Research on Variable Structure Intelligent Control of Permanent Magnet Synchronous Servo Motor Based on Sensor

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Abstract: Permanent magnet synchronous servo motor(PMSSM) is a kind of motor with excellent performance and wide application prospect. With the rapid development of modern power electronics technology, microelectronics technology and modern control theory, permanent magnet synchronous motors are increasingly applied to various control occasions. In the past motor control systems, sensors are usually used to directly measure parameters such as motor speed. However, the increase of sensors not only increases the cost of the motor, the complexity of the control system and the inconvenience of installation in special environment, but also reduces the reliability of the system. Firstly, an integral sliding surface is proposed based on the mathematical model of permanent magnet synchronous servo motor. Then, an appropriate control law is chosen to solve the problem of high frequency chattering in sliding control. Finally, a load observer is designed to obtain the unknown load torque in the control law. The simulation results show that the control strategy of permanent magnet synchronous servo motor based on sliding mode variable structure has high control precision and good operation performance.

1. Introduction

Before 1960s, the hydraulic motor driven by stepping motor or the direct drive of power stepping motor was the center, and the position control of the system was mostly open loop system. This period was the heyday of the hydraulic system [1]. With the passage of time, a large number of various types of motors have emerged, and their status in the national economy, work and life, and aerospace has become more and more prominent. In recent years, scholars at home and abroad have made more and more researches on the servo control system of permanent magnet synchronous servo motor, among which sliding mode variable structure control scheme has been paid close attention by experts and scholars at home and abroad. In order to overcome the defects brought by mechanical sensors to the motor system, research and development of a control method without position and speed sensors with low cost, good reliability and simple maintenance has become one of the research hotspots in the field of motor control technology. This control method is called sensorless control technology. Document [2] proposes a complementary sliding mode variable structure control method, establishes a linear servo motor control system model, combines a complementary sliding mode surface with a generalized sliding mode surface, and designs a complementary sliding mode variable structure controller. Document [3] applies exponential reaching law to sliding mode variable structure controller, and obtains the incremental expression and position expression of sliding mode controller. In this paper, a linear observer for system uncertainty is designed and supplemented by a dynamic neural network to compensate for its uncertainty. An on-line neural network parameter regulator is also designed to ensure higher observation comprehensiveness and lower chattering degree. The actual operation results of PMSSM show the effectiveness and practicability of the method.

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2. System Description

2.1 Mathematical Model of Pmssm

PMSSM has the advantages of small ripple coefficient of electromagnetic torque, fast dynamic response, stable operation, strong overload capability, etc. it is very suitable for use under the condition of large load torque variation. As shown in fig. 1, the stator of the permanent magnet synchronous servo motor has three-phase windings a, b and c, the rotor is permanent magnet, a, b and c are respectively connected with the axes of the three-phase windings, and θ_r is the rotor position angle. In the establishment of the mathematical model, the input current is taken as positive. Each group of coils will generate positive flux linkage when passing forward current. The electromagnetic coupling relationship between stator and rotor parameters is very complex, which makes it impossible to accurately analyze the variation law of stator and rotor parameters of synchronous motor, thus bringing many difficulties to the analysis and control of PMSSM. In order to simplify the analysis of PMSSM, a realistic and feasible mathematical model of synchronous motor is established [4].

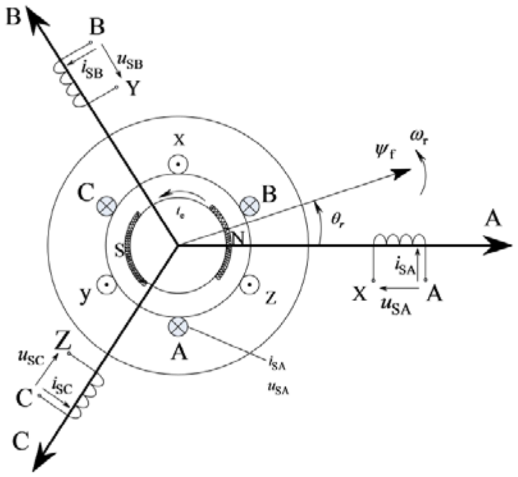

Fig.1 Pmssm Physical Model

Compared with common synchronous machines, PMSSM stator structure has little difference and consists of three-phase armature windings and iron cores, and the three-phase armature windings are usually connected in star shape. The rotor of PMSSM uses permanent magnets, eliminating excitation windings, slip rings and brushes, and the motor structure is relatively simple.

According to the above analytical model of PMSSM, the voltage equation of PMSSM in three-phase stationary coordinate systems a, b and c is [5]:

$$\begin{cases} u_A = R_{iA} + P\psi_A \\ u_B = R_{iB} + P\psi_B \\ u_C = R_{iC} + P\psi_C \end{cases} \quad (1)$$

Where r is the stator winding resistance; P is a differential operator, p = d/dt; ψ_A, ψ_B, ψ_C is the flux linkage of the three-phase winding chain.

The flux linkage in A, B and C three-phase coordinate system is the sum of its self-inductance flux linkage and the mutual inductance flux linkage of other windings to it, as well as the flux linkage generated by the permanent magnet exciting magnetic field chain passing through A, B and C windings. The flux linkage equation is:

$$\begin{cases} \psi_A = L_A i_A + M_{AB} i_B + M_{AC} i_C + \psi_f \cos\theta \\ \psi_B = M_B i_A + L_B i_B + M_{BC} i_C + \psi_f \cos(\theta - 2\pi/3) \\ \psi_C = M_{CA} i_A + M_{CB} i_B + L_C i_C + \psi_f \cos\theta(\theta + 2\pi/3) \end{cases} \quad (2)$$

Where L_A , L_B , L_C is the stator winding self-inductance; M_{AB} , M_{BC} , M_{CA} is mutual inductance between stator windings; ψ_f is the excitation flux linkage of the rotor permanent magnet pole; θ is the electrical angle between the axis of the phase A winding and the axis of the fundamental magnetic field of the permanent magnet.

The embedded rotor structure can make full use of the reluctance torque generated by the asymmetry of rotor magnetic flux, improve the power density of the motor, improve the dynamic performance of the motor compared with the surface type, and make the manufacturing process simpler. Since the stator three-phase windings are 120 each other, the mutual inductance between each phase is symmetrical, and the air gap of the motor is uniform, the self-inductance and mutual inductance of A, B and C windings are constant regardless of the rotor position. So there are:

$$\begin{cases} L = L_A = L_B = L_C \\ L_1 = M_{AB} = M_{BA} = M_{AC} = M_{CA} = M_{BC} = M \end{cases} \quad (3)$$

In this system, the stator windings of the three-phase permanent magnet synchronous servo motor are connected in a star shape, and the three-phase stator current meets Kirchhoff's current law at the neutral point of the armature winding, i.e. the sum of the three-phase currents equals zero, so the zero sequence component of the stator current equals zero. Since PMSSM is star connection, the three-phase current should meet $i_A + i_B + i_C = 0$, and substituting equation (3) into equation (2) gives the flux linkage equation [6]:

$$\begin{cases} \psi_A = (L - L_{L_1}) i_A + \psi_f \cos\theta = L_0 i_A + \psi_f \cos\theta \\ \psi_B = (L - L_{L_1}) i_B + \psi_f \cos(\theta - 2\pi/3) = L_0 i_B + \psi_f \cos(\theta - 2\pi/3) \\ \psi_C = (L - L_{L_1}) i_C + \psi_f \cos(\theta - 2\pi/3) = L_0 i_C + \psi_f \cos(\theta - 2\pi/3) \end{cases} \quad (4)$$

Substituting equation (4) into equation (1) to obtain the stator voltage equation is:

$$\begin{cases} u_A = R i_A + L_0 P i_A - \psi_f \omega \sin\theta \\ u_B = R i_B + L_0 P i_B - \psi_f \omega \sin(\theta - 2\pi/3) \\ u_C = R i_C + L_0 P i_C - \psi_f \omega \sin(\theta + 2\pi/3) \end{cases} \quad (5)$$

The flux linkage equation (4) and voltage equation (5) of PMSSM in a, b and c three-phase coordinate systems are a set of differential equations with variable coefficients. the coefficients of the differential equations vary with the relative positions of the stator and rotor and are a function of time. Therefore, synchronous motor is a nonlinear, time-varying and multivariable system. Considering that the D axis can coincide with the excitation component of the stator current and the Q axis coincides with the torque component of the stator current in the two-phase rotating coordinate system, decoupling control of the motor torque and excitation can be realized in the dq coordinate system, so that the speed regulation strategy of the AC motor is similar to that of the DC motor, and the speed regulation performance of the AC motor is greatly improved.

2.2 Foc Coordinate Transformation

The mathematical model of permanent magnet synchronous servo motor in α, β coordinate system can be obtained in dq coordinate system through Park transformation. the direction of permanent magnet flux linkage of permanent magnet synchronous servo motor is set as d axis (straight axis) and the direction 90 degrees ahead of d axis is q axis (cross axis). then the two-phase stationary coordinate systems α, β are transformed into two-phase rotating coordinate systems d, q rotating with ω, namely Park transformation, and the control mode of DC motor is obtained in this rotating coordinate system. Commonly used is rotor dq0 coordinate system. Since the electrical parameters of permanent magnet synchronous servo motor are closely related to the rotor position angle, the coordinate system must be established in dq0 coordinate system in order to simplify the mathematical model and decouple the rotor position angle.

Permanent magnets are installed on the rotor, and the stator and the rotor have electromagnetic coupling relationship through the air gap magnetic field. Due to the relative motion between the stator and the rotor, the electromagnetic coupling relationship is very complicated, which brings difficulties to the analysis and control of the motor. The mathematical expression of PMSSM vector coordinate transformation is commonly expressed as [7]:

$$\begin{cases} u = C_u u^{'} \\ i = C_i i^{'} \end{cases} \quad (6)$$

In the formula, u and i are the voltage and current in the coordinate system of A, B and C; $u^{'}$ and $i^{'}$ are the voltage and current in the coordinate system of α, β , 0 or d and q; C_u and C_i are transformations matrix.

Stator flux linkage of PMSSM is generated by stator three-phase winding current and rotor permanent magnet. flux linkage generated by stator three-phase winding current is related to rotor position angle. flux linkage generated by rotor permanent magnet is also related to rotor position. rotor permanent magnet generates back potential in each phase winding. When carrying out PMSSM coordinate transformation, the principle of unchanged motor power before and after transformation [8] shall be observed. Set

$$u = [u_1, u_2, \cdots, u_n]^T \qquad i = [i_1, i_2, \cdots, i_n]^T \quad (7)$$

$$u^{'} = [u^{'}_1, u^{'}_2, \cdots, u^{'}_n]^T \qquad i^{'} = [i^{'}_1, i^{'}_2, \cdots, i^{'}_n]^T \quad (8)$$

After Clarke transformation, the coefficient matrices of stator flux linkage equation and voltage equation are still related to rotor position angle θ_e, which is troublesome to analyze and calculate, and further decoupling of rotor position angle is needed. Since the power is unchanged before and after the conversion, then,

$$\begin{cases} P = u_1 i_1 + u_2 i_2 + \cdots + u_n i_n = u^T i \\ P^{'} = u_1^{'} i_1^{'} + u_2^{'} i_2^{'} + \cdots + u_n^{'} i_n^{'} = u^{'T} i^{'} \\ P = P^{'} \end{cases} \quad (9)$$

Substituting equation (6) into equation (9) yields:

$$u^T i = (C_u u^{'})^T C_i i^{'} = u^{'T} C_u^T C_i i^{'} = u^T i^{'} \quad (10)$$

So,

$$C_u^T C_i = E \quad (11)$$

When $C_u = C_1 = C$ is selected,

$$C^T = C^{-1} \quad (12)$$

It can be seen that the angle decoupling of the three-phase permanent magnet synchronous servo motor can be realized only when the rotor dq0 coordinate system is established. It is concluded that under the condition of constant power before and after transformation and the same transformation matrix for voltage and current, the inversion of the transformation matrix is equal to its transposition, and such coordinate transformation belongs to orthogonal transformation.

Clarke transformation is shown in Figure 2. Clarke transformation is the transformation from three-phase stationary coordinate systems A, B and C to two-phase stationary rectangular coordinate systems α and β, abbreviated as 3s/2s transformation, i.e. a symmetrical two-phase alternating current motor replaces a symmetrical three-phase alternating current motor, wherein symmetry is specified, and each winding of the rotor has the same number of turns and distribution with the same resistance. However, the sampling period of the system may only be 0.0001 seconds. When the control algorithm is discretized and the microprocessor is used for calculation, if the actual values of these quantities are directly substituted into the calculation, the processing is very difficult, and overflow of the calculation results is easy to occur, resulting in large calculation errors [9]. Therefore, the vector control strategy is adopted to realize the variable frequency speed regulation of permanent magnet synchronous servo motor, and only the outer speed ring and the inner current ring need to be designed. Vector control can be attributed to the distribution control of stator current D-axis and Q-axis components. Different distribution control results in different load carrying capacity, efficiency and power factor of the motor.

Assuming that the magnetomotive force waveform is distributed sinusoidally, when the three-phase total magnetomotive force is equal to the two-phase total magnetomotive force, the projection of the three-phase winding magnetomotive force on the α and β axes should be equal to the projection of the two-phase winding magnetomotive force on the α and β axes, and the product of the magnetomotive force and the effective number of turns of each phase is proportional to the current, so it can be obtained:

$$\begin{cases} N_2 i_\alpha = N_3 i_A - N_3 i_B \cos 60^\circ - N_3 i_C \cos 60^\circ \\ N_2 i_\beta = N_3 i_B \cos 30^\circ - N_3 i_C \cos 30^\circ \end{cases} \tag{13}$$

Transformed:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{N_3}{N_2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{14}$$

Where N_3 and N_2 respectively represent the effective turns of each phase winding of the stator of the three-phase motor and the two-phase motor.

Because in the two-phase stationary coordinate system, its space vector rotates at synchronous speed in space, and the two-phase voltage changes all the time, PMSSM cannot be analyzed like DC motor. Therefore, it is necessary to transform each physical quantity from the static coordinate system to the synchronous rotating coordinate system by means of coordinate transformation. The research shows that the two conditions are equivalent. Maximum torque/current ratio control is a frequently used control strategy in salient pole permanent magnet synchronous servo motor system. Using the scalar value formula of the mathematical model of the motor for calculation can limit the variables calculated by the system control algorithm to a certain range, thus avoiding the overflow of results easily generated in the calculation process as far as possible and being beneficial to reducing the errors generated in the calculation process.

3. Simulation of Spwm-Foc System

In the PMSSM control system, instead of continuous sinusoidal alternating current, the three-phase stator is fed with sinusoidal pulse width modulation waveforms in the form of pulse square waves, such as SPWM and SVPWM. Among them, SPWM is a pulse width modulation method that uses square waves with different widths to equivalent sine waves. Among them, the computer simulation technology is to use the computer to simulate and study the performance of the research object according to the mathematical model of the research object, thus revealing the internal motion of the system and the dynamic performance of the system. It can change continuously and purposefully according to the current state of the system, forcing the system to move according to a predetermined "sliding mode" state trajectory. Because the variable structure control strategy can obtain a new motion trajectory and has new characteristics that the original structure does not have, the variable structure control can be well adapted to the control of uncertain systems. Replacing ordinary sinusoidal AC voltage with SPWM voltage can effectively suppress the low harmonic components in the output voltage, reduce torque ripple and expand the speed regulation range of the motor [10].

Firstly, the set speed command is compared with the detected rotor speed signal, and the i_q^* command is output through the speed regulator ASR. Then, by detecting the current input into the PMSSM three-phase winding, Clarke and Park coordinate transformation are used to obtain the current i_d and i_q on the d and q axes, which are compared with the given d and q axis currents. The established mathematical model is often treated approximately. At the same time, due to the different industrial and mining conditions, its motor parameters often change, such as resistance and inductance parameters caused by temperature rise. The three-phase voltage modulation signal of SPWM modulator is obtained by outputting the direct-axis and cross-axis voltages u_d and u_q through respective current regulators ACR, and by two-phase rotation/three-phase static coordinate transformation 2r/3s. Through the organic integration of these functional modules, the simulation model of PMSSM vector control system can be built in Matlab/Simulink, and the control algorithm of double closed loops can be realized. The schematic diagram of the system is shown in fig. 2.

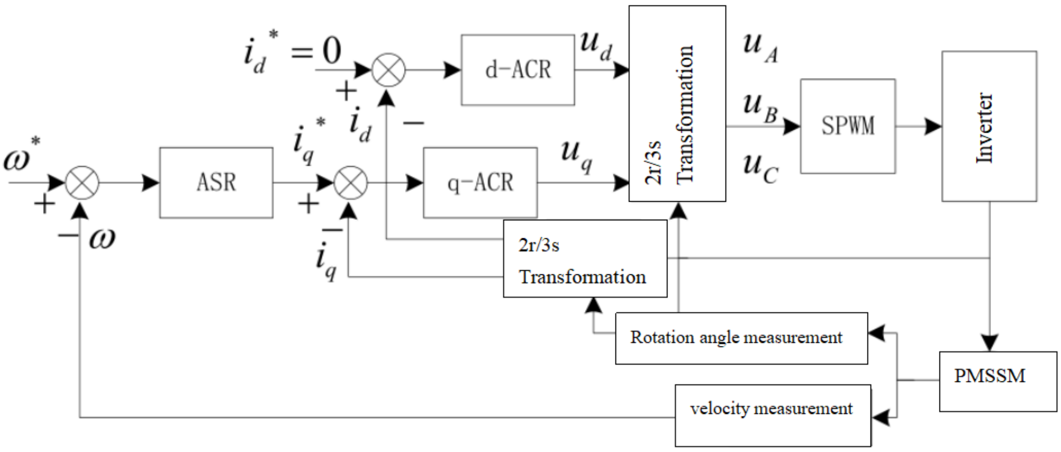

Fig. 2 Schematic Diagram of Spwm-Foc System

The main circuit of the system consists of DC power supply, inverter and permanent magnet synchronous servo motor. The excitation type of permanent magnet synchronous servo motor is sine wave. The three-phase phase current supplied by the inverter to the motor is also sine wave, so SVPWM method can be adopted. SVPWM modulation is based on the principle that the space voltage vector synthesized by the three-phase pulse voltage output by the inverter is equal to the space voltage vector synthesized by the three-phase sine wave voltage expected to be output. Considering the uncertainty in the motor system, the sliding mode variable control strategy can make full use of its advantages, making sliding mode observer and sliding mode control widely used in permanent magnet synchronous servo motor system. This paper focuses on the estimation of motor speed by using sliding mode observer. The module parameters of the motor (stator resistance, excitation flux, stator D-axis inductance, stator Q-axis inductance, moment of inertia, polar pair), speed regulator ASR and current regulators ACR-d and ACR-q are shown in Table 1. The motor speed, current and angle signals are taken from the detection module of permanent magnet synchronous servo motor.

Table 1 Spwm-Foc System Parameters

PMSSM	Stator resistance 2.775Ω	Excitation flux 0.175Wb
	Stator d-axis inductance L_d 0.00185H	Stator q-axis inductance L_q 0.00185H
	Moment of inertia J =0.0018 kg m^2	Number of pole-pairsP=8
rpm governor	Proportionality coefficient $K_{p\omega}$ =8	Integral coefficient $K_{i\omega}$ =1
d-axis current regulator	Proportionality coefficient K_{pd} =13	Integral coefficient K_{id} =12
q-axis current regulator	Proportionality coefficient K_{pd} =5	Integral coefficient K_{iq} =6

Through the above analysis, it can be seen that the structure of the system will change with the switching of the control vector U, and the design purpose is to change the system structure, so that the stability, existence and accessibility of the system will meet the requirements. In this paper, when voltage source inverter is used for power supply, the PWM waveform is generated by selecting the switching state of the inverter based on the circular flux linkage generated by the three-phase symmetrical sinusoidal voltage, which makes the actual flux linkage approach the circular flux linkage trajectory and can better improve the utilization efficiency of the power supply voltage. The simulation results are shown in fig. 3. the system sampling time is 2e-6s and the simulation time is 0.5s. Among them, 3(a) is the speed waveform, PMSSM is started with no load, and a load of 5N.m is applied at 0.2s the waveform fluctuates slightly. Fig. 3(b) is a torque waveform in which a load torque of 5N.m is applied at 0.2s; Fig. 3(c) shows the waveform of three-phase stator current, which fluctuates greatly and is not smooth. Fig. 3(d) shows the line voltage ABu output by the inverter.

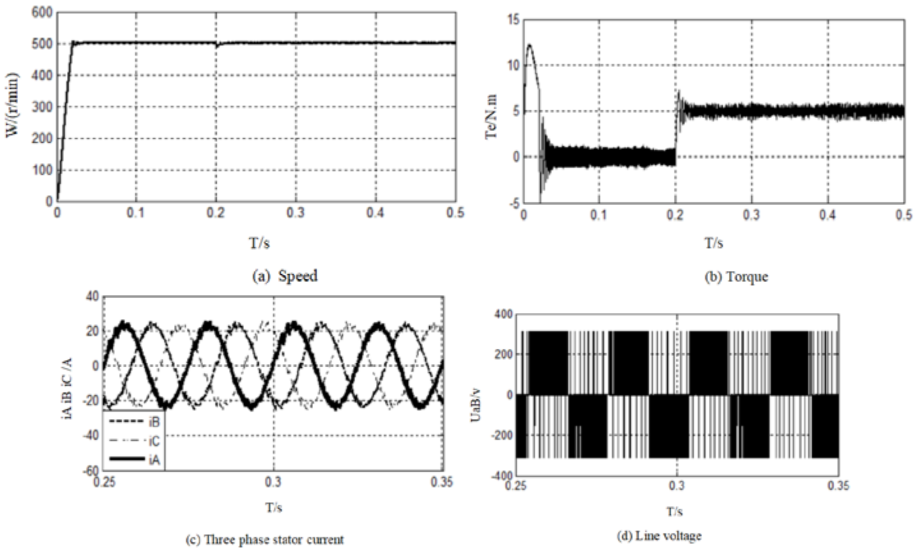

Fig. 3 Spwm-Foc System Simulation Waveform

When the conventional SPWM is fully modulated, the fundamental peak value of the output line voltage is $\sqrt{3}U_d/2$, i.e. its DC voltage utilization rate is about 0.766. The peak value of fundamental wave voltage measured by FFT Analsis function in powergui module is 258.4V, the given DC voltage is 310V, and the voltage utilization rate is about 0.766, which accords with the theoretical analysis result. The speed of PMSSM will fluctuate during startup and sudden load application, but it can stabilize quickly. When the stable speed is reached, although the jitter is suppressed by the saturation function, the rotation speed of the motor is still not smooth enough. From the whole simulation results, it can be seen that the motor vector control system adopting the PMSSM model has wide speed regulation range, good dynamic response and small steady-state error. therefore, the paper uses the PMSSM model in the simulation of the following chapters and has certain reliability.

4. Conclusion

Based on the basic structure and working principle of PMSSM, this paper establishes a mathematical model in three-phase stationary coordinate systems a, b and c. Because the mathematical model is complex and difficult to analyze, Clarke and Park transformations are introduced, and the three-phase stationary coordinate systems A, B and C are changed into two-phase rotating coordinate systems d and q. The sensorless control system of permanent magnet synchronous servo motor based on sliding mode observer is built in Matlab, and the chattering in sliding mode observer is weakened by saturation function. Finally, the experimental simulation proves that the control system has better performance. The simulation results show that the vector control system using the mathematical model of PMSSM can achieve better dynamic and static performance, and the dynamic process is completely consistent with the theoretical analysis, which provides a good foundation for the research work in the following chapters.

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