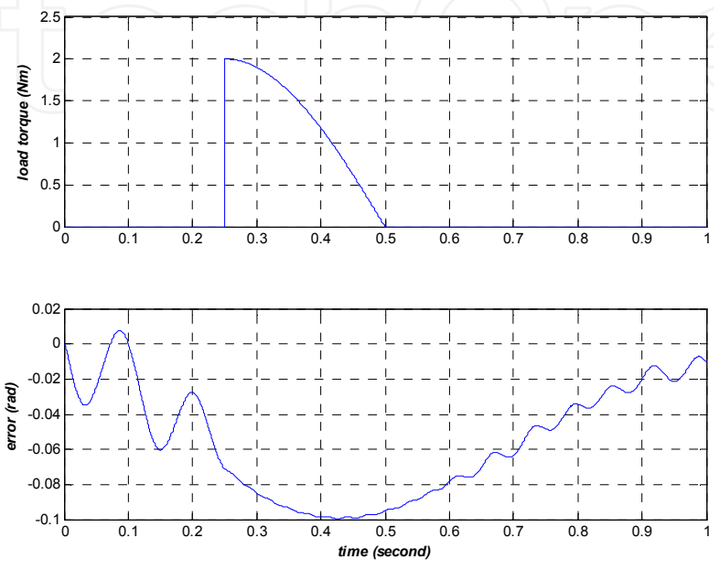


Fig. 6. Tracking error of motor with the load torque disturbance.

The Figure 6 shows the controller is strong robustness versus the load torque variations. The error of angular position does not exceed 0.1 rad even though the load perturbation.
To sum up, this section takes the multiple-input multiple-output nonlinear permanent magnet synchronous motor as control object, and designs a robust high order sliding mode controller with differentiator, through the state feedback linearization to decouple the system. The simulation results show that, despite the existence of parameter uncertainties and external disturbances, the system still has a better dynamic performance and robustness, which is due to higher order sliding mode control converge within limited time. Comparing with the traditional sliding mode control, high order sliding mode control eliminates the chattering phenomenon. And the better test results prove the feasibility of the theory.

2.2.2 States estimation

The parameters and state estimation of permanent magnet synchronous motor has been more concerned in motor control. As the motor itself is a typical nonlinear, multivariable system with strong coupling, there are a lot algorithms to improve the motor control performance in recent years. Earlier off-line estimation of the static dynamic system can not satisfy the control requirements; the use of extended Kalman filter (EKF) usually have a group of high order nonlinear equations, which is not conducive to the calculation (Yan, 2006), and its stability is also a local stable; In least squares procedure, the matrix forgotten

factor (Poznyak et al, 1999; Poznyak, 1999) is used to solve non-static parameter identification; as a result of sliding mode control with strong robustness and global convergence, In recent years, sliding mode observer (Floret-Pontet, 2001; Koshkouei, 2002) has been used for dynamic system state and parameter estimation, but the observer feedback gain is usually not easy to choose.

With the development of nonlinear theory, in order to enhance the performance of permanent magnet synchronous motor, many advanced control strategies have been proposed and used in motor control, which requires the state of motor can be measured, such as mechanical angular position, rotational speed, the electrical current and so on. Hence mechanical, electromagnetic or photoelectric sensor are needed, as well known to all, the sensors have many other shortcomings such as drift, friction, high costs, as well as electromagnetic interference caused by additional conductors. Therefore, the control system should be as possible as release the use of sensors to ensure the reliability and stability, which requires the system observer to precisely estimate the value of the state.

The high order sliding mode control is widely used in last decade, which take high order derivetives of sliding mode variables to substitute original discrete control, so that the chattering disappears in the high order differentiation. This section uses a high order sliding mode observer with differentiator algorithm to estimates the value of state variables. In this case, it removes the speed and current sensors of motor, and a better control precision and accurate state estimation are obtained.

In this section, the mathematical model of PMSM is the same with above section (33). In order to make control effectiveness more smooth, the relative order is raised artificially. Considering control input $\dot{u}$ as a new input, original sliding mode variable (35) and (37) are transformed into

$$\begin{aligned} \ddot{s}_1 &= A_1' + B_{11}'\dot{u}_1 \\ s_2^{(4)} &= A_2' + B_{21}'\dot{u}_1 + B_{22}'\dot{u}_2 \end{aligned} \tag{51}$$

Then, the coefficient matrix of original system A_1, A_2, B_{11}, B_{21} and B_{22} become new matrixes A_1', A_2', B_{11}', B_{21}' and B_{22}'. Where,

$$\begin{aligned} A_1' &= k_4(k_4x_3 + k_5x_2x_4 + k_6u_1) + k_5[(k_1x_3 + k_2)x_4 + k_3x_2]x_4 \\ &\quad + k_5x_2(k_7x_2 + k_8x_2x_3 + k_9x_4 + k_{10}u_2) - \ddot{x}_{3ref} \end{aligned}$$

$$\begin{aligned} A_2' &= (k_1k_5x_4^2 + k_1k_7x_3 + k_1k_8x_3^2 + k_2k_7 + k_2k_8x_3 + k_3^2)[(k_1x_3 + k_2)x_4 + k_3x_2] \\ &\quad + (k_1k_4x_4 + k_1k_7x_2 + 2k_1k_8x_2x_3 + k_1k_9x_4 + k_2k_8x_2 + k_1k_{10}u_2 + k_1k_3x_4)(k_4x_3 \\ &\quad + k_5x_2x_4 + k_6u_1) + 2k_1k_5x_2x_4 + k_1k_6u_1 + k_1k_9x_3 + k_2k_9 + k_1k_3x_3 + (k_1k_4x_3 \\ &\quad + k_2k_3)(k_7x_2 + k_8x_2x_3 + k_9x_4 + k_{10}u_2) - x_{3ref}^{(4)} \end{aligned}$$

$$B_{11}' = k_6 \ ;$$

$$B_{21}' = k_1k_6x_4 \ ;$$

$$B_{22}' = (k_1x_3 + k_2)k_{10} \ ;$$

Next, it still is high order sliding mode controller design that make the sliding mode variables converge into origin within limited time in the sliding mode surface. In another word, it should satisfy following conditions.

$$\begin{aligned} S_1 &= \{x \in X \mid s_1(x,t) = \dot{s}_1(x,t) = 0\} \\ S_2 &= \{x \in X \mid s_2(x,t) = \dot{s}_2(x,t) = \ddot{s}_2(x,t) = \dddot{s}_2(x,t) = 0\} \end{aligned} \tag{52}$$

Let $s = [\ddot{s}_1, s_2^{(4)}]^T$, $u = [\dot{u}_1, \dot{u}_2]$, this control object is equivalent to stable of following multi-input multi-output system in limited time.

$$s = A' + B'u \tag{53}$$

Due to $s_2^{(4)}$ effected by $\dot{u}_1$ and $\dot{u}_2$, the output of this system are coupled. Here, input-output feedback linearization technology is used to decouple system.

$$u = \frac{1}{L_g L_f^{r-1} h(x)} (w - L_f^r h(x)) = B'^{-1} \cdot [-A' + w] \tag{54}$$

After decoupling, the relative degree of s_1 equals 2, so 2 order sliding mode control law is adopted

$$w_1 = -\alpha_1 \operatorname{sgn}(\dot{s}_1 + |s_1|^{1/2} \operatorname{sgn}(s_1)) \tag{55}$$

Where, α_1 is a positive constant. Now, we use the output of sliding mode differentiator z_{01} and z_{11} to estimate the value of s_1 and $\dot{s}_1$.

$$\begin{aligned} \dot{z}_{01} &= v_{01}, \quad v_{01} = -\lambda_{01} |z_{01} - s_1|^{1/2} \operatorname{sgn}(z_{01} - s_1) + z_{11} \\ \dot{z}_{11} &= -\lambda_{11} \operatorname{sgn}(z_{11} - v_{01}) \end{aligned} \tag{56}$$

For the motor's angular position control, 4 order sliding mode control law is used. In this case, we only adjust a single parameter α_2 to make the system converge within limited time.

$$\begin{aligned} w_2 = -\alpha_2 \operatorname{sgn}\{\dddot{s}_2 + 3[(\ddot{s}_2)^6 + (\dot{s}_2)^4 + |s_2|^3]^{1/12} \operatorname{sgn}[\ddot{s}_2 + (|\dot{s}_2|^4 \\ + |s_2|^3)^{1/6} \operatorname{sgn}(\dot{s}_2 + 0.5|s_2|^{3/4} \operatorname{sgn}(s_2))]\} \end{aligned} \tag{57}$$

Similarly, the output z_{02}, z_{12}, z_{22} of 3 order differentiator is used to estimated sliding mode variables $s_2, \dot{s}_2, \ddot{s}_2$.

$$\begin{aligned} &\dot{z}_{02} = v_{02}, \quad v_{02} = -\lambda_{02} |z_{02} - s_2|^{3/4} \operatorname{sgn}(z_{02} - s_2) + z_{12}; \\ &\dot{z}_{12} = v_{12}, \quad v_{12} = -\lambda_{12} |z_{12} - v_{02}|^{2/3} \operatorname{sgn}(z_{12} - v_{02}) + z_{22}; \\ &\dot{z}_{22} = v_{22}, \quad v_{22} = -\lambda_{22} |z_{22} - v_{12}|^{1/2} \operatorname{sgn}(z_{22} - v_{12}) + z_{32} \\ &\dot{z}_{32} = -\lambda_{32} \operatorname{sgn}(z_{32} - v_{22}) \end{aligned} \tag{58}$$

Generally speaking, in the actual system not all the state variables is measurable. Sometimes, due to the limitation of condition, some state variables can not be measured. Therefore, it requires the controller can estimate state variables of system as possible as accurate.

PMSM only uses the position sensors, taking the use of high order sliding mode control techniques, so that its speed and the current state variable are estimated online. In this way, it avoids the use of other sensors, at the same time ensures the motor position tracking progress.

In the design of controller, we have obtained that

$$\dot{s}_1 = k_4 x_3 + k_5 x_2 x_4 + k_6 u_2 - x_{3ref}$$

$$\dot{s}_2 = x_2 - \dot{x}_{1ref}$$

$$\ddot{s}_2 = \ddot{x}_1 - \ddot{x}_{1ref} = (k_1 x_3 + k_2) x_4 + k_3 x_2 - \ddot{x}_{1ref} \tag{59}$$

From the above equations, we can calculate the speed estimation of synchronous motor $\tilde{x}_2 = \dot{s}_2 + \dot{x}_{1ref}$, so the current estimation expressed by

$$\begin{aligned} \tilde{x}_3 &= \frac{1}{k_4}[\dot{s}_1 - k_5 \tilde{x}_4 (\dot{s}_2 + \dot{x}_{1ref}) - k_6 u_2] \\ \tilde{x}_4 &= \frac{\ddot{s}_2 - k_3 (\dot{s}_2 + \dot{x}_{1ref}) + \ddot{x}_{1ref}}{k_1 \tilde{x}_3 + k_2} \end{aligned} \tag{60}$$

For calculating $\tilde{x}_3$ and $\tilde{x}_4$, considering sliding mode variables $\dot{s}_1$, $\dot{s}_2$, $\ddot{s}_2$ and u_2 as known value, adopt recursive algorithm to get

$$\begin{aligned} \tilde{x}_{3(j+1)} &= \frac{1}{k_4}[\dot{s}_{1(j)} - k_5 \tilde{x}_{4(j)} (\dot{s}_{2(j)} + \dot{x}_{1ref}) - k_6 u_{2(j)}] \\ \tilde{x}_{4(j+1)} &= \frac{\ddot{s}_{2(j)} - k_3 (\dot{s}_{2(j)} + \dot{x}_{1ref}) + \ddot{x}_{1ref}}{k_1 \tilde{x}_{3(j)} + k_2} \quad j = 1, 2, \cdots \end{aligned} \tag{61}$$

Where, j is the j-th sample point of system, $j+1$ is the next sample point. Through the above recursive equation, current estimation $\tilde{x}_3$ and $\tilde{x}_4$ are obtained. Take these estimation into the control system so that save the sensors. Thereby, system become more simple and reliability.

In the simulation, we use the DutyMAX95-BSC060300 permanent magnetic synchronous motor. The parameters of motor are $P = 3$, $R = 3.3\Omega$, $L_d = 0.027H$, $L_q = 0.0034H$, $\psi_f = 0.341Wb$, $B = 0.0034N \cdot m \cdot s$, $J = 0.0037kg \cdot m^2$. A phase current of the maximum accepted value is $6.0A$, the load torque maximum value is $6N \cdot m$, and angular velocity is $3000rpm$.

The parameter of controller are $\alpha_1 = 5$ and $\alpha_2 = 50$; the parameter of sliding mode differentiator are $\lambda_{01} = 2$, $\lambda_{11} = 1.5$, $\lambda_{02} = 25$, $\lambda_{12} = 25$, $\lambda_{22} = 33$ and $\lambda_{32} = 500$.

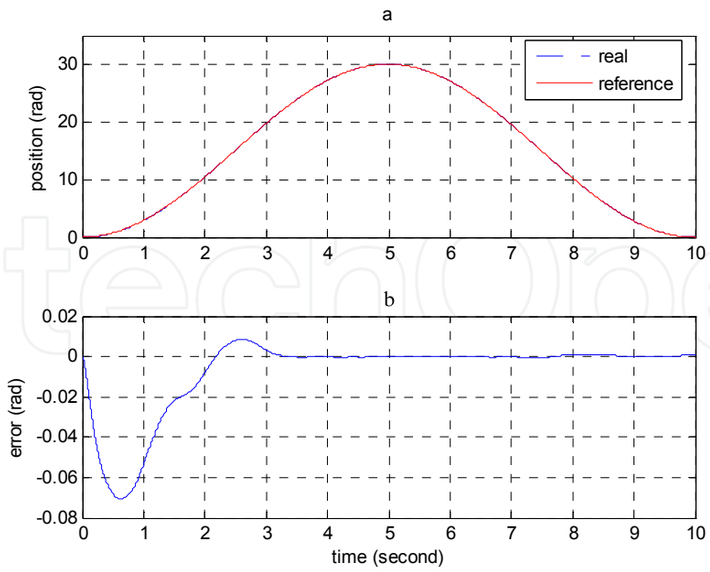


Fig. 7. Position tracking and error curve of PMSM.

From the figure 7 above, it can be seen that the permanent magnet synchronous motor control system has good performance. This figure shows the permanent magnet synchronous motor can precisely track the given position. And the error between reference and the actual position feedback is shown in Figure 7 below. The maximal error does not exceed to 0.08 rad.

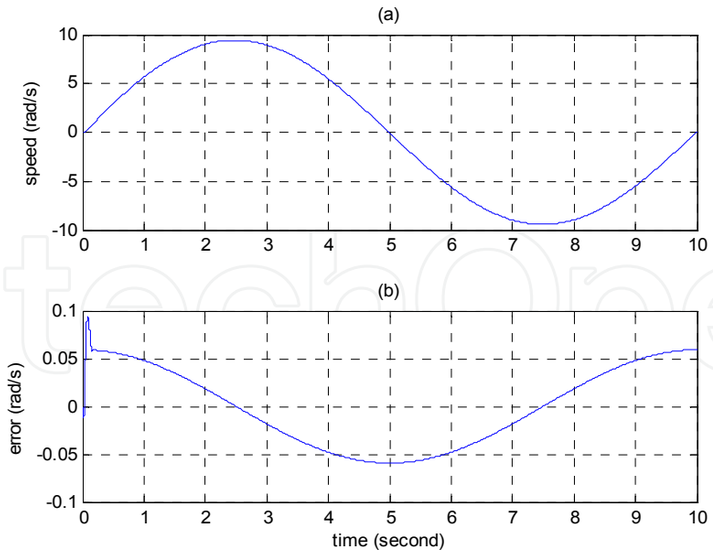


Fig. 8. Speed estimation and error curve of PMSM.

The figure 8 above shows the motor angular speed by derivative of the motor's angular position. The figure 8 below shows the error between the estimation of the electrical angular speed.

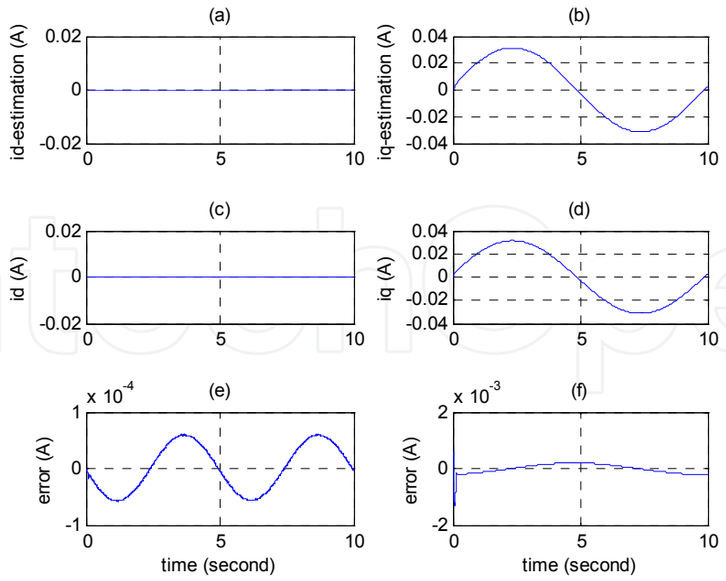


Fig. 9. The direct/quadrature axis currents and their estimations.

For permanent magnet synchronous motor, its angular position, speed and current are system state values. The figure 9(a), (b), (c), (d) shows that the estimated value and actual current value of direct axis and quadrature axis respectively. The figure 9(e), (f) are the error between actual current value and the estimated value. In this figure, the error of direct axis current is between $\pm 1.0\times 10^{-4}(A)$, and the error of quadrature axis is between $\pm 1.0\times 10^{-3}(A)$.

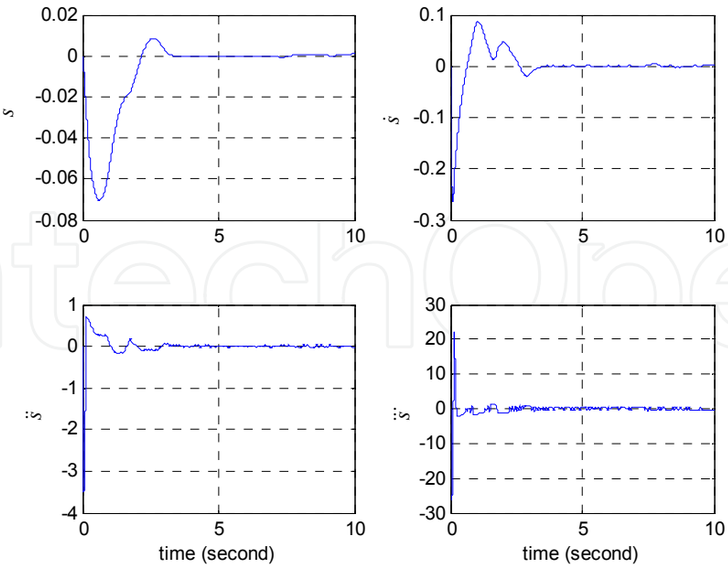


Fig. 10. System sliding mode variables curve.

The figure 10 is the convergence curve of sliding mode variable and its high order derivatives. From the figure we can clearly see that the discrete control law acts on the high

order sliding mode surface, which makes the lower sliding mode surface smooth. That is the reason why high order sliding mode control can eliminate the chattering.
This subsection focuses on a state estimation of PMSM online. In the practical systems, not all the state variables are measurable, or because of objective reasons they are often not easy to measure. In this section, we just use the motor position sensor, through the high order sliding mode control with differentiator, to achieve the state variables of motor estimation online. The simulation results show that the PMSM control system has good dynamic performance, while the electrical angular speed and d-q axis current are estimated precisely.

2.2.3 Torque disturbance identification

In high precious servo control, the disturbance load will impact servo control. Therefore, the estimation of the disturbance load is very necessary to reduce its influence. Usually in the actual system, the disturbance load torque is often random and uncertain. So, this requires the controller can estimate the value of state variables as accurately as possible. This section will use the arbitrary order sliding mode differentiator, to calculate the high order derivative of sliding mode variables online, so as to avoid the complexity of differential calculation. Then, through the expression of the unknown disturbance load torque, it is estimated. Take the estimation as system input, thereby enhancing the system performance. In the simulation, the position and current sensors of PMSM are used. Adopt high order sliding mode control, its disturbance torque is estimated online. Then, the unknown uncertain external disturbance torque can be entered as a known value so that improve the motor position tracking accuracy.
In order to facilitate the description, the mathematical model of motor still use system state equation (31) in d-q axis coordinate. The meaning of the parameters remains unchanged. Then, from the mathematical model of PMSM, the following solution can easily get

$$\tilde{T}_l = p[(L_d - L_q)x_3 + \psi_f]x_4 - B\tilde{x}_2 - J\dot{\tilde{x}}_2 \tag{62}$$

In equation (62), $\tilde{T}_l$ is the estimation of external torque. $\tilde{x}_2$ and $\dot{\tilde{x}}_2$ are the estimation of angular speed and angular acceleration respectively.
From the controller of previous section, the following expression can be obtained

$$\begin{aligned} \dot{s}_2 &= x_2 - \dot{x}_{1ref} \\ \ddot{s}_2 &= \ddot{x}_1 - \ddot{x}_{1ref} = \dot{x}_2 - \ddot{x}_{1ref} \end{aligned} \tag{63}$$

Therefore, the above equation (63) can solve the estimation of angular speed and angular acceleration.

$$\begin{aligned} \tilde{x}_2 &= \dot{s}_2 + \dot{x}_{1ref} \\ \dot{\tilde{x}}_2 &= \ddot{s}_2 + \ddot{x}_{1ref} \end{aligned} \tag{64}$$

Until now, if we can get the 1 and 2 order derivative of sliding mode variable s_2, the estimation of state variable $\tilde{x}_2$ and its differentiation $\dot{\tilde{x}}_2$ can be solved. According to the principle of high order sliding mode differentiator, $\dot{s}_2$ and $\ddot{s}_2$ in equation (64) can be estimated by the output of differentiator z_{12} and z_{22}.

$$\begin{aligned}
\dot{z}_{02} &= \nu_0, \quad \nu_0 = -130\,|\,z_{02} - s_2\,|^{2/3}\,\mathrm{sgn}(z_{02} - s_2) + z_{12} \\
\dot{z}_{12} &= \nu_1, \quad \nu_1 = -150\,|\,z_{12} - \nu_0\,|^{1/2}\,\mathrm{sgn}(z_{12} - \nu_0) + z_{22} \\
\dot{z}_{22} &= -500\,|\,z_{22} - \nu_1\,|
\end{aligned} \tag{65}$$

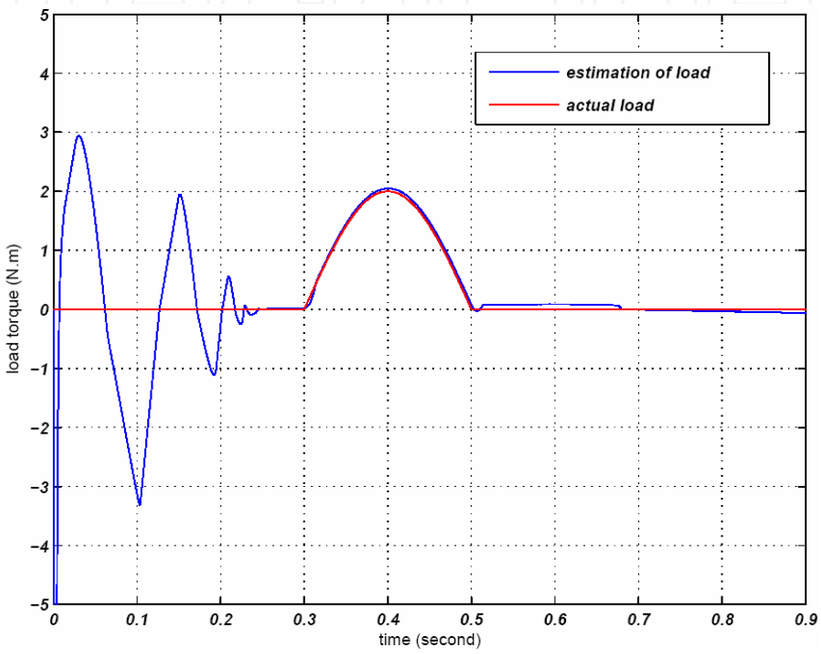


Fig. 11. External disturbance load torque and its estimation of motor. Available into the equation (62).

$$\tilde{T}_l = p[(L_d - L_q)x_3 + \psi_f]x_4 - B(z_{12} + \dot{x}_{1ref}) - J(z_{22} + \ddot{x}_{1ref}) \tag{66}$$

Through calculation online, the estimation of disturbance load is obtained. Take the estimated value into the control system so that the uncertain disturbance load become the determine input. In this case, the system performance is improved effectively.

From the figure 11 we can see that, taking use of high order sliding mode with differentiator, disturbance load torque get a better estimation. Disturbance torque is estimated online successfully so that it is no longer unknown uncertainties factor. It also improves the performance of the system. The maximum torque value is $2N \cdot m$ in the figure. The sliding mode variable converges into origin at the 0.25s.

The figure 12 shows that the actual angular position track reference of PMSM with the disturbance load. From the figure we can see that the maximum error of the angular position is not more than 0.12 rad. The system gets a better control performance.

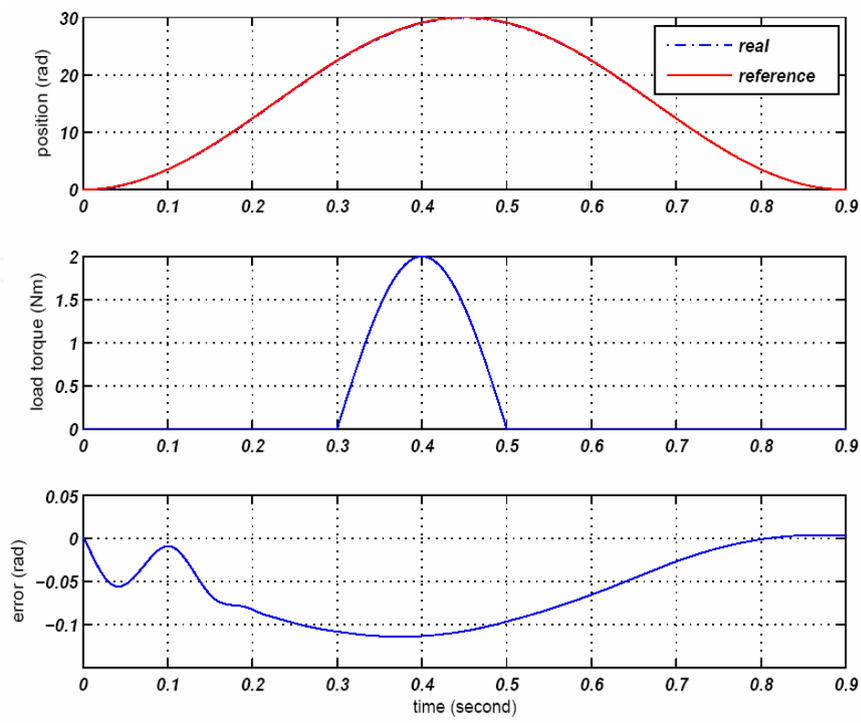


Fig. 12. Position tracking curve with load torque disturbance.

2.4 Experimental results and analysis

The dSPACE is a equipment of control exploitation and test system based on MATLAB/Simulink that is from Germany. It implements seamless link with the MATLAB/Simulink completely. It can complete the control algorithm design, test and implementation, overcoming the shortage of the traditional control system, for example, the difficult to achieve the complex algorithm and the long development cycle. It has advantages of high speed, ease to use and user-friendly.

Taking DS1005PPC control board as the core, with DS2001AD acquisition board, DS2002/2003 multi-channel AD acquisition board, CP4002 Multi-I/O board, DS2102DA output board, DS3002 incremental encoder interface board, we constitute a standard component hardware parts of dSPACE DS1005 system, which is used in this experiment.

After the completion of the experimental platform, the development steps of control system for PMSM based on the dSPACE include the following points:

1. MATLAB/Simulink modeling and off-line simulation. Take use of MATLAB/Simulink to establish a mathematical model for the simulation object, and design control programs. At the same time, complete the system off-line simulation.
2. Input/output interface (I/O) experimental model. In the MATLAB/Simulink environment, we need to retain module that is downloaded to the dSPACE. Select the real-time control required for I/O modules from the RTI library. Replace the original connection relationship with the hardware interface, and configure I/O parameters. In some special cases, we also need to set up hardware and software interrupt priority levels.

3. The dSPACE/RTW provides tools to automatically generate code and download. Since MATLAB and dSPACE with seamless connectivity features, a simple operation can complete real-time C code generation, compile, link and download for the target system. In other word, model is downloaded into target board DS1005PPC as running program.
4. The dSPACE integrated experiment and debugging. The dSPACE provides real-time ControlDesk software as well, which changes the parameters and real-time control.

The figure 13 is a control system in MATLAB/Simulink environment with the dSPACE/RTI module.

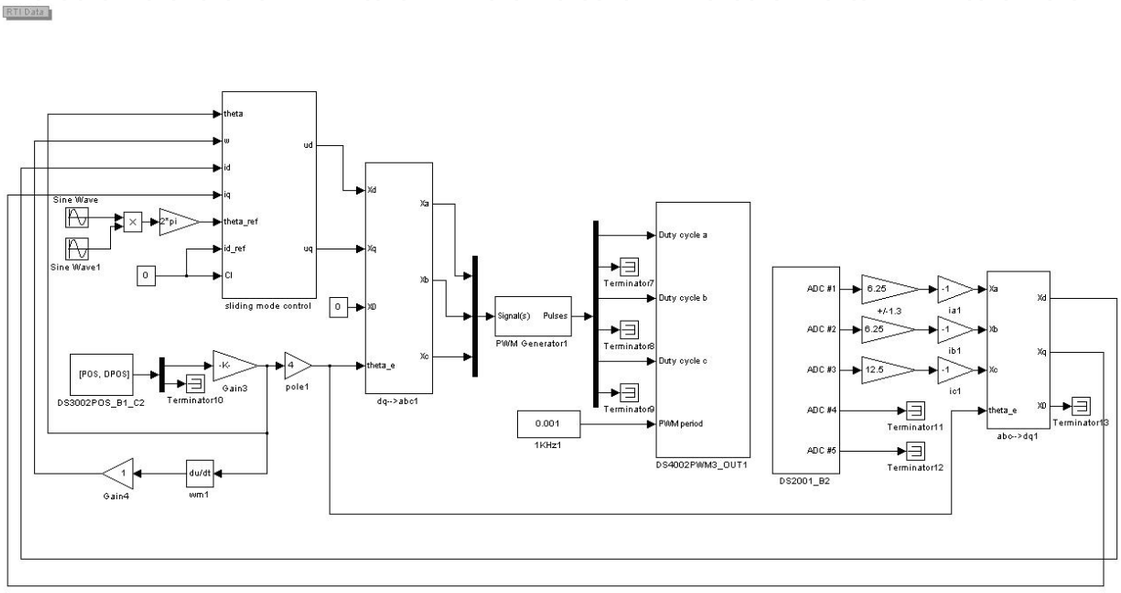


Fig. 13. MATLAB/Simulink environment based on dSPACE/RTI control system.

i. Content and intention:

1. Validate feasibility of high order sliding mode control in PMSM;
2. Test system using high sliding mode control whether it can release chattering phenomenon;
3. Test system using high sliding mode control whether it has robustness.

ii. Equipments:

Name	Type	Unit	Amount
dSPACE controller	DS1005	Dais	1
DC regulated power	WYK-303B2	Dais	1
Slide-wire rheostat	BX8D-3/7	Dais	3
Switch regulated power	S-100-24	Dais	1
Universal meter	LINI-T/UT58A	Dais	1
Ondoscope	Tektronix/TDS2024	Dais	1
Industrial computer	ADLINK	Dais	1

Table 1. The list of experimental equipments.

iii. Experimental procession:

Step 1: Off-line simulation. According to the principle of high order sliding mode control and differentiator, combining with chapter 5 of the application for permanent magnet synchronous motor, the theoretical simulation is researched in the MATLAB/Simulink firstly. In detail, set the sampling frequency and differential equation solution, and save the .mdl model file;

Step 2: After the control algorithm verification, remove the inverter model and motor model replaced by the physical prototypes of actual system. And then complete all of the system interface, including the A /D, D/A, I/O, PWM and other interfaces of the dSPACE. Afterwards, compile on-line to generate. cof configuration file;

Step 3: Check all connections are correct. After that, start the dSPACE. Compile and download files real-time (RTI) in the environment of MATLAB/Simulink. At this moment, algorithm program code is downloaded to the DSP core program area of dSPACE controller;

Step 4: Start the dSPACE/ControlDesk. Create an experimental file .prj in the interface, and design the required .lay layer file. Observe compiler-generated variable file .sdf in order to facilitate observe the real-time dynamic performance of the system;

Step 5: After the completion of the above, check the status of external devices is good or not. Finally, start bus power, while start system operation in dSPACE/ControlDesk interface.

iv. Controlled device:

The controlled object in experiments uses non-salient pole permanent magnet synchronous motor of Delta's ASMT series, whose main parameters are as follows table 2:

Name	Value	Unit
Resistance	$R = 3.052$	Ω
Inductance	$L_d = 8.4$	mH
Rating Power	$P = 1.0$	kW
Torque	$T = 3.3$	$N \cdot m$
Pole-pairs	$N_p = 4$	---
Voltage	$U = 300$	V
Speed	$n_N = 3000$	r / min
Rotary inertia	$J = 0.00026$	$kg \cdot m^2$

Table 2. Parameters of PMSM in experiment d.

Host-computer control surface adopts visual man-machine surface the dSPACE/ControDesk to realize data acquisition and display. Figure 14 is pictorial diagram based on the dSPACE control system. The system consists of inverter, isolation circuit, detection circuit, power circuit and etc.

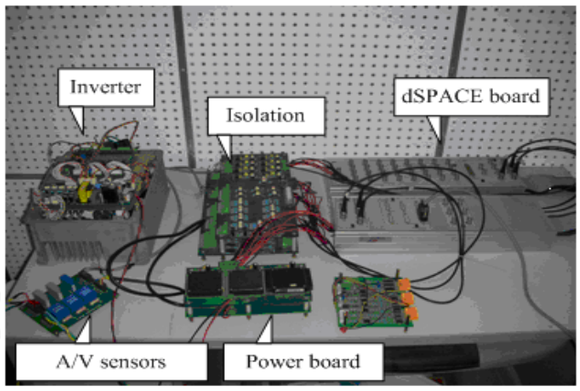


Fig. 14. Control system hardware circuit with dSPACE interface.

v. Waveform:

Because the research of nonlinear system high order sliding mode control theory still is in primary stage, it is face with much challenge. For example, it strictly requires all of the system functions are smooth, and norm-bounded. Otherwise, there is the higher derivative of reference value in control law. In our experiment, 60V DC regulated power is supplied. Experiment is tested under the conditions above. The main test results are following.

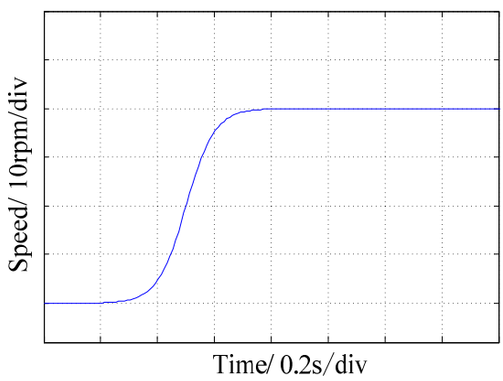


Fig. 15. Speed reference curve of PMSM.

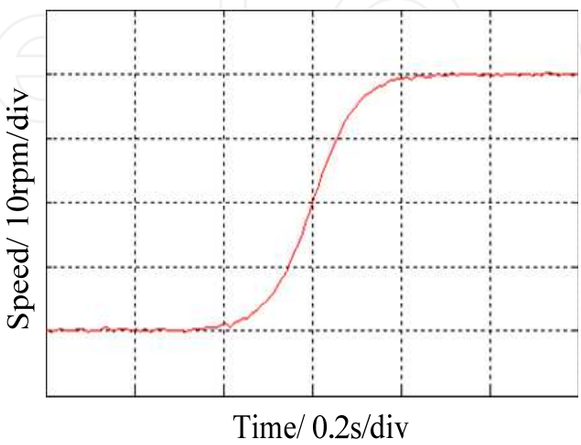


Fig. 16 Dynamic speed feedback curve.

High order sliding mode control law has high derivative of reference signal, so the reference signal must be smooth and continues enough function. For testing speed dynamic response of PMSM in the experiment, the reference signal is set as Fig. 15. Actual measurement of speed dynamic response is shown in Fig. 16.
By comparing Fig. 15 and Fig 16, nonlinear PMSM holds good dynamic tracking character with high order sliding mode control.

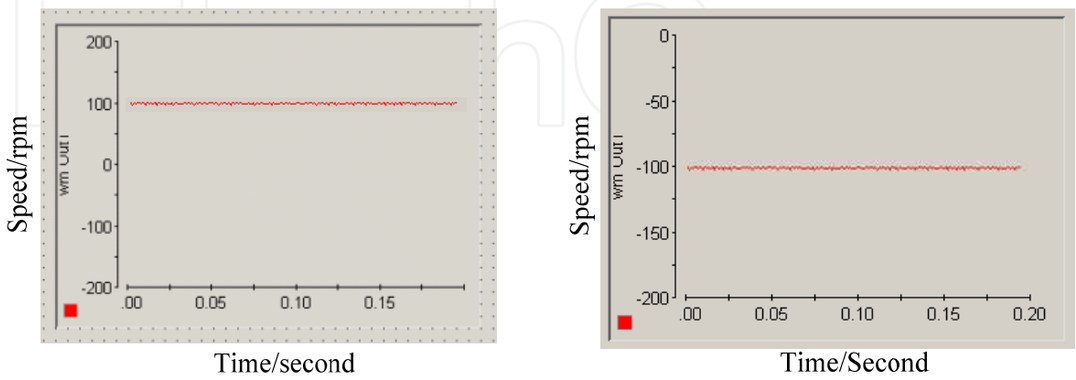


Fig. 17. Steady speed of clockwise/ Anti-clockwize displayed in dSPACE/ControlDesk.

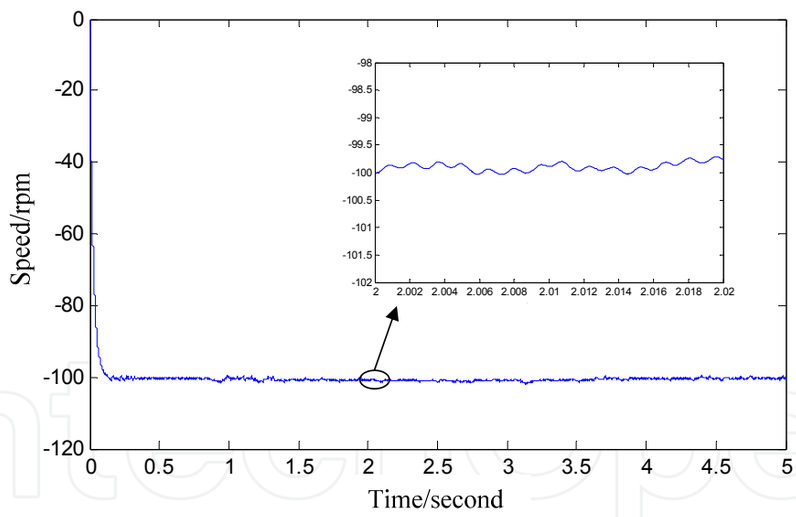


Fig. 18. Speed curve of PMSM in MATLAB/Simulink using traditional sliding mode control.

Fig. 17 is steady speed clockwise/anti-clockwise curve of PMSM. It is can be seen that the PMSM also takes on good steady performance.
The Fig. 18 is outline simulation speed waveform of PMSM using traditional sliding mode control. It displays anti-clockwise speed waveform of PMSM. And the Fig. 19 is outline simulation speed curve of PMSM using high order sliding mode. After partial amplification, comparing with Fig. 18, high order sliding mode control is provided with the ability of avoidance chattering. But, its algorithm is more complicated than tradition. The adjusting time is longer, too.

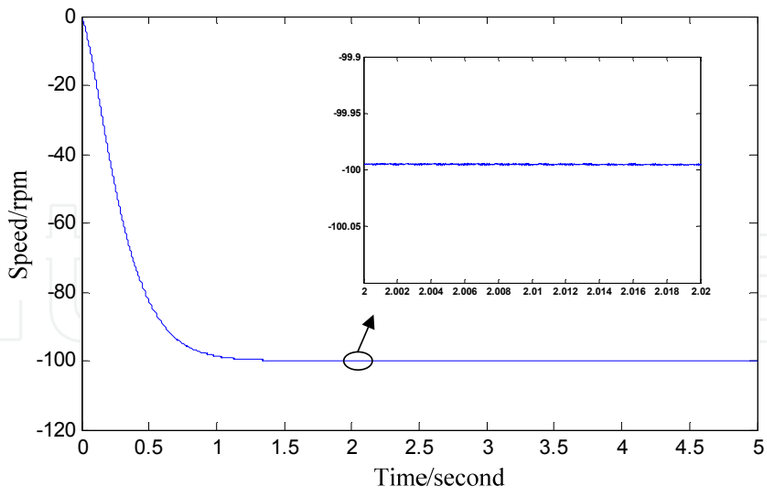


Fig. 19. Speed curve of PMSM in MATLAB/Simulink using high order sliding mode control.

To validate experiment intention 2 and 3, show high order sliding mode control with free chattering and robustness, the experiment designs traditional sliding mode controller, too. Simulation and actual measurement are recorded in order to compare with high order sliding mode.

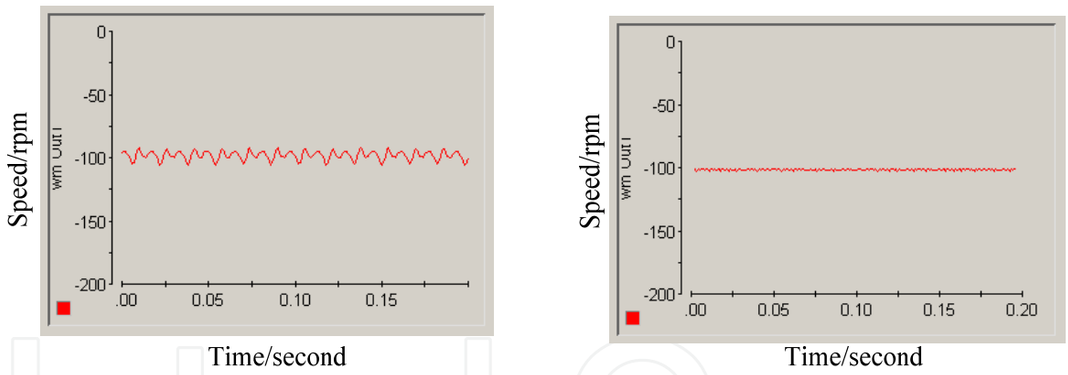
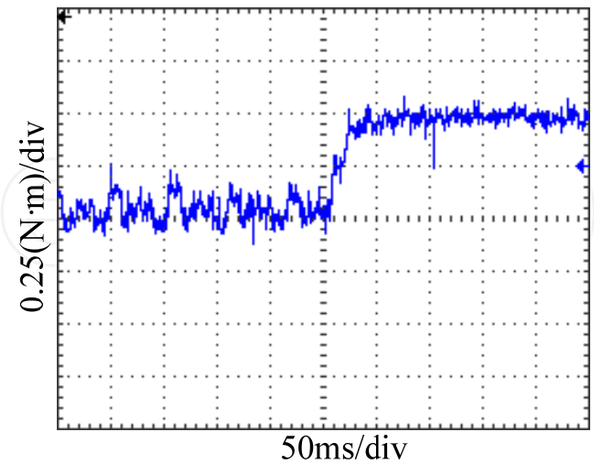


Fig. 20. Speed curve in dSPACE/ControlDesk using traditional/high order sliding mode control.

Due to the traditional sliding mode control uses discontinues control law acting on sliding mode manifold surface, chattering problem is caused. The great of the coefficient in sliding mode control law, the faster of convergence, when the system enter into sliding mode, chattering phenomenon is more obvious. The left figure of Fig. 20 is actual measurement speed curve of PMSM, which adopts conventional sliding mode control. The control law is $u = -K_i \operatorname{sgn} s$, in current loop $K_1 = 5$, in speed loop $K_2 = 8.2$. From the comparison of Fig. 20, we can obtain a conclusion that chattering is released in high order sliding mode.

Hereto, both of simulation and experiment results prove that high order sliding mode control can reduce the chattering phenomenon which exists in conventional. Following experiment will test the robustness of high order sliding mode control.



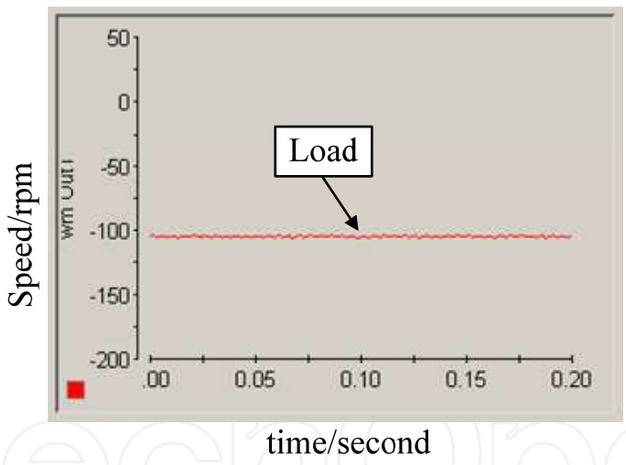


Fig. 21. Speed curve of 0.5 $N \cdot m$ disturbance load in dSPACE/ControlDesk.

The PMSM is a typical complex system because of elevated temperature, saturation, time delay and a good many elements. These reasons lead to the synchronous motor is nonlinear, variation parameter, close coupled system. For the sake of testing high order sliding control, which is insensitive to the parameter uncertainness and disturbance, experiment is injected about 0.5 $N \cdot m$ external load disturbance at the 0.01 second. The speed actual measurement waveform is shown in Fig. 21. From this figure, speed curve is smooth without flutter. The

experiment result illuminates high order sliding mode control reserves robustness of conventional sliding mode.
Experimentally verified, high order sliding mode control provides an effective method to improve accuracy and robustness further for nonlinear systems

3. Conclusion

This chapter applies the research of nonlinear control and high order sliding mode control theory in PMSM control, and achieves robust control for a PMSM in spit of the internal parameter uncertainties and unknown external disturbance load torque. The simulation results show good performance; in addition, the estimation online of system state variables is also one of the hot issues in the control field. In this chapter, a new design based on high order sliding mode with differentiator for PMSM, access to the state variable estimation; Besides, unknown uncertain load impacts the performance of motor control. In order to improve system performance, this chapter also achieves external disturbance load estimation online. It makes sure the load can be accurately estimated.
This chapter described dSPACE physics experiment control platform the build and development process in detail. Through the dSPACE real-time control platform, the nonlinear high order sliding mode control theory research is applied to the control of permanent magnet synchronous motor. The experimental results and simulation results are consistently indicate that synchronous motor has better dynamic performance and steady accuracy, proves the feasibility of this technology in practical application systems; It is also verified by high order sliding mode control technique that preserves the robustness of traditional sliding mode control. The high order sliding mode essentially eliminates the chattering caused by discrete control law. From another point of view, the simulation and physical experiment provide a certain reference value for the nonlinear systems high order sliding mode control further application.

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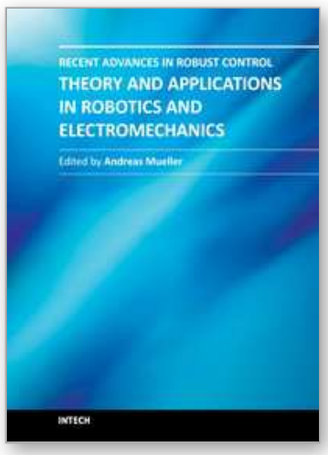
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Robust control has been a topic of active research in the last three decades culminating in H_2/H_\infty and \mu design methods followed by research on parametric robustness, initially motivated by Kharitonov's theorem, the extension to non-linear time delay systems, and other more recent methods. The two volumes of Recent Advances in Robust Control give a selective overview of recent theoretical developments and present selected application examples. The volumes comprise 39 contributions covering various theoretical aspects as well as different application areas. The first volume covers selected problems in the theory of robust control and its application to robotic and electromechanical systems. The second volume is dedicated to special topics in robust control and problem specific solutions. Recent Advances in Robust Control will be a valuable reference for those interested in the recent theoretical advances and for researchers working in the broad field of robotics and mechatronics.

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