



# Position Sensorless Control of Brushless DC Motor Based on Sliding Mode Observer

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**Abstract.** In order to realize the position sensorless control of brushless DC motor, a position sensorless control method of brushless DC motor based on sliding mode observer is proposed. In order to reduce the chattering of the system, a smooth hyperbolic tangent function is introduced. Therefore, the control system can obtain a smooth linear back-EMF estimate without adding a low-pass filter and a phase compensation module, thereby avoiding the phase lag of the back-EMF estimate. The estimated BLDC motor position sensorless back EMF signal corresponds to 3 virtual Hall signals, and 6 discrete commutation signals are directly obtained, thus eliminating the need for fixed phase shift circuit and phase shift angle calculation. Simulations and experiments show that the proposed method can accurately estimate the line back EMF of the position sensorless brushless DC motor, and achieve the research goal of precise control of the position sensorless brushless DC motor.

**Keywords:** Sliding mode observer · DC motor · Sensor

## 1 Introduction

Brushless DC motors have the advantages of simple structure, high reliability, and high power density, and have been widely used in many fields. Brushless DC motors usually use the rotor position sensor to detect the rotor position in real time to achieve commutation. However, the disadvantages of the position sensor limit the application of brushless DC motors. Therefore, in recent years, the position sensorless control of brushless DC motors has become researched. Among the hot spots, the back EMF method is currently the most widely used brushless DC motor sensorless control method. The back EMF method usually detects the opposite EMF or the zero-crossing point of the line back EMF and calculates the ideal commutation point [1].

In this paper, a sensorless control method of Brushless DC motor based on sliding mode observer is proposed. The specific research ideas are as follows:

Firstly, by improving the sign function of the sliding mode observer, the continuous and smooth function of the sensor is obtained, and the data investigation and correction control are carried out to effectively solve the lag caused by the weakening of the observer, which leads to the oscillation of the estimated value up and down.

Secondly, based on the line voltage equation of Brushless DC motor, taking the line back EMF as the expanded state quantity, a new state equation is established.

Then, the sliding mode observer is improved to realize the accurate estimation of line back EMF of Brushless DC motor on the premise of reducing chattering

Finally, the estimated line back EMF signal is corresponding to three virtual Hall signals, so as to establish the commutation logic of Brushless DC motor, realize the double closed-loop control of Brushless DC motor without position sensor, and draw a conclusion through experiments.

## 2 Brushless DC Motor Sensorless Control

### 2.1 Brushless DC Motor Without Position Sensing Information Collection

With the increasing application of high-performance permanent magnet motors, the requirements for its control performance are getting higher and higher. In order to meet the high performance needs of the brushless DC motor speed control system, the closed-loop control link is essential [4]. The traditional method is to install mechanical sensors on the motor shaft, such as resolvers, photoelectric encoders, tachogenerators, etc. These sensors generally can accurately obtain the motor speed and rotor position information in real time, and realize the closed-loop control of the motor. However, the use of mechanical sensors will increase system cost and reduce system reliability, and mechanical sensors are susceptible to environmental factors such as temperature and humidity, which limit the application of motors. Therefore, position sensorless control technology has received more and more attention and research [5]. Therefore, a position sensorless control method of brushless DC motor based on sliding mode observer is proposed. Mechanical sensors are not installed on the shaft of the motor. Instead, the voltage, current and other signals measured in the motor are used to estimate the motor by a certain method. The rotor position and speed information of the rotor, and then realize the closed-loop control of the motor. During the rotation of the brushless DC motor, the permanent magnet excitation field generates induced electromotive force in the stator winding [6]. The method of estimating the spatial position off by means of the induced electromotive force generated in the stator winding by the permanent magnet excitation flux linkage is an estimation method based on the electromagnetic relationship. Among them, the direct calculation method and the estimation method based on the back electromotive force or the stator flux linkage belong to the estimation method based on the basic electromagnetic relationship of the brushless DC motor. For the surface type brushless DC motor, in the three-phase static ABC coordinate system, there are:

$$u_s = R_s i_s + L_s \frac{di_s}{dt} + j\omega_r \psi_f \quad (1)$$

Among them,  $j\omega_r \psi_f$  is the induced electromotive force, and the position  $d$  of the rotor in the shaft system is the axis component of the induced electromotive force  $L_s$ . Using the strategy of separately controlled starting and automatic control operation, we

can get:

$$\begin{aligned}
 e_0 &= j\omega_r \psi_f = j\omega_r \psi_f (u_s \cos \theta_r + j \sin \theta_r) \\
 &= -\omega_r \psi_f u_s \sin \theta_r + j\omega_r \psi_f \cos \theta_r \\
 &= e_\alpha + ju_s e_p
 \end{aligned}
 \tag{2}$$

In the formula,  $\theta_r$  is the electrical angle between the rotor flux vector  $R_s$  and the stator  $i_s$  axis. After the rotor is positioned, a rotating magnetic field is given to the motor stator to start the motor. After starting, the sliding mode observer continuously observes the current and speed of the motor. When the motor starts to its current and voltage meet the predicted calculation, then switch to automatic control mode operation [7]. Using the current following characteristics of the sliding mode observer, the observed current is close to the actual current value. The block diagram of the position sensorless control system is as follows (Fig. 1):

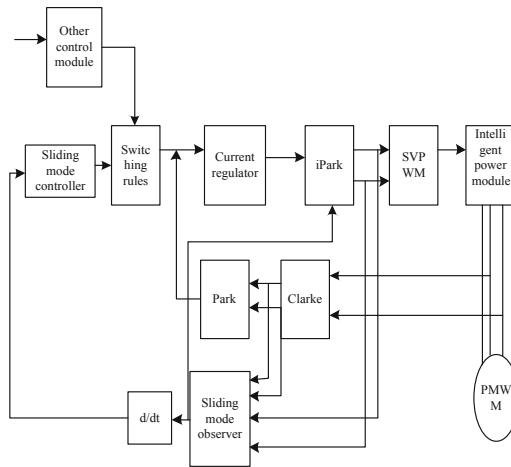


Fig. 1. Block diagram of a position sensorless control system

The control system is mainly composed of sliding mode controller, sliding mode observer, other control modules, switching rules, current regulators, Park converters, Clarke converters, Park inverters, SVPWM modules, smart power modules and brushless DC motors, etc. Link composition [8]. Among them, SCM is used to realize the zero-speed start of the motor. SMO collects the stator voltage and current signals and estimates the rotor position and speed; SMC realizes the smooth transition of the system from the other control mode to the automatic control mode when the output current error of the two control modes approaches zero [9]. The stator voltage equation in the two-phase stationary coordinate system is

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + p \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix}
 \tag{3}$$

Where  $u_\alpha, u_\beta$  is the stator voltage in the  $a\beta$  coordinate system;  $i_\alpha, i_\beta$  is the stator current in the  $a\beta$  coordinate system,  $R_s$  is the stator resistance,  $L$  is the stator inductance, and  $p$  is the differential operator;  $E_\alpha, E_\beta$  is the back electromotive force in the  $a\beta$  coordinate system, And is further described as

$$\begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} E = 4.44N_s k_{N_s} \phi_m \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} f_1 \quad (4)$$

In the formula,  $N_s$  is the number of stator windings in series per phase;  $k_{N_s}$  is the stator fundamental winding coefficient,  $\phi_m$  is the air gap magnetic flux per pole,  $f_1$  is the stator frequency;  $\theta$  is the angle between the back electromotive force and its  $\alpha$  axis component, then:

$$T_{em} = J\dot{\omega}u_\alpha + B_m\omega u_\beta + T_L(E_\alpha - E_\beta) \quad (5)$$

In the formula,  $\dot{\omega}$  and  $J$  are the motor speed and its first derivative respectively;  $\omega$  is the moment of inertia,  $B_m$  is the friction coefficient;  $T_L$  is the load torque, and  $T_{em}$  is the electromagnetic torque. The open-loop estimation method based on the mathematical model is simple in calculation and intuitive, and because it does not use integral links and regulators, it has a fast dynamic response [10]. This open-loop estimation method relies on the mathematical model of the motor. The motor parameters selected in the model are usually the parameters when the motor is working in a steady state, and the motor parameters will be in a dynamic state due to temperature changes, magnetic circuit saturation effects and other factors during operation. Changing. Changes in motor parameters will affect the accuracy of rotor position and speed estimation.

## 2.2 Position Sensorless Adaptive Algorithm for DC Motor

Model reference adaptive system is an effective method of rotor position and speed estimation, which has developed into a mature positionless control. The accuracy of the reference model in the model reference adaptive method directly affects the accuracy of identification. The position accuracy estimated by this method is related to the selection of the model, and it is necessary to ensure that the position deviation can be accurately estimated. After obtaining the position deviation, there must be a reasonable adaptive law to ensure the stability of the system and the robustness to parameter changes while ensuring the convergence speed. This method is computationally intensive and requires a digital signal processor with high-speed computing capabilities. The principle is shown in the figure (Fig. 2).

The essence of the state observer is to reconstruct the state of the control system, use the directly measurable variables in the original system as the input signal of the newly constructed system, and make the output signal of the constructed new system equal to the state of the original system under certain conditions. The reconstructed system is called an observer. The observer-based estimation method has the advantages of good dynamic performance, high stability, and strong parameter robustness. The disadvantage is that the speed regulation effect is not ideal at low speed, and the algorithm is complicated and the calculation amount is large. In recent years, the rapid development of some

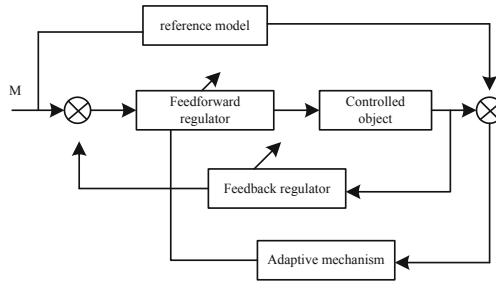


Fig. 2. The principle of position sensorless adaptive DC motor

high-speed signal processors DSP has greatly promoted the application of the observer method in position sensorless control. At present, the commonly used observers include Kalman filter, sliding mode observer and so on. Sliding mode variable structure control means that according to the current state of the system, the structure of the feedback controller changes purposefully and continuously in accordance with the predetermined control law. Through the continuous change of the control system structure, the structure of the system is finally switched back and forth at a very high frequency, and the state point of the system performs a high-frequency up and down movement, that is, sliding mode operation. The advantages of the sliding mode variable structure control system are that it is insensitive to parameter changes, robust to external disturbances, and has fast dynamic response performance. The sliding mode observer method is to design the control loop in the general state observer into a sliding mode variable. The form of the structure makes the sliding mode observer method have parameter robustness that the general state observer does not have. Because in the actual variable structure control system, the switching device always exhibits certain time and space relay characteristics and system inertia, etc., these factors will make the variable structure system exhibit inherent chattering. The existence of jitter makes the steady-state accuracy of the control system poor, so debounce is the key problem to be solved by the sliding mode observer method. The mathematical model of the brushless DC motor in the three-phase static ABC coordinate system is a set of variable coefficient differential equations, which are more complicated. In order to simplify the mathematical model of the permanent magnet motor, a two-phase stationary a coordinate system and a two-phase rotating L coordinate system are introduced. Transform each physical quantity from the three-phase coordinate system to the two-phase static voltage equation:

$$\begin{cases} \frac{di_\alpha}{dt} = -R_i \frac{i_\alpha}{L_c} - \frac{e_\alpha}{L_c} + \frac{u_\alpha}{L_c} \\ \frac{di_\beta}{dt} = -R_s \frac{i_\beta}{L_s} - \frac{e_\beta}{L_s} + \frac{u_\beta}{L_s} \end{cases} \quad (6)$$

The standard current of the dynamic equivalent circuit of the brushless DC motor in the two-phase rotating coordinate system is Z. When the motor is at a standstill, the voltage equation can be simplified to:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_i} & 0 \\ 0 & \frac{1}{Z_q} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} \quad (7)$$

The back EMF equation is:

$$\begin{cases} e_\alpha = -\psi_f \omega_x i_d \sin \theta \\ e_\beta = \psi_f \omega_r i_q \cos \theta \end{cases} \quad (8)$$

The voltage equation of the brushless DC motor in the coordinate system is:

$$\begin{cases} u_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \\ u_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d \end{cases} \quad (9)$$

As the brushless DC motor speed control system is widely used in some high-precision fields, the requirements for the performance of the control system and the speed control system are getting higher and higher. By detecting the three-phase current and obtaining the alternating and direct axis currents after coordinate transformation, the current inner loop is formed; the feedback speed  $n$  is detected by the position sensor, and the outer speed loop is formed. The parameters of the surface-mount brushless DC motor are shown in Table 1.

**Table 1.** Self-adaptive parameters of brushless DC motor

Parameter	Numerical value	Company	Parameter	Numerical value	Company
Rated voltage $U_N$	310	v	Resistance per phase $R_S$	1.5	$\Omega$
Rated power $P_N$	0.8	kW	d-axis inductance $L_d$	1.48	mH
Rated speed $n_N$	3000	rpm	q-axis inductance $L_q$	1.48	mH
Rated torque $T_N$	2.6	N.m	Line number of optical encoder	2500	p/r
Rated current $I_N$	4.2	A	Flux per pole $\Phi$	$1.779 \times 10^{-3}$	Wb
Mechanical moment of inertia J	$1.03 \times 10^{-4}$	Kg.m <sup>2</sup>	Polar logarithm $P_n$	2	

The basic requirements of the brushless DC motor control system can be summarized as the system's wide speed range, simple control, and high reliability. Torque control has fast response, high precision, small waveform, etc. From the motion equation of the motor, it can be seen that the control of the brushless DC motor is the control of the electromagnetic torque, and the control of the speed and position can be achieved through the control of the electromagnetic torque of the motor. The torque equation of the brushless DC motor can be transformed into:

$$\begin{aligned} T_e &= p_n (\psi_d i_q - \psi_q i_d) \\ &= p_n \psi_f i_q + p_n (L_d - L_q) i_d i_q \end{aligned} \quad (10)$$

The speed and current double closed-loop control structure and  $p_n$  current control strategy are adopted. The control system mainly includes: speed setting  $i_d, i_q$  speed loop PI regulator, current loop PI regulator, Park/Clarke inverse transformation, SPWM modulation, three-phase inverter, surface-mount brushless DC motor, current sensor, Clarke transformation, Park transformation and a position sensor for detecting the position and speed of the rotor.

### 2.3 Realization of Sensor Control of Brushless DC Motor

The brushless DC motor system adopts a vector control scheme based on physical sensors, and the rotor information fed back in the system is directly measured by the position sensor. At the same time, a new sliding mode observation algorithm is attached to the brushless DC motor, and the adaptive detection method of the rotor position of the brushless DC motor system has different effects at low speed and high speed. The rotor position estimation method suitable for low speed and the rotor position estimation method suitable for high speed have different mechanisms for estimating the rotor position. The rotor position estimation method suitable for low speed is to obtain the rotor position information by detecting the salient poles of the motor, applying different excitation methods and different signal detection and separation methods. The rotor position estimation method suitable for high-speed uses the back EMF of the motor to obtain the rotor position information. The sliding mode observers and full-dimensional and reduced-dimensional observers mentioned above are all suitable for high-speed rotor information detection methods. Therefore, in order to improve the performance of the brushless DC motor system at startup, an open-loop/closed-loop switching module is designed. The principle of open-loop/closed-loop switching module is introduced below. The figure below is the block diagram of the open-loop/closed-loop switching module (Fig. 3).

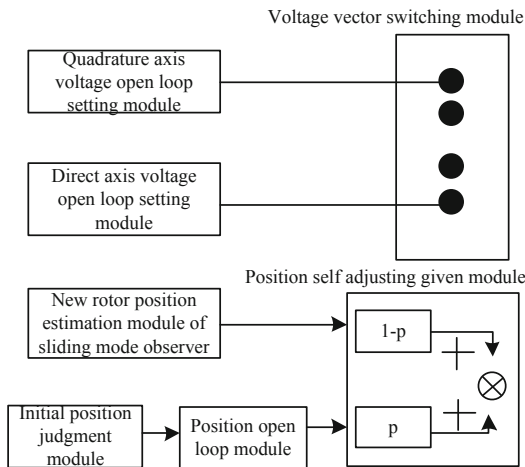


Fig. 3. Block diagram of the open-loop and closed-loop switching control module

Combining the above analysis, in a complete chopping excitation interval, the winding has gone through three stages: current establishment, current chopping, and freewheeling shutdown. When the winding chopper is turned on, the power supply voltage  $U_{dc}$ . For forward access, the winding voltage balance equation is shown in the formula.

$$+U_{dc} = Ri + T_e L(\theta) \frac{di}{dt} + T_e i \omega \frac{dL(\theta)}{d\theta} \quad (11)$$

There are two types of winding chopper shut-off: zero voltage freewheeling and negative pressure freewheeling. The input voltages are 0 and  $U_{dc}$  respectively. The winding voltage balance equations in the zero voltage and negative pressure freewheeling states are as shown in formulas (12) and (13). Shown:

$$0 = Rj + L(\theta) \frac{di}{dt} + i\omega \frac{dL(\theta)}{d\theta} \quad (12)$$

$$-U_{dc} = Ri + L(\theta) \frac{di}{dt} + i\omega \frac{dL(\theta)}{d\theta} \quad (13)$$

From the theoretical analysis of sliding mode variable structure control, the sliding mode can be designed according to the actual expected control performance. In addition, due to the characteristics of the continuous change of the control system structure during the control process, the variable structure control system can maintain the original control performance under the influence of the internal parameter changes of the system and the disturbance of the external environment, and has good robustness. However, from the perspective of the entire control process, the control quantity  $u$  of sliding mode variable structure control is constantly switched, which is a discontinuous function of the state quantity. This control method is a discontinuous control method. In addition, because the actual switching device always has time relay characteristics and space relay characteristics, as well as the influence of factors such as system inertia, state measurement errors, etc., in the actual sliding mode variable structure control, the sliding mode motion is not like theoretical The above is generated on the pre-designed sliding mold surface, but a kind of back and forth traversal near the sliding mold surface, resulting in high-frequency vibration. This phenomenon is the chattering of the sliding mode control system.

The existence of chattering will have an adverse effect on the control system: on the one hand, it will affect the control accuracy of the control system and increase the energy consumption of the system. On the other hand, it can also cause unmodeled high-frequency motion components in the system and cause high frequency in the system oscillation. In the actual current chopping control, in order to make the torque output more smooth and stable, the width of the chopping loop is usually set to be small, and the current change between each chopping on and chopping off cell is small, and the chopping state The duration is short and the rotor displacement angle is not significant. Therefore, it can be approximately considered that the phase current and phase inductance remain unchanged in each chopping on and off interval, which is reflected in the formula, that is, the adjacent chopping on and off on the right side of the equation The voltage drop of the winding of the first term and the electromotive force of the third term are equal in the process of chopping off.

The current position sensorless control system of brushless DC motors is a vector control system. When the motor speed is within the low speed range of zero speed or nearby, it is impossible to avoid the control dead zone and observing the dead zone. At this time, the speed loop in the vector control system is in an open loop state. Therefore, it is necessary to adopt other control methods to realize the zero-speed start or stop of the motor without changing the structure of the vector control system. In order to ensure the smooth start or stop of the motor, it is necessary to ensure that the amplitude of the stator circular rotating magnetic field generated by the system and the The phase can increase or decrease steadily. The change law of the voltage space vector during the starting process is given (Fig. 4):

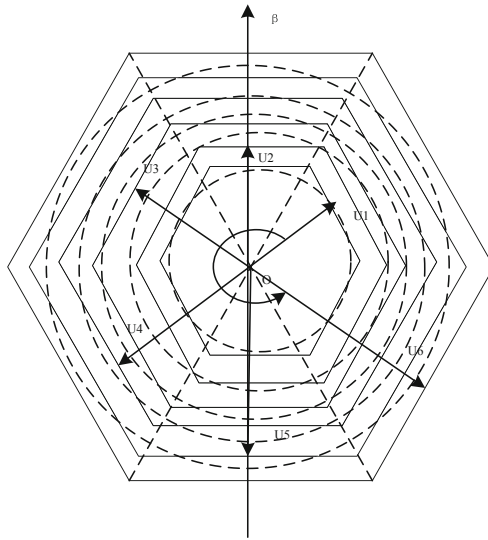


Fig. 4. Variation law of stator voltage space vector

In the figure, the  $\alpha$  axis and  $\beta$  axis respectively represent the components of the voltage space vector in the stationary two-phase  $\alpha, \beta$  coordinate system; the dotted circles nested in each other are the state trajectories produced by the voltage space vector rotating one circle when the amplitude is constant;  $U$  is For the six voltage space vectors that increase in the order of counterclockwise rotation, with the increase of the vector amplitude, the motor speed will increase accordingly, so as to realize the smooth start of the motor. In the separate control mode, the electromagnetic torque is easily affected by various disturbances of the power grid, load and the motor itself, which causes the rotor speed and the synchronous speed of the stator rotating magnetic field to be inconsistent, that is, the motor is out of step. Torque is easily affected by various disturbances of the power grid, load and the motor itself, which causes the rotor speed to be inconsistent with the synchronous speed of the stator rotating magnetic field, that is, the motor loses

synchronization.

$$\begin{cases} T_{cm} = \frac{uE}{|Z|\omega} \sin(\delta + \alpha_Z) - \frac{E^2 R_s}{|Z|^2 \omega} \\ Z = -U_{dc} R_s + j\omega L \\ \alpha_Z = 90^\circ - \phi_Z = 90^\circ - \arctan\left(\frac{\omega L}{R_s}\right) \\ \omega = 2\pi f + U_{dcl} \end{cases} \quad (14)$$

In the above algorithm, E is the control interference coefficient, in order to shorten or even eliminate the approaching motion process in sliding mode control, make the system speed as low as possible when switching from the other control mode to the automatic control mode, and strengthen the robustness of the entire speed regulation process. Awesome.

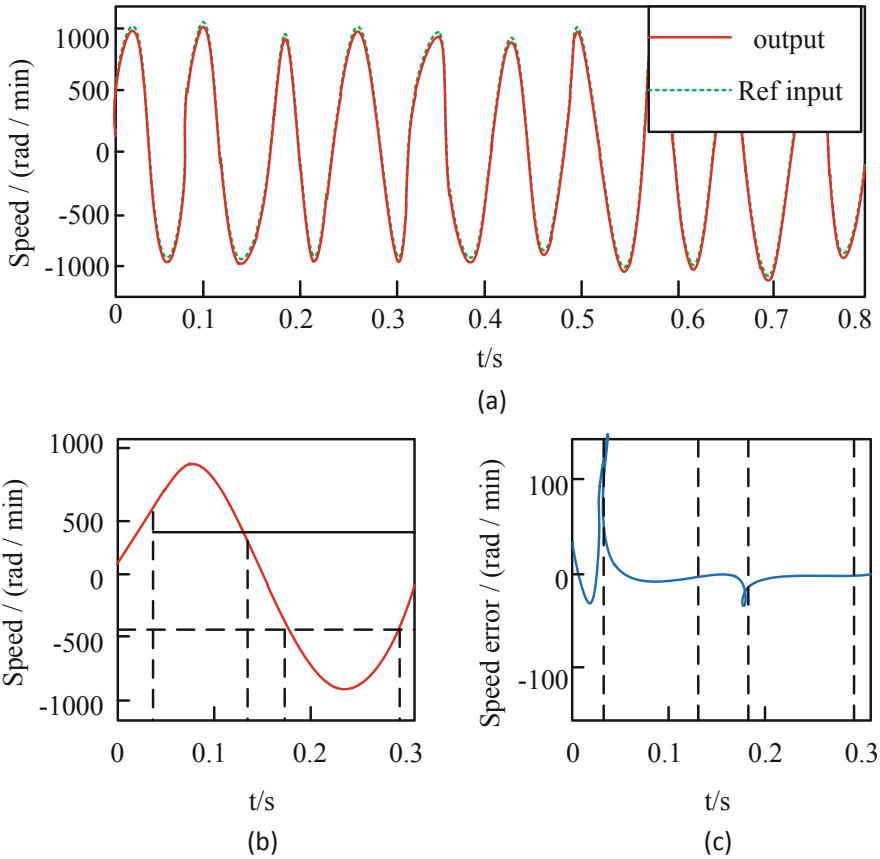
### 3 Analysis of Results

In order to verify the effectiveness of the method proposed in this paper, a simulation model is established using Matlab/Simulink, and the traditional sliding mode observer is compared with the improved sliding mode observer proposed in this paper. The motor parameters in the simulation are shown in the table (Table 2):

**Table 2.** Brushless DC motor parameters

Parameter	Numerical value	Parameter	Numerical value
Rated power P/W	70	Stator resistance R/ $\Omega$	0.3
Rated voltage $U_N$ /V	24	Stator inductance $L_l$ /mH	0.45
Rated torque $T_N$ /(N · m)	0.23	Rated speed $n_t$ /(r/min)	3000
Rated current $I_N$ /A	4	Polar logarithm p	5

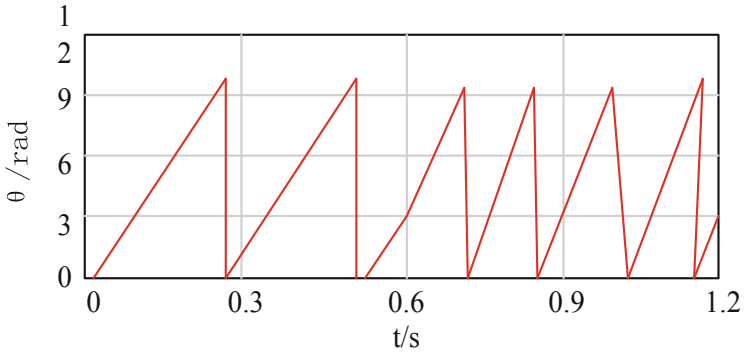
On the basis of applying the variable voltage and frequency conversion control strategy to the brushless DC motor control start, the SMO is added to predict the rotor position and the motor speed, and the position sensorless control system of the brushless DC motor is completed in real time according to the prediction results Switching of automatic control mode. In order to verify the system response characteristics of the algorithm proposed in this paper when the motor is located near zero speed and the control mode is switched, the system simulation results with the superposition of ramp and sine wave signals as input are given. The simulation uses Matlab as a tool, and the speed output response and following error with the superposition of ramp and sine wave signal as input are shown in the figure (Fig. 5):



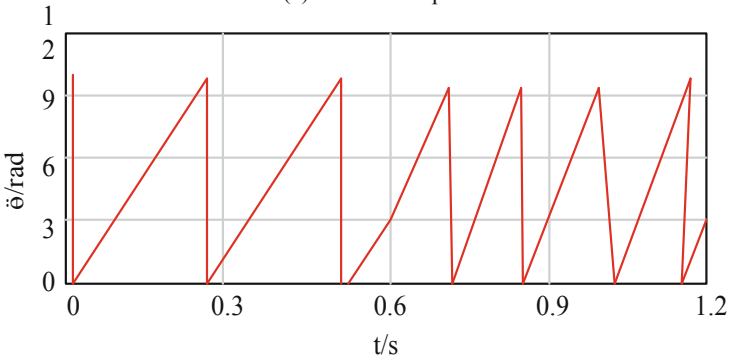
**Fig. 5.** Sensor control speed output response and following error curve

nges step by step is given. In the simulation, the brushless DC motor set speed is switched from 30 r/min to 50 r/min at 0.4 s, and the load torque is 100 Nm. Among them, Figure a is the actual rotor position waveform, Figure b is the estimated rotor position, Figure c is a partial enlarged view of the actual and estimated rotor position in 0.4 s (Fig. 6).

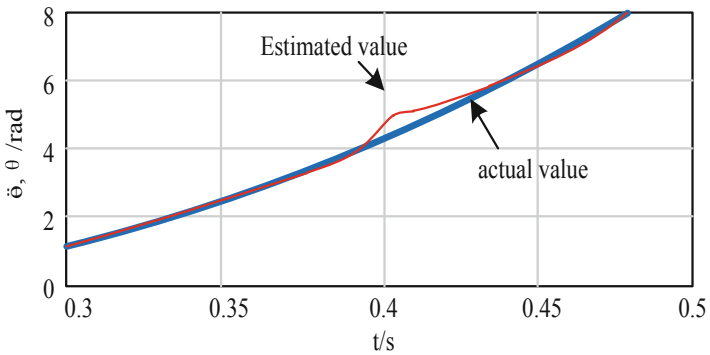
The above simulation results show that the two main problems of traditional sensor control are: when the motor starts, the rotor position estimation error is large; the rotor position estimation value and the back EMF estimation value have large chattering and have a certain hysteresis. Chattering is an inherent problem of sliding mode observers. The discontinuity of sliding mode variable structure control makes the estimated value chatter larger. The hysteresis of position estimation is caused by the phase delay caused by the first-order low-pass filtering. The control method in this article has solved the above problems to a great extent, can better guarantee the safety of countless DC motors, solve the control dead zone problem under the position sensorless control mode, and better realize the control mode from the other control mode to the automatic control mode. The smooth transition of the system fully meets the research requirements.



(a) Actual rotor position



(b) Estimating rotor position



(c) Compared with the estimated rotor position, the actual rotor position is partially enlarged at 0.4s

**Fig. 6.** Waveform when the sensor control speed step changes

In order to verify the effectiveness of this method, the sensorless control time of reference [3] method and this method is adopted, and the results are shown in Table 3.

**Table 3.** Control time without position sensor under different methods

Number of iterations	Sensorless control time/s	
	Literature [3] methods	Paper method
10	15	0.1
20	18	0.2
30	22	0.5
40	24	0.3

It can be seen from Table 3 that the control time without position sensor is different under different methods. When the number of iterations is 10, the sensorless control time of the method in document [3] is 15 s, and the sensorless control time of the text method is 0.1 s. When the number of iterations is 30, the sensorless control time of the method in document [3] is 22 s, The sensorless control time of the text method is 0.5 s. The sensorless control time of this method is much lower than that of other methods, which shows that the control efficiency of this method is high.

## 4 Concluding Remarks

A sensorless control method of Brushless DC motor based on sliding mode observer is proposed in this paper. The variable voltage variable frequency control strategy is used for other control starting. Combined with the prediction function of sliding mode observer for rotor angle and speed, according to the principle of current following and speed following, the time-varying sliding mode controller is used to switch the control system from other control mode to automatic control mode. Simulation and experiments show that the control strategy proposed in this paper has good application value and achieves high comprehensive control performance.

In the future, we will study how to obtain more accurate sensor control accuracy.

**Fund Projects.** Research on Sensorless Control of Brushless DC motor based on sliding mode observer (YZK2015045).

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