A sliding mode and synergetic control approaches applied to Permanent Magnet Synchronous Motor

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Abstract. This paper presents a novel nonlinear speed control for a permanent magnet synchronous motor (PMSM) using the synergetic approach to control theory (SACT) and sliding mode control (SMC). The traditional proportion integral derivative (PID) control is widely used in the permanent magnet synchronous motor (PMSM) speed control system because of its simple control method, but it is difficult to meet the high precision control requirements. Recent research has reported that the PMSM is being increasingly used in high-performance applications, such as robots and industrial machines, which require speed controllers that provide not only accuracy and high performance, but also flexibility and efficiency in the design process and implementation. It has also been reported that the best approach to achieve high-performance in a PMSM drive is to consider the whole nonlinear motor dynamics in the controller synthesis. Many control schemes using varied nonlinear strategies have been presented; however, most of them are very complex to design and implement, even when they show good performance. We propose a nonlinear control scheme based on the SMC-SACT, which allows the designer to generate the required control laws by following a direct method. This paper proposes a new motor speed control approach based on methods of synergetic control theory, which combines the traditional speed closed-loop control and synergetic control. Then, an sliding-mode disturbance observer is proposed to estimate lumped uncertainties directly, to compensate strong disturbances and achieve high servo precisions. Simulation and experimental results both show the validity of the proposed control approach.

1. Introduction

Technological advances in the electrical drives field have allowed the research and the industrial sector to set very demanding requirements concerning drive performance and efficiency [2]. Among AC drives, the permanent magnet synchronous motor (PMSM) drives have demonstrated desirable features in a wide range of applications. A considerable amount of research has been devoted to investigate both linear and nonlinear control strategies that can provide efficiency, accuracy and robustness to motor drives. For high-performance and precise speed control of a PMSM, linear control and linearization techniques have shown limitations while nonlinear control strategies have been demonstrated to be suitable solutions to deal with the PMSM’s nonlinearities. In a PMSM, the nonlinear coupling between the stator winding currents and the rotor speed is the main nonlinearity that needs to be addressed [3], [4], [5].

In the permanent-magnet synchronous motor (PMSM) control system, the classical proportional integral (PI) control technique is still popular due to its simple implementation [14]. However, in a practical PMSM system, there are large quantities of the disturbances and uncertainties, which may
come internally or externally, e.g., unmodeled dynamics, parameter variation, friction force, and load disturbances. It will be very difficult to limit these disturbances rapidly if adopting linear control methods like PI control algorithm. Therefore, many nonlinear control methods have been adopted to improve the control performances in systems with different disturbances and uncertainties, e.g., sliding-mode control (SMC) [12], robust control [13],[14],[16], backstepping control [16], adaptive control [19], intelligent control [18], [20], predictive control [21], and so on. In these nonlinear control methods, SMC method is well known for its invariant properties to certain internal parameter variations and external disturbances, which can guarantee perfect tracking performance despite parameters or model uncertainties.

In order to realize the efficient control of PMSM drive system and the robustness of the system, this paper focuses on the PMSM system architecture and core control algorithm based on sliding mode control and synergetic approach control. The system uses double closed-loop control, the speed loop is controlled by a new algorithm, real-time observation of the internal non-linear factors and external disturbances caused by "internal and external disturbance"; current loop using PI control, control The motor stator current converges rapidly to steady state, which is designed to improve the system dynamics, static control performance and robustness to load disturbance [6].

2. Mathematical Model Of Permanent Magnet Synchronous Motor
In order to simplify the analysis, we establish permanent magnet synchronous motor mathematical model as the following treatment. Assuming that the rotor permanent magnetic field is distributed in the air gap space as a sine wave[7]. Under the above assumption, the mathematical model of the permanent magnet synchronous motor based on the dq synchronous system is established. The model system of equations follows:

\[
\begin{bmatrix}
\dot{i}_d \\
\dot{i}_q \\
\dot{\omega}
\end{bmatrix} = \begin{bmatrix}
\frac{R}{L} i_d + \rho \omega i_q \\
\frac{R}{L} i_q - \rho \omega i_d - \frac{\psi_f}{L} \omega \\
\frac{3 \psi_f}{2J} i_q - \frac{T_L}{J} - \frac{B}{J} \frac{\omega}{\omega}
\end{bmatrix} + \begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix} u_d + \begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix} u_q
\]

\( T_r = 1.5 \psi_f i_q \) 

(1)

State variables:
- \( i_d, i_q \) : d- and q-axis stator currents
- \( u_d, u_q \) : d- and q-axis stator voltages
- \( \omega \) : Rotor electrical speed in angular frequency
- \( R \) : Per-phase stator resistance
- \( L \) : Stator inductance
- \( \psi_f \) : Flux due to the rotor magnets
- \( J \) : Moment of Inertia
- \( T_L \) : Load torque
- \( p \) : Number of pole pairs
- \( B \) : Damping coefficient
- \( T_e \) : Electrical magnetic torque

The load torque \( T_L \) can be considered an unknown constant or inaccessible disturbance for the system shown in (2) Its adaptive estimation will be considered in the paper.

The design of the nonlinear controller, which is presented in detail, requires that the PMSM third-order
nonlinear system shown in (1). This variable can be introduced as part of the definition of the function when the third-order system is augmented with a new state variable \( \xi \).

\[
\xi = \omega^* - \omega
\]  

(3)

Augmented variables:
\( \xi \) : The angular speed error.

In this specific application, it is an appropriate and convenient design step.

3. Controller Design

3.1. SACT Design

Introduced in the last decades, synergetic control has rapidly gained acceptance not only by the robust control community but also by the industrial partners, as illustrated by its implementation in power electronics and its industrial application in battery charging [23], [24]. We briefly introduce the basics of synergetic control synthesis for an n-order nonlinear dynamic system described by (4):

\[
\dot{x} = f(x,u,t)
\]

(4)

Where \( x \) is the state vector, \( u \) is the control input vector of dimension \( m \), and \( t \) is time.

The design process of synergetic control algorithm for an n-order nonlinear dynamic system described by the (1) is as follows:

1) Select the macro variables defined in terms of (5). These macro variables can be defined as linear combinations of state variables.

\[
\Psi_s = (x_1, x_2, \ldots, x_n)
\]

(5)

The control will force the system to operate on the manifold:

\[
\Psi_s = 0
\]

(6)

2) Set the dynamic evolution of macro-variables by the following (7):

\[
T \dot{\Psi}_s + \varphi(\Psi_s) = 0
\]

(7)

Where \( \varphi \) is the function of \( \Psi_s \) to be selected, \( T \) is time constant and defines the speed of convergence of macro-variables to manifolds \( \Psi_s = 0 \).

To ensure the stability of (8), the function \( \varphi \) must satisfy following conditions:

\[
T \dot{\Psi}_s + \Psi_s = 0
\]

(8)

\[
\varphi_s(0) = 0, \varphi_s'(\Psi_s)\Psi_s > 0
\]

(9)

It’s obvious that equation (9) will vary with function \( \varphi \) and parameter \( T \).

In this paper, we select the function \( \varphi \) which makes (10) established:

\[
T \dot{\Psi}_s + \Psi_s = 0
\]

(10)

The method described in the previous section requires that we define the same number of variables \( \Psi \) as control channels in the system. The selected variables for our case are shown (11):

\[
\Psi = k_1 \xi + k_2 \int \xi dt
\]

(11)

Where \( k_1, k_2 \) are controller parameter.

Combine (3), (10) and (11), we obtain:

\[
T(-k_1 \omega + k_2 (\omega^* - \omega)) + k_1 \xi + k_2 \int \xi dt = 0
\]

(12)

Solve (10), the control variables are:

\[
i_\theta = \frac{2J}{3p\psi_f} \left( \frac{1}{J} (B \omega + T_e) + \left( \frac{1}{T} + \frac{k_1}{k_2} \right) \xi + \frac{k_2}{Tk_1} \int \xi dt \right)
\]

(13)
3.2. Error Analysis
From (12), it can be written as
\[ T_k \ddot{\xi} + (T_k + k_1)\dddot{\xi} + k_2 \int \ddot{\xi} dt = 0 \]  
(14)

Then it can obtain a second order system model by
\[ T_k \ddot{\xi} + (T_k + k_1)\dddot{\xi} + k_2 \xi = 0 \]  
(15)

To solve \( \xi \), solving differential equation, and then
\[ T_k P^2 + (T_k + k_1)P + k_2 = 0 \]  
(16)

Where \( P \) is differential operator.
\[ P_1 = -\frac{1}{T} \quad P_2 = -\frac{k_2}{k_1} \]  
(17)

Where \( P_1, P_2 \) are the two roots of the equation.
We can obtain the error.
\[ \xi = K_1 e^{-\frac{1}{T}} + K_2 e^{-\frac{k_2}{k_1}} \]  
(18)

Where \( K_1, K_2 \) is constant.
As time increases, the error gradually converges to zero. By the error formula we can see, we can make the system fast and stable by adjusting \( T, k_1, k_2 \). It can make the system fast and stable compared to some traditional PID algorithm.

Once the variables have been defined, the SACT design procedure is merely algebraic; therefore, it is possible to automatize it. We have created a computer-aided control system design automation toolbox to streamline the SACT synthesis process and generate our control laws in an error-free manner.

3.3. Design of Sliding Mode Load Torque
In actual systems, the damping coefficient is generally unknown because the environment changes. Since the load torque cannot be measured directly in practical application, we considered the load torque and friction torque as a whole. It can be expressed as follows:
\[ i_q = \frac{2J}{\psi} \left( \frac{T_{\psi}}{J} + \frac{k_2}{k_1} \right) \xi + k_2 \int \ddot{\xi} dt \]  
(19)

In order to achieve torque estimate, we designed a sliding mode load torque observer. In the sliding mode variable structure, the point and the starting point is usually not much meaning, but the end point has a special meaning[9]. Because the switching surface are the end point in a region of all points, once the movement point approaching the area is "attracted" in the area of movement. At this point, it is said that all the moving points on the switching surface are the end points of the "sliding mode area", referred to as "sliding mode area". The movement of the system in the sliding mode is called "sliding mode motion"[15].
\[ s = \ddot{\xi} = 0 \]  
(20)

If the friction factor \( B \) is ignored, PMSM mathematical model can be simplified as follows:
\[ \begin{align*}
\dot{\omega} &= \frac{3\psi_\ell i_q}{2J} - \frac{T_{\psi}}{J} \\
\dot{T}_{\ell} &= 0
\end{align*} \]  
(21)

Taking electrical angular velocity and load torque as the observation objects. The sliding-mode surface is chosen as \( s = \ddot{\xi} = 0 \). Then, sliding-mode observer is designed as follows:
\[ \begin{align*}
\dot{\omega} &= \frac{3\psi_\ell i_q}{2J} - \frac{1}{J} \dot{T}_{\ell} + U \\
\dot{T}_{\ell} &= gU
\end{align*} \]  
(22)
Where $\hat{\omega}$ is observed value of electrical angular velocity, $\hat{T}_L$ is observed value of load torque estimate, $U = k \text{sgn}(s)$ is sliding-mode control function, $k$ is slip mode gain, $g$ is feedback gain. Then, the error equation can be obtained by subtracting (22) from (20):

$$
\begin{align*}
\dot{e}_1 &= -\frac{1}{J} \dot{e}_2 + U \\
\dot{e}_2 &= gU
\end{align*}
$$

(23)

Where $e_1 = \hat{\omega} - \omega$ is speed estimation error, $e_2 = \hat{T}_L - T_L$ is load estimation error.

From the theory of sliding mode control, the following relations can be obtained, which means that the reaching condition of sliding-mode ($s\dot{s} \leq 0$) can be satisfied.

$$
s\dot{s} = e_1 \dot{e}_1 = e_1 (k \text{sgn}(s) - \frac{1}{J} e_2) \leq 0
$$

(24)

And then:

$$
k \leq \left| -\frac{1}{J} e_2 \right| < 0
$$

(25)

According to the sliding mode area on the movement point must be the termination point of this requirement, when the movement point to reach the slide surface near ($s = \dot{s} = 0$).

$$
\begin{align*}
U &= \frac{1}{J} e_2 \\
\dot{e}_2 &= gU
\end{align*}
$$

(26)

Further, the load torque error equation is obtained:

$$
\dot{e}_2 - \frac{g}{J} e_2 = 0
$$

(27)

From the SACT theory, System stability condition is $-g/J > 0, J > 0$ and then $g < 0$. At the same time, the above load torque error equation can be obtained.

$$
e_2 = \hat{T}_L - T_L = c e_2^g
$$

(28)

Where $c$ is constant, the approach speed is determined by the feedback gain $g$.

As can be seen from the above analysis of the extended sliding mode observer, the model gain $k$ and the feedback gain $g$ of the selection range of reasonable selection parameters. The sliding mode observer is stable and accurate observation of the load torque.

Fig.1. The principle diagram of sliding-mode load torque observer

3.4. Analysis of Chattering Suppression of Load Torque Observer

The chattering phenomenon caused by the sliding mode variable structure control is unavoidable. The strength of the shock affects the performance of the control system directly, so the reasonable suppression of chattering has become the key to sliding mode control.
Considering the effect of buffeting on the load torque observer by the entry, sliding mode is known

\[ U = k \text{sgn} e_i = \frac{P}{J} e_z + Z \]  

(29)

Where \( Z \) is the chattering signal.

Substituting (15) into the second square of (12), we can obtain:

\[ \frac{-J}{gp} \dot{e}_2 + e_z = -\frac{J}{p} Z \]  

(30)

Transfer Function as follows:

\[ \frac{e_z}{nZ} = \frac{1}{Ts + 1} \]  

(31)

Where \( n = -\frac{J}{p} \), \( T = -\frac{J}{(gp)} \).

From the above transfer function, the chattering signal \( Z \) is filtered through a low-pass filter as shown in Figure 2. The chattering signal which is filtered and the actual load torque is added as an observation of the torque. So the output of the observer can be

\[ Z \xrightarrow{n} \frac{1}{Ts + 1} e_z \xrightarrow{T_i} \hat{T}_i \]

Fig. 2. Chattering suppression structure of the load torque Observer

4. Simulation and Analysis of MATLAB

The diagram of control system is shown in Fig.3. The SMC-SACT is adopted to control PMSM speed. In order to improve disturbance rejection ability of control system, proposed sliding-mode load torque observer is used as the input of speed SACT regulator. To examine the control performance of the SMC-SACT for a PMSM, a numerical simulation was carried out by using MATLAB/Simulink.

Fig.3. The diagram of system control

The simulation and experimental parameters of PMSM are shown in table I. The parameters of PMSM are the consistent in simulation and experiment.

| Symbol | Quantity            | Value          |
|--------|---------------------|----------------|
| \( \Phi \) | magnetic flux       | 0.55Wb         |
| \( B \)  | damping coefficient | 0.001N·m·s     |
| \( P \)  | rated power         | 2.2kW          |
\[ J \] equivalent inertia $0.00154 \text{ kg m}^2$
\[ p \] number of pole pairs $2$
\[ R \] stator resistance $3.45 \Omega$
\[ L \] stator inductance $0.012 \text{H}$
\[ U_S \] rated voltage $380 \text{V}$
\[ I_S \] rated current $5.1 \text{A}$

The parameters of core control algorithm are shown in table II. The simulation step is $1e^{-6}$. The parameters of SACT are $k_1$, $k_2$, $T$. The parameters of SMC are $g$, $k$. By changing their values, we can observe the effect of the parameters on the system.

| Parameter | Fig.4 | Fig.5 | Fig.6 | Fig.7 |
|-----------|-------|-------|-------|-------|
| $k_1$     | 1     | 1     | 1     | 1     |
| $k_2$     | 100   | 100   | 20/100/180 | 100 |
| $T$       | 0.005 | 0.005 | 0.005 | 0.01/0.005/0.001 |
| $g$       | -400/-600/800 | -600 | -600 | -600 |
| $k$       | -500 | -500 | -500 | -500 |

Fig.4 shows that fast tracking of load torque can be realized by using different $g$. Due to the presence of the friction torque, it will be more than the given value. In the simulation, speed reference is 450r/min to 750r/min and the load torque is stepped from 0N.m to 2/4/6N.m at 0.1s. Fig.5 shows that the speed response of PMSM control system when load torque is added suddenly. It is clear that the method based the sliding-mode load torque observer has satisfying disturbance suppression ability.

![Fig.4. Estimated load torque of the SMC (simulation).](image-url)
Fig. 5. Speed in the case of load disturbances.

When speed reference is 450r/min to 750r/min and the load torque is 0N.m. Fig.6 shows that the speed response of PMSM control system can be influenced by using different $k_2$. Fig.7 shows that the speed response of PMSM control system can be influenced by using different $T$. Through the above data show that the greater $k_2$ and $T$, the faster the response of the system, but there will be overshoot.

Fig. 6. Speed response under the change of parameter $k_2$

Fig. 7. Speed response under the change of parameter $T$
When speed reference is 450r/min to 750r/min and the load torque is 0N.m. Fig.8 show that SACT has a small static error, fast response, high precision. When the load torque is stepped from 0N.m to 2N.m at 0.1s, Figure 9 shows SACT is more resistant to load disturbance disturbances. The performance indicators of the two control systems are shown in table III. The following performance indicators (including the rise time \( t_r \), overshoot \( \delta \)) and the anti-jamming performance indicators (including the dynamic drop \( \Delta n_{max} \) and recovery time \( t_v \)) are analyzed.

### Table 3 Performance Of Two Control Systems For No-Load Operation

| Performance   | PI       | SACT     |
|---------------|----------|----------|
| \( \delta(\pm2\%) \) | 0.8\%   | 0        |
| \( t_r/s \)      | 0.0048  | 0.0059   |
| \( \Delta n_{max}/r/min \) | 0.9     | 0.6      |
| \( t_v/s(\pm5\%) \) | 0.1     | 0.05     |

**Fig.8. Speed response of two algorithms**

**Fig.9. Speed response of gaining load**
5. Experimental Verification
Relevant experiments have been done in TMS320F2812 digital control board, CPU frequency is 150MHz. ADC sampling frequency is 8MHz. Switching frequency is 2MHz. The experimental bench is shown in Fig.10.

In order to verify dynamic performance of SMC-SACT, Fig.11 has presented the control performance of SACT with the load change of 1Nm under the 750 r/min speed. The experiment is coincided with the simulation results. Fig.12 show the speed response of PMSM control system when load torque is added from 0Nm to 2Nm at t = 0.1s suddenly. Fig.13 shows the on-line experimental estimate of the load torque. Due to the presence of the friction torque of the motor itself, the estimated value of the starting load torque is not zero. After the motor is loaded, the estimate can be quickly and steadily.
Fig. 12. Speed in the case of sudden load increase

Fig. 13. Estimated load torque of the SMC

Fig. 14 has presented the control performance of two algorithms with the load change of 1Nm under the 450 r/min speed. Fig. 15 show the system's anti-load disturbance capability when load torque is added from 0Nm to 2Nm at \( t = 0.1s \) suddenly. The experimental results show that SACT can make the system stabilize faster. The steady state error is small, and the ability of anti-load disturbance is stronger.

Fig. 14. Experimental waveform of speed
6. Conclusion
In this paper, we have developed an approach to the problem of permanent magnet synchronous motor control speed, which allowed us to design SMC-SACT algorithm, while ensuring satisfactory static and dynamic performance and good insensitivity to disturbances acting on the system and the uncertainties on the parameters. Compared to PI, SACT algorithm parameters are easier to adjust the optimal parameters in addition to these performance advantages.

This research work has investigated a novel nonlinear speed control for a permanent magnet synchronous motor (PMSM) using the synergetic approach to control theory (SACT). In this paper, both the design and implementation of the SACT controller for this application have been explained in detail. The SACT requires the creation of macrovariables to define a set of manifolds that form an invariant manifold. We also demonstrate that the nonlinear control laws generated by the SACT procedure are suitable for digital control implementation, due to the simplicity of their online calculation. The satisfactory performance is verified through the comparison of the experimental and simulation results. A sliding mode control algorithm is applied to load torque observer, and the simulation model of the control system is built and the experiment is carried out. The results show that SMC-SACT design has a fast dynamic response, good tracking speed performance and strong ability to overcome the steady state error of the system.

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