A Novel Servo Motor Vector Technique for the Control of Industrial Robots

Xinhua Yan, Xinxing Yan, Kezhi Zhang

Nobot intelligent equipment (Shandong) Co., Ltd., liaocheng, China 252000.
Email: yanxinghualc@163.com

Abstract - Vector control algorithm was first used to solve the torque control problem of AC motor. At present, vector control strategy has been used in AC asynchronous motor more mature. In addition, permanent magnet synchronous motor (PMSM) has been more and more widely used in national defense, industrial and agricultural production, and daily life due to its own advantages. Therefore, this paper studies the application of vector control algorithm in permanent magnet synchronous motor (PMSM). In this paper, the working principle of permanent magnet synchronous motor (PMSM) is discussed, and the mode of PMSM is constructed. Then, the control principle of vector control algorithm is discussed, and its control model is constructed. In addition, a complete program is built by Simulink, and the simulation is carried out.

Keywords - Vector control; Permanent magnet synchronous; Asynchronous.

I. INTRODUCTION

Asynchronous motor, also called induction motor, is a kind of AC motor, which is produced by the interaction between air-gap rotating magnetic field and induction current of rotor windings, so as to realize the conversion of mechanical and electrical energy into mechanical energy. Triple-phase asynchronous motors are mainly used as motors to drive various production machinery, such as fans, pumps, compressors, machine tools, light industrial and mining machinery, threshers and crushers in agricultural production, processing machinery in agricultural by-products, and so on. The utility model has the advantages of simple structure, easy manufacture, cheaper, reliable operation, sturdiness and durability, high operation efficiency and suitable working characteristics [1-2]. Permanent magnet synchronous motor (PMSM) is a synchronous motor with synchronous rotating magnetic field generated by permanent magnet excitation. Permanent magnet as rotor produces rotating magnetic field, triple-phase stator windings react through armature under rotating magnetic field to induce triple-phase symmetrical current. Compared with the traditional motor, PMSM does not need excitation current, and does not need damping winding under the condition of inverter power supply, and has higher efficiency and power factor, and the volume of PMSM is smaller than that of asynchronous motor of the same capacity [3-4]. In addition, the driving mode is mainly divided into three types: constant speed drive, speed control drive and precision control drive and so on. However, the interference of current coupling, friction, load change and so on are inevitable in the operation of PMSM. Because of these disturbances, it is difficult to describe PMSM with accurate mathematical model, such as current coupling, friction force, load change and so on, which make it difficult for us to describe PMSM with accurate mathematical model. It is difficult to suppress disturbance quickly if linear control method is used. Vector control was first put forward in the 1960s, which was first applied to asynchronous motor; then it was transplanted to permanent magnet synchronous motor [5]. Compared with square wave control, it has many advantages, such as low torque ripple, smooth motor operation, quitter, wide speed range and so on, so it is more and more widely used in motor control.

II. LITERATURE SURVEY AND LIMITATIONS OF CURRENT MODELS

The effectiveness of sliding mode control is proved in Ref [6] by studying the sliding mode controller and simulating by Simulink. The parameters of PI controller are optimized in Ref [7] by particle swarm optimization (PSO). In addition, the stable operation of the motor is achieved by constructing a fuzzy controller. In Ref [8], the control system is constructed through current loop, velocity loop and position loop. The simulation results show that the system has the advantages of fast response, small overshoot and high precision. A new vector control strategy (VC) based on extended state observer (ESO) is proposed in Ref [9] for the control of permanent magnet synchronous motor with only phase current. In addition, the fault of phase current sensor is solved by ESO. A vector control strategy for permanent magnet synchronous motor (PMSM) based on DSP 2812 is developed in Ref [10]. In addition, the algorithm can be used for real-time or off-line computation. A novel molecular theory optimization algorithm for adaptive chaotic dynamics is proposed in Ref [11], which is used to calculate the optimal parameters of PID controller. In addition, the effectiveness of the algorithm is verified by simulation experiments. Ref [12] improved the medium and high-speed position estimation based on sliding mode observer to improve the performance of sensor-less vector control for permanent magnet synchronous motor (PMSM). In addition, the I-f startup method is used to avoid the problems existing in V-f startup strategy. In Ref [13], the related principle of vector algorithm is introduced by studying the vector algorithm. In Ref [14], the realization of unit model of permanent magnet synchronous motor
(PMSM) and vector control of permanent magnet synchronous motor (PMSM) are studied in detail. In addition, the unit model solving method of permanent magnet synchronous motor is deduced in detail, and the basic physical quantities and their basic values are obtained. In Ref [15], a load torque estimation scheme based on nonlinear disturbance observer and EKF cascade is proposed to eliminate load torque sensor. In Ref [16], the real-time implementation of field programmable gate array (FPGA) vector control scheme is reported by hardware-in-the-loop simulation. In addition, this method will be used to propel the PMSM of electric motorcycles, which will then be integrated into more complex experimental devices. In Ref [17], a simplified model of permanent magnet synchronous motor (PMSM) based on space vector pulse width modulation (SVPWM) is proposed, and the id = 0 rotor field-oriented vector control strategy of PMSM servo system is determined. In addition, the feasibility of the control strategy is verified by simulation experiments. A large number of references are proposed and showed that vector control has a strong advantage in motor control.

III. MOTOR MODELS

A. Mathematical Model of Permanent Magnet Synchronous Motor

The electromagnetic relationship of permanent magnet synchronous motor (PMSM) is very complicated, such as the interaction between windings and windings, the interaction between windings and permanent magnets, and the existence of some nonlinear factors, such as saturation of magnetic circuit. Therefore, it is difficult to establish a very accurate mathematical model. In order to simplify the analysis process, a number of parameters with less significant impact are often overlooked, making the following assumptions [18]:

1. The stator armature windings generate sinusoidal induced EMF, and the air-gap magnetic field of the rotor permanent magnet is also distributed in the air-gap space as sine waves;
2. The eddy current and hysteresis loss of the iron core are ignored;
3. The saturation of the stator iron core is ignored; the inductance parameter is invariable and the magnetic circuit is linear;
4. The damping winding of rotor is neglected.

A1. Mathematical Model of Permanent Magnet Synchronous Motor in Triple-Phase Static Coordinate System

The internal structure of triple-phase permanent magnet synchronous motor is equivalent to the circuit diagram model in circuit theory, which includes stator triple-phase resistance, inductance and back electromotive force as shown in Figure 1. Thus, the triple-phase voltage equation of stator can be obtained.

\[
\begin{align*}
    u_a &= R_a i_a + \frac{d}{dt} \psi_a \\
    u_b &= R_a i_b + \frac{d}{dt} \psi_b \\
    u_c &= R_a i_c + \frac{d}{dt} \psi_c
\end{align*}
\]

(1)

where \(u_a, u_b, u_c\) is the triple-phase stator voltage of the permanent magnet synchronous motor, \(i_a, i_b, i_c\) is the triple-phase stator current of the permanent magnet synchronous motor, \(R_a\) is the resistance of each phase winding of the permanent magnet synchronous motor, \(\psi_a, \psi_b, \psi_c\) are the triple-phase stator flux of the permanent magnet synchronous motor. The triple-phase stator magnetic linkage equation can be obtained from the diagram as follows:

\[
\begin{align*}
    \psi_a &= L_{aa} i_a + M_{ab} i_b + M_{ac} i_c + \psi_f \cos \theta_e \\
    \psi_b &= M_{ba} i_a + L_{bb} i_b + M_{bc} i_c + \psi_f \cos(\theta_e - 120^\circ) \\
    \psi_c &= M_{ca} i_a + M_{cb} i_b + L_{cc} i_c + \psi_f \cos(\theta_e + 120^\circ)
\end{align*}
\]

(2)

where \(\psi_f\) is the flux linkage between the rotor permanent magnet and the stator winding; \(L_{aa}, L_{bb}, L_{cc}\) denote the mutual inductance coefficient between stator windings; \(\theta_e\) is the angle between the axis of the rotor pole and the axis of the stator winding in phase of the motor.

Figure 1 Equivalent circuit diagram of phase permanent magnet synchronous motor

Figure 2 Schematic diagram of magnetic synchronous motor in triple-phase stationary coordinate system
The torque equation is:

\[ T_n = -n_p \left\{ i_a \sin \theta + i_b \sin \left( \theta - \frac{2\pi}{3} \right) + i_c \sin \left( \theta - \frac{4\pi}{3} \right) \right\} \]

(3)

### A2. Mathematical Model of Permanent Magnet Synchronous Motor in Two-Phase Static Coordinate System \( \alpha \)-Axis and \( \beta \)-Axis

**Voltage equation:**

\[
\begin{align*}
    u_\alpha &= R_i i_\alpha + \omega \psi_L \cos \theta \\
    u_\beta &= R_i i_\beta + \omega \psi_L \sin \theta 
\end{align*}
\]

(4)

**Magnetic linkage equation:**

\[
\begin{align*}
    \psi_\alpha &= L_i i_\alpha + \frac{3}{2} \omega \psi_f \cos \theta \\
    \psi_\beta &= L_i i_\beta + \frac{3}{2} \omega \psi_f \sin \theta 
\end{align*}
\]

(5)

**Moment equation:**

\[ T_e = i_\beta \psi_f \cos \theta - i_\alpha \psi_f \sin \theta \]

(6)

### A3. Mathematical Model of Permanent Magnet Synchronous Motor under DQ Axis

For permanent magnet synchronous motor (PMSM), the \( d \) axis and the rotor pole axis coincide with each other in the \( d-q \) two phase synchronous rotation coordinate system. The \( q \) axis is counterclockwise ahead of the \( d \) axis 90°. The angle between the \( d \) axis and the stator winding in phase A of the motor is \( \theta_e \). The rotor rotates at an electric angular velocity of \( \omega_e \) in space. The \( ABC \) triple-phase static coordinate system and the \( d-q \) two-phase synchronous rotating coordinate system are shown in Figure 1-3.

The torque equation is:

\[ T_e = \frac{3}{2} n_p \left\{ \psi_q i_q - \psi_d i_d \right\} \]

(9)

Combination of (4) and (6) gives:

\[ T_e = \frac{3}{2} n_p \left[ \psi_q i_q + (L_d - L_q) i_d i_q \right] \]

(10)

The torque balance expression of triple-phase permanent magnet synchronous motor is as follows

\[ j \frac{d^2 \theta_e}{dt^2} + D \frac{d \theta_e}{dt} + K J_\omega = T_e - T_l \]

(11)

where \( \theta_e \) is the mechanical angle; \( T_e \) is the load torque; \( j \) is the moment of inertia; \( D \) is the friction and the wind resistance torque coefficient; \( K \) is the torsional elastic torque coefficient which is proportional to the rotational speed.

Generally, \( K \) can be approximately equal to zero; \( \omega_e = \frac{d \theta_e}{dt} \), and load torque \( T_l \) can be incorporated into friction resistance moment, which makes the calculation of dynamic equation simpler, namely

\[ \frac{j}{n_p} \frac{d \omega_e}{dt} = T_e - T_l \]

(12)

It can be seen from formula (7) that the electromagnetic torque of PMSM basically depends on the stator \( AC / DC \) current component. In PMSM, the rotor flux is invariable. Therefore, the rotor flux orientation method is used to
control the permanent magnet synchronous motor, that is, the rotor flux is on the d axis.

The first item in formula (7) is the permanent magnet torque of permanent magnet synchronous motor (PMSM)

\[ T_e = \frac{3}{2} n_p \cdot \psi_r \cdot i_q \]

The second is magnetoresistance torque

\[ T_e = \frac{3}{2} n_p \cdot (L_d - L_q) \cdot \psi_r \cdot i_q \]

When the rotor \( L_d < L_q \), both the permanent magnetic torque and the magneto resistive torque exist at the same time. The maximum output torque can be obtained under the minimum current amplitude by controlling and adjusting the magneto resistive torque flexibly and effectively.

When the rotor \( L_d = L_q \), there is only electromagnetic torque, there is no magneto resistive torque. Torque is

\[ T_e = \frac{3}{2} n_p \cdot \psi_r \cdot i_q = \frac{3}{2} n_p \cdot \psi_r \cdot i_q \sin \beta \]

It can be seen that the maximum torque can be obtained when \( \beta \) is 90 degrees, that is, the torque can be maximized when \( i_q \) coincides with the q-axis. Since the rotor is permanent magnet, the permanent magnet motor can be controlled by adjusting the direct current \( i_s \) as long as the rotor \( i_q \) is perpendicular to the d-axis, as is the control of the DC motor.

B. Mathematical Model of Asynchronous Motor

To improve the performance of AC motor speed control system and understand the vector control technology, it is necessary to study the mathematical model of asynchronous motor. Master the relationship between voltage, current, flux linkage, electromagnetic torque, slip angular frequency and motor parameters. The mathematical model of asynchronous motor is a high order, nonlinear, strong coupling multivariable system. When studying the multivariable mathematical model of asynchronous motor, we usually make the following assumption [19]: Triple-phase winding symmetry, ignoring spatial harmonics. Ignoring the saturation of the magnetic circuit, the self-inductance and mutual inductance of each winding are linear. Ignore core wear.

B1. Mathematical Model of Induction Motor in Triple-Phase Static Coordinate System

(1) Voltage equation

Triple-phase stator winding voltage equation

\[
\begin{align*}
u_a &= R_s \cdot i_a + \frac{d\psi_a}{dt} \\
u_b &= R_s \cdot i_b + \frac{d\psi_b}{dt} \\
u_c &= R_s \cdot i_c + \frac{d\psi_c}{dt}
\end{align*}
\]

(14)

Triple-phase rotor winding voltage equation

\[
\begin{align*}
u_a &= R_s \cdot i_a + \frac{d\psi_a}{dt} \\
u_b &= R_s \cdot i_b + \frac{d\psi_b}{dt} \\
u_c &= R_s \cdot i_c + \frac{d\psi_c}{dt}
\end{align*}
\]

(15)

(2) Magnetic linkage equation

Stator magnetic linkage equation

\[
\begin{align*}
\psi_a &= L_{AA} \cdot i_a + L_{AB} \cdot i_b + L_{AC} \cdot i_c + L_{Aa} \cdot i_a + L_{Ab} \cdot i_b + L_{Ac} \cdot i_c \\
\psi_b &= L_{BA} \cdot i_a + L_{BB} \cdot i_b + L_{BC} \cdot i_c + L_{Ba} \cdot i_a + L_{Bb} \cdot i_b + L_{Bc} \cdot i_c \\
\psi_c &= L_{CA} \cdot i_a + L_{CB} \cdot i_b + L_{CC} \cdot i_c + L_{Ca} \cdot i_a + L_{Cb} \cdot i_b + L_{Cc} \cdot i_c
\end{align*}
\]

(16)

Rotor magnetic linkage equation

\[
\begin{align*}
\psi_a &= L_{Aa} \cdot i_a + L_{Ab} \cdot i_b + L_{Ac} \cdot i_c + L_{Aa} \cdot i_a + L_{Ab} \cdot i_b + L_{Ac} \cdot i_c \\
\psi_b &= L_{Ba} \cdot i_a + L_{Bb} \cdot i_b + L_{Bc} \cdot i_c + L_{Ba} \cdot i_a + L_{Bb} \cdot i_b + L_{Bc} \cdot i_c \\
\psi_c &= L_{Ca} \cdot i_a + L_{Cb} \cdot i_b + L_{Cc} \cdot i_c + L_{Ca} \cdot i_a + L_{Cb} \cdot i_b + L_{Cc} \cdot i_c
\end{align*}
\]

(17)
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(3) Torque equation

\[ T_e = -p_n * M_{ST} \left[ (i_{d,a} + i_{d,b} + i_{d,c})^* \sin \theta + (i_{d,a} + i_{b,b} + i_{c,c})^* \sin \left( \theta + \frac{2\pi}{3} \right) + (i_{d,a} + i_{b,b} + i_{c,c})^* \sin \left( \theta + \frac{4\pi}{3} \right) \right] \] (18)

(4) Equation of motion

\[ \frac{j}{p_n} \frac{d\omega}{dt} = T_e - T_L \] (19)


Stator voltage equation

\[ \begin{align*}
    u_{d,a} &= R_i i_{d,a} + p\psi_{a,a} \\
    u_{b,b} &= R_i i_{b,b} + p\psi_{b,b}
\end{align*} \] (20)

Rotor voltage equation

\[ \begin{align*}
    u_{d,a} &= R_i i_{d,a} + p\psi_{a,a} - \omega_i \psi_{r,a} \\
    u_{b,b} &= R_i i_{b,b} + p\psi_{b,b} + \omega_i \psi_{r,b}
\end{align*} \] (21)

Stator magnetic linkage equation

\[ \psi_{m,a} = L_i i_{d,a} + L_m i_{q,a} \] (22)

Rotor magnetic linkage equation

\[ \begin{align*}
    \psi_{r,a} &= L_i i_{d,a} + L_m i_{q,a} \\
    \psi_{r,b} &= L_i i_{b,b} + L_m i_{q,b}
\end{align*} \] (23)

Electromagnetic torque equation

\[ T_e = p_n L_i \left( i_{d,a} i_{d,a} - i_{b,b} i_{b,b} \right) \] (24)

Equation of motion

\[ \frac{j}{p_n} \frac{d\omega}{dt} = T_e - T_L \] (25)

where \( \omega_i \) is the rotational angular velocity of the rotor; the stator winding resistance. \( R_i \) is rotor winding resistance. \( L_i \) is self-inductance of stator winding; \( L_L \) is self-inductance of rotor winding; \( L_m \) mutual inductance of stator and rotor windings; \( p_n \) is the magnetic pole logarithm.

B3. Mathematical Model of Induction Motor under DQ Axis

The mathematical model in the stator synchronous rotating d-q coordinate system is written according to the convention of the motor. Stator voltage equation

\[ \begin{align*}
    u_{d,a} &= R_i i_{d,a} + p\psi_{a,a} - \omega_i \psi_{r,a} \\
    u_{b,b} &= R_i i_{b,b} + p\psi_{b,b} + \omega_i \psi_{r,b}
\end{align*} \] (26)

Rotor voltage model

\[ \begin{align*}
    \psi_{r,a} &= L_i i_{d,a} + L_m i_{q,a} \\
    \psi_{r,b} &= L_i i_{b,b} + L_m i_{q,b}
\end{align*} \] (27)

Stator magnetic linkage equation

\[ \psi_{m,a} = L_i i_{d,a} + L_m i_{q,a} \] (28)

Rotor magnetic linkage equation

\[ \begin{align*}
    \psi_{r,a} &= L_i i_{d,a} + L_m i_{q,a} \\
    \psi_{r,b} &= L_i i_{b,b} + L_m i_{q,b}
\end{align*} \] (29)

Electromagnetic torque equation

\[ T_e = p_n L_i \left( i_{d,a} i_{d,a} - i_{b,b} i_{b,b} \right) \] (30)

In the above formula \( R_s, R_r \) are stator resistance and rotor resistance respectively. \( L_s, L_r, L_m \) are stator self-inductance, rotor self-inductance, stator rotor leakage inductance and mutual inductance respectively. \( u_{d,a}, u_{b,b}, u_{d,b}, u_{b,a} \) are the stator voltage and rotor voltage respectively. \( D \)-axis component and \( Q \)-axis component. \( i_{d,a}, i_{b,b}, i_{d,b}, i_{b,a} \) are the stator current and rotor current respectively. \( D \)-axis component and \( Q \)-axis component. \( \psi_{d,a}, \psi_{b,b}, \psi_{r,a}, \psi_{r,b} \) is stator flux and rotor flux respectively; \( D \)-axis component and \( Q \)-axis component. \( \omega_s, \omega_r, \omega_o \) are the motor synchronous angular velocity, rotor angular velocity and slip angular velocity; \( p_n \) and \( p \) are polar logarithms and differential operators respectively; \( V_s \) is the amplitude of stator phase voltage.

If the rotor flux is oriented so that the direction of the rotor flux is in the direction of the d axis of the synchronous rotating coordinate system, then there is \( \psi_{d,a} = \psi_{r,a} \), bringing \( \psi_{d,b} = 0 \) into equation (29) is

\[ \begin{align*}
    i_{d,a} &= \frac{\psi_{r,a} - L_m i_{q,a}}{L_r} \\
    i_{b,b} &= \frac{-L_m i_{q,b}}{L_r}
\end{align*} \] (31)

Because of the internal short circuit of the squirrel cage rotor, there is \( u_{d,a} = u_{b,b} = 0 \), which is available by bringing its summation (27) into the equation (31).

\[ \omega_s = \frac{L_m i_{q,b}}{T_{\psi_r}} \] (32)
The formula $T_r$ is the rotor time constant, which is expressed as $T_r = L_r / R_r$.

Substitute (30) available from equation (31)

$$T_r = P \frac{L_m}{L_r} i_d \psi_r$$  

(34)

In steady state, ignoring $i_d$ dynamic variation, we can infer the formula $P i_d = 0$, equation (27) can be written as

$$\psi_r = L_m i_d$$  

(35)

Substituted expressions (35) for expressions (33) and (34) are available, respectively.

$$\omega_r = \frac{i_m}{T_j s_h}$$  

(36)

$$T_r = P \frac{L_m^2}{L_r} i_d \psi_r$$  

(37)

In addition, in the static triple-phase coordinate system of ABC, the electromagnetic torque can be written as follows if the stator resistance voltage drop is ignored.

$$T_e = \frac{3}{2} P \frac{R_s \omega_s V_s^2}{[R_e^2 + \omega_s^2 (L_m + L_p)^2]} \omega_i$$

C. Vector Control

Cl. Vector Control Coordinate Transformation

(1) Triple-phase to two-phase static coordinate system transformation (Clarke transform)

The transformation of the static coordinate system is the transformation between $A$, $B$, $C$ of triple-phase static windings and $\alpha \beta$ of two-phase static windings, as shown in Figure 4.

$$
\begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix} =
\begin{bmatrix}
    -\frac{1}{2} & -\frac{1}{2} \\
    \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix}
$$

The inverse transformation is:

$$
\begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix} =
\begin{bmatrix}
    1 & 0 \\
    -\frac{1}{2} & \frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
    i_{\alpha} \\
    i_{\beta}
\end{bmatrix}
$$

(2) Two-phase static-two-phase rotational coordinate system transformation (Park transform)

Transformation between two-phase static windings $\alpha$ and $\beta$ and two-phase rotating $d-q$ (MT) coordinates, as shown in Figure 5

Figure 5: Transformation between two-phase static and two-phase rotating coordinate systems

Transformation from two-phase static to two-phase rotating coordinates:

$$
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix}
$$

Transformation from two-phase rotation to two-phase static coordinates:
C2. Vector Control Principle of Permanent Magnet Synchronous Motor

The speed control of permanent magnet synchronous motor (PMSM) is realized by torque control in the final analysis. After the transformation from triple-phase static coordinate system ABC to two-phase rotating coordinate system d-q, the control of permanent magnet synchronous motor becomes simpler. As can be seen from the vector control schematic diagram 2-3, the vector control system is mainly composed of the following parts:

(1) SVPWM module. The advanced modulation algorithm is employed to reduce current harmonics and improve DC bus voltage utilization;
(2) Current reading module. The stator current is measured by a precision resistor or current sensor;
(3) Rotor speed / position feedback module. Hall sensor or incremental phototronic encoder is used to obtain accurate rotor position and angular velocity information, and sensorless detection algorithm can also be used to measure the rotor position and angular velocity;
(4) PID control module;
(5) Clark, Park and anti-Park transform module.

Figure 6: rotor field-oriented vector control schematic diagram of permanent magnet synchronous motor

Vector control system with the cooperation of the above modules is easy to achieve a variety of control algorithms, the implementation process can be divided into the following steps:

The phase current $i_a$ measured by the current reading module is transformed from the triple-phase static coordinate system to the two-phase static coordinate system $i_a$ and $i_b$ by Clark transformation; $i_a$ and $i_b$ are combined with rotor position $\theta_{rd}$ and transformed from two-phase static coordinate system to two-phase rotating coordinate system $i_{ds}$ and $i_{qs}$ by Park transform;

(3) The rotor speed position feedback module compares the measured rotor angular velocity $\omega_r$ with the reference speed $\omega_r^*$, and generates the reference current $i_{qs}^*$ by PI regulator;

(4) The reference currents $i_{ds}^*$ and $i_{qs}^*$ are compared with the actual feedback currents $i_{ds}$ and $i_{qs}$, and the reference currents $i_{ds}^*=0$ are converted into voltage $v_{ds}$ and $v_{qs}$ by PI regulator.

(5) The voltages $v_{ds}$ and $v_{qs}$ are combined with the detected rotor angular positions $\theta_{rd}$ to transform them into voltages $v_d$ and $v_q$ in the two-phase static coordinate system;

(6) Voltage $v_d$ and $v_q$ are modulated into six-channel switching signals by SVPWM module to control the switching of triple-phase inverter.

IV. SIMULATION RESULTS

A. Establishment of Simulation Modules

(1) Triple-phase to two-phase static coordinate transformation.

$$
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b
\end{bmatrix}
$$

$$
\begin{bmatrix}
i_a \\
i_b
\end{bmatrix} = \begin{bmatrix}
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{3}} \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{3}} \\
0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q \\
i_{ds}^*
\end{bmatrix}
$$
(2) Two-phase static-two-phase rotation coordinate transformation:

\[
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix}
\]

(3) Two-phase rotation-two-phase static coordinate transformation:

\[
\begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix}
\]
(4) SVPWM module is composed of four parts. As shown in the figure below, the advanced modulation algorithm is used to reduce current harmonics and improve the utilization of DC bus voltage. Triple-phase circuits are further filtered and regulated by this model.

(5) Through the motor angle calculation module, the different angles of the motor at each time can be calculated in real time.
B. Simulation Waveforms

Through the simulation results, we can see that the proposed vector control algorithm can achieve good speed regulation performance of the motor. Figure 12 shows the triple-phase current waveform, triple-phase electric waveform is a sine wave, can play a good control role. At the same time, through the speed given and feedback waveform shown in figure 13, it can be seen that the designed model can achieve the speed of the following. At the same time, through the IQ current given in Figure 14 and the feedback value, it can be seen that the current can also achieve good follow.

V. CONCLUSION

Compared with asynchronous motor, vector control has better control strategy on permanent magnet synchronous motor. Through simulation results, it is not difficult to see that the distribution of vector control is regular, which makes it work. Its reliability is guaranteed. Its regular distribution also guarantees the stability. In addition, the vector control algorithm is universal, using this algorithm, we can apply to other schemes. In addition to an additional approach, it is also conducive to solving more problems. Therefore, in the vector control algorithm, we can do more research.

ACKNOWLEDGEMENT

This paper is funded by the Key Research and Development Plan Project of Shandong Province (NO: 2016ZDJS02A02).

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