An Optimization Algorithm for Direct Torque Control of Industrial Robot Servo Motors

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Abstract - To solve the problem of complexly modeling control system in the conventional, a method for direct torque control driving system of industrial robot asynchronous motor is proposed based on MATLAB/ Simulink by employing the space vector pulse width modulation (SVPWM). The structure and blocking modeling method are employed. Meanwhile, the stator flux linkage control of the principle of direct torque control (DTC) system is analyzed and improved. Finally, through MATLAB/Simulink simulation, the effectiveness of the algorithm is verified. Simulation results show that the introduction of space vector modulation combined with direct torque control (SVM_DTC) control system model achieve good control effect and make the magnetic linkage more accurate.

Keywords - Servo motor; Direct torque control; Space vector modulation; Direct vector control system model; Control system of SVM_DTC

I. INTRODUCTION

Accompanied by the development of industrial robot, servo motor, servo motor alternating current (AC) speed regulating system become more and more widely employed. AC speed regulation control theory has been rapidly developed and more and more advanced control methods were applied to AC speed regulation [1]. Since the simple system structure, direct torque control, fast torque dynamic response and robustness of motor parameters and so on, direct torque control (DTC) has received extensive attention [2-3]. Ref [4] proposed a direct torque control (DTC) scheme based on vector space decomposition for T-type neutral point clamp (T-NPC) three-level inverter feeding double stator winding permanent magnet synchronous motor (PMSM) driving, an efficient solution is provided for high power and high reliability applications. DTC speed control system does not need to make the control model of the AC motor to DC by rotating coordinate transformation, which simplifies the control algorithm and structure of the controller and realizes the speed regulation of high dynamic performance [5-6]. However, the conventional DTC employs the torque and magnetic chain hysteresis comparator to directly control the motor torque and flux linkage by selecting a suitable voltage space vector from the pre-made switch table according to certain rules. The analysis Ref [7] shows that this method of selecting the voltage vector cannot meet the dual requirements of the system for torque and flux linkage, which will lead to large flux linkage and torque ripple in the DTC system. In addition, the switching frequency of the conventional DTC system is not constant, the capacity of the power device is not fully utilized, and when the high-power IGBT requires low switching frequency, the switching device is easily burned.

Space vector modulation (SVM) can not only improve the stable state and performance of the system, but also make inverter switching frequency approximately constant. Thus, it is considered as a promising method which improve the stable state and performance of DTC. Lascu [8], adopted two PI regulators to realize voltage vector calculation of the space vector modulation (SVM_DTC) of asynchronous motor. At present, the research of this algorithm focuses on verifying the validity of the algorithm through MATLAB model and is based on the simple implementation of DSP platform [9-18]. Ref [10-11] verified the excellent control effect of the algorithm by MATLAB/Simulink simulation, but it does not give PI adjustment parameters and does not consider the limit of switching frequency in the actual system. Ref [12-13] gave a simple implementation of this algorithm bases on DSP, but the DSP platform is limited by the hardware and software conditions. Meanwhile it is difficult to realize the optimization of the system and the complex algorithm in the engineering application. Ref [14-15] proposed an improved direct torque prediction method based the principle of non-periodic direct torque prediction of AC motor. The feasibility of the algorithm is verified. However, due to the limitations of the prediction method, it has not been applied to the engineering field yet. Ref [16-18] proposed a sigma incremental modulation scheme based on space vector for multistage voltage source inverter. At the same time, the reference space vector is quantized directly and the results show that it has good practicability.

In this paper, the principle of direct torque control (DTC) system controlled is analyzed and improved by stator flux, and the model of space vector control system is leaded to make the flux observation more accurate. The defects of DTC control system are verified by MATLAB/Simulink simulation. On this basis, it is applied to the frequency conversion system platform of the control system based on the asynchronous motor space vector modulation (SVM_DTC), and has achieved good control effect.
II. CONTROL PRINCIPLE

A. System Principle Diagram of Direct Torque Control

The schematic diagram of direct torque control (DTC) system is shown in Fig.1, which is controlled by stator flux linkage. It controls asynchronous motor’s speed and flux and the output of the speed regulator ASR as the given signal $T_e^*$ of the electromagnetic torque. After the $T_e^*$, the torque control inner loop is set, it can restrain the influence on the rotor system by changing the flux. Thus, the speed and the magnetic chain subsystem are nearly decoupled. From the point of view of overall control structure, the direct torque control system can achieve higher static and dynamic performance.

The concrete working principle is as follows: to use the parameters measured in the motor running and establish the motor model, the two-phase current of a real-time measured motor and the voltage of the intermediate DC link is analyzed and calculated. The stator flux and actual torque of the motor are obtained, and then the given values of the magnetic chain and the torque respectively are compared. The deviation enters into and adjust the flux linkage and torque regulator (two-point hysteresis regulator) respectively, and the deviation is limited to a given tolerance range. The output of the regulator directly controls the PWM control signal of the inverter. Thus, the inverter generates the desired voltage vector, thereby regulating the motor torque.

![Fig. 1 Principle block diagram of direct torque control (DTC) system.](image)

B. The Relationship between Magnetic Chain and Voltage Vector

According to the asynchronous machine equation, to analyze handily and ignore the resistance voltage drop, the following equation can be obtained

$$\frac{d}{dt} \Psi_s = u_s - R_s i_s \approx u_s$$  \hspace{1cm} (1)

After discretization of the equation, it can be obtained

$$\Psi_s(n) = \Psi_s(n-1) + u_s(n-1) T_s$$  \hspace{1cm} (2)

where $T_s$ denotes the sampling period.

Since $T_s$ is very small, which is usually tens of microseconds or hundreds of microseconds, the angle $\omega$ between the flux chains is very small, so the magnitude of the flux linkage increases.

$$\Delta \Psi_s = |\Psi_s(n)| - |\Psi_s(n-1)| \approx |u_s(n-1)|T_s \cos \omega$$ \hspace{1cm} (3)

The effect of voltage vector on stator flux:

1. $\theta_{\psi} = \pm \pi / 2$, $\Delta \Psi_s = 0$, the amplitude of the stator flux is basically constant;
2. $-\pi / 2 \leq \theta_{\psi} \leq \pi / 2$, $\Delta \Psi_s > 0$, the amplitude of stator flux is increasing;
3. $\pi / 2 < \theta_{\psi} < \pi$, $-\pi / 2 < \theta_{\psi} < -\pi$, $\Delta \Psi_s < 0$, the amplitude of stator flux is reducing.

Therefore, the following conclusion can be obtained: the result of the action of the vector makes the magnetic...
flux amplitude increase when the absolute value of the angle between the voltage vector and the current flux vector is less than 90 degrees; the result of the action of the vector makes the magnetic flux amplitude reduce when the absolute value of the angle between the applied voltage and the current flux vector is more than 90 degrees; the result of the action of the vector makes the magnetic flux amplitude remain unchanged when the absolute value of the angle between the voltage vector and the current flux vector is equal to 90 degrees (including zero vector).

C. The Relationship between Torque and Voltage Vector

1. Once the voltage ahead of the voltage vector of stator flux is applied, $\frac{d\psi_{m}}{dt} > 0$, the torque will increase.
2. Once the voltage behind the voltage vector of stator flux or zero vector is applied, $\frac{d\psi_{m}}{dt} < 0$, the torque will be reduced.

D. Switch State Table

To reduce the torque ripple, it is natural to consider changing the hexagon flux linkage trajectory into a circular flux linkage trajectory. Due to asynchronous motor supply voltage power by the three-phase symmetrical sinusoidal, the stator flux is round. Therefore, by selecting the non-zero voltage space vector and zero vector reasonably so that the switch state of the inverter can be changed according to a certain rule, there will be the ability to control the circular flux track with constant amplitude and rotation. However, because the voltage space vector of the inverter is discrete and the switching frequency is limited, the control of the stator flux can only make the stator flux close to the circle in a certain range of tolerance.

To determine the space position of an instantaneous stator flux accurately, according to the direction of action of $U_{1}(100), U_{2}(110), U_{3}(010), U_{4}(011), U_{5}(001), U_{6}(101)$), the track of the original hexagon magnetic chain is divided into six sectors, each area accounts for $\pi / 3$ electric degrees, signing $\theta(1), \theta(2) \cdots \theta(6)$ respectively, that is:

$$\frac{2m-3}{6} \leq \theta(m) \leq \frac{(2m-1)}{6} \; (m = 1, 2, \cdots, 6) \; (4)$$

According to the angle of the stator flux, it is divided into six sectors, which is shown in Fig.3. By the relationship between the voltage vectors, torque vectors and the magnetic chain, when the sector is 1, the selection of the voltage vector $U2$ will increase the flux linkage and the torque, and the selection of $U3$ will reduce the flux linkage and increase the force moment. A selection of voltage vector $U6$ will increase the flux linkage and decrease the torque. The selection of voltage vector $U5$ will reduce the flux linkage the torque. Selecting the voltage vector $U0(000)$ or $U7(111)$ will make the magnetic field unchanged and the torque decrease.

Note: FD: indicates that the flux increases; FI: indicates the flux decreases; TD: indicates the torque decreases; TI: indicates the torque increases.

Combining the magnetic chain switch signal $T_w$, torque switch signal $T_d$ and stator flux sector signal, the appropriate stator voltage vector is selected to ensure only one switch change at a time to control the motor torque and magnetic chain based on the principle of torque regulation priority. The switch selection table is as follows:

<table>
<thead>
<tr>
<th>$D_w$</th>
<th>$D_T$</th>
<th>$\theta(m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>(u_5(110))</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>(u_6(111))</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td>(u_6(101))</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>(u_6(010))</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>(u_6(000))</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>(u_6(001))</td>
</tr>
</tbody>
</table>
**Note:** $D_1, D_2$ is the output of the hysteresis controller, "1" indicates that the given value is more than the actual value. "-1" means that the given value is less than the actual value. "0", which means that the given value is equal to the feedback value.

### III. CONSTRUCTION OF THE MODEL OF DIRECT VECTOR CONTROL SYSTEM

#### A. A Brief Introduction to the Model

The model is divided into five parts: three phase AC motor, IGBT module, 3s/2s transform module, voltage and current transform, flux observer and switch state selection module.

#### B. Stator Flux Observer

There are three kinds of stator flux observers, including the flux observation model based on the stator voltage and current, the magnetic chain observation model based on the stator current and the speed, and the magnetic chain observation model based on the stator voltage and current and the speed. In this paper, the flux observer based on stator voltage and current is selected, and the observation model is shown in Figure 5.

#### C. Switch State Selection Module

1. The calculation of the amplitude and angle of the flux linkage and the control model of the torque and flux hysteresis comparator are shown in Figure 6.

2. Computing sector (Flux sector) according to the angle.

3. According to the results of the current hysteresis output and the situation in the sector, the appropriate amount of voltage is selected from the switch state table to produce the corresponding switch amount, which is shown in Figure 8.

![Fig. 4 DTC control system model.](image-url)
Fig. 5 flux observer model based on stator voltage and current.

Fig. 6 switch state selection module

Fig. 7 parameter design of selector module.
D. Simulation Results

The parameters of the three phase AC asynchronous motor are as follows: $P=15$ kW, the stator resistance $R_s=0.2147 \Omega$, the rotor resistance $R_r=0.2205 \Omega$, the stator inductance $L_s=0.000991$ H, the rotor inductance $L_r=0.000991$ H, and the motor inertia $J=0.102 \text{kg} \cdot \text{m}^2$. Torque PI regulator: $K_p=50$, $K_i=10$. The rotational speed is $1420 \text{r/min}$, and the load is started. The stator flux linkage trajectory, current, speed and torque variation waveforms are shown in Figure 9.

Fig. 8 switch quantity model.

Fig. 9 simulation results of the DTC system (in Chinese for processing, program or picture)
The simulation waveform shows that the system achieves the set speed within less than 0.09s. In the case of starting or loading, the track of the magnetic chain cannot reach the ideal circular trajectory; the three-phase stator current is a sine wave of 120-degree phase angle of mutual difference; although the response of torque and speed is faster, there is still a certain torque ripple on the whole.

IV. CONSTRUCTION OF SVM-DTC CONTROL SYSTEM MODELS

A. Control System Based on SVM_DTC

The traditional DTC adopts the torque and hysteresis loop comparator. In this way, the appropriate voltage space vector is selected from the prefabricated switch table to control the torque and magnetic chain of the motor directly. This control will lead to large torque ripple in the DTC system. In addition, the switching frequency of the conventional DTC system is not constant, and the capacity of the power device cannot be fully utilized. Thus, it is easy to destroy the switch device when the high power IGBT requires the low switching frequency. The space vector (SVM) modulation mode can not only improve the steady-state performance of the system, but also make the switching frequency of the inverter approximately constant.

The block diagram of the SVM_DTC system is shown in Fig. 12. Among them, the reference voltage vector \( U_{\text{ref}} \) estimator and the SVM unit replace the flux linkage, torque hysteresis comparator and switch table in conventional DTC. In Fig. 12, the stator flux linkage value, the electromagnetic torque value and the magnetic flux linkage position angle \( \theta \) of the stator voltage and current signal of the motor are calculated by the full speed flux linkage model. The difference between the stator flux and the electromagnetic torque value and the given value is the reference voltage vector \( U_d \) and \( U_q \) under the rotating coordinate system by PI. After Park transformation, the reference voltage vector \( U_{\text{ref}} \) in the static coordinate system is used as the input of the SVM unit, and the switching control PWM signal is obtained through the space vector pulse width modulation.

B. A Brief Introduction to the Model

The model is divided into five parts: three phase AC motor, IGBT module, 3s/2s transform module, voltage and current conversion, flux observer, PID and PWM generation module.

C. PID and PWM Generation Modules

The output of the flux linkage and torque PI regulator is taken as the voltage value, and the reference voltage needed to generate SVPWM is obtained through coordinate transformation. The specific module model is shown in Figure 14.
D. Simulation Results

The motor and parameter settings used in the simulation are the same as that used in the DTC model. From Figure 15, it can be seen that the stator flux trajectory obtained by the control model of the SVM-DTC algorithm is closer to a circle; the torque response is very fast, and because the torque is lower than the DTC algorithm model, the torque response is fast and at the same time. The steady state of the stator current is better than that of the DTC model, and the range of current fluctuation is not large. Therefore, a better stable state can be achieved compared with DTC, and the speed response time is slower than that of the DTC model, about 0.13s. However, the overall response effect of the control model based on SVM-DTC algorithm is very good both in the starting acceleration or in the steady state, which can prove that the algorithm can be applied to the actual system.
V. CONCLUSION

In this paper, the principle of DTC algorithm is described. Since the DTC algorithm has a certain torque ripple and the stator flux trajectory is poor, the DTC algorithm is redesigned. Based on the DTC algorithm model, a new control system model based on the SVM-DTC algorithm is formulated, and the DTC system is added to the DTC system by using the full speed model of the magnetic chain. The MATLAB/Simulink simulation demonstrate that it has good control effect. The shape of stator flux track is close to the circle, and the pulsation of torque and speed has also been changed to a certain extent. The operation results show that all the performance indexes have achieved good results, and the switching frequency is constant.

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REFERENCE


