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Research on an AC Servo Control System for Industrial Lockstitch Sewing Machine

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Abstract Aimed at the actual demand for the performance of industrial lockstitch sewing machine used in garment industry, the vector control method and direct torque control method of the servo control system for industrial lockstitch sewing machine are studied in this paper. In order to meet the actual needs, on the basis of analysis for these two traditional control methods, an ac servo control system based on the algorithms of phase-locked loop and sliding mode observer is studied in depth, and the Matlab/simulink simulation tool is used to build a simulation model to verify its feasibility in the application of industrial lockstitch sewing machine.

1. Introduction

The servo control system for industrial lockstitch sewing machine generally adopts the three-phase permanent magnet synchronous motor (PMSM) [1] as its power element for operation. Because of its good stability, rapidity and high precision, the servo control system has been widely used in the sewing industry, robot, automatic production line with mechanical arm and other fields [2].

With higher and higher requirements for the industrial lockstitch sewing machines, the range for speed regulation of the PMSM is required to be extended from the original 220sti/min ~ 4300sti/min to 220sti/min ~ 6000sti/min. After the range for speed regulation is raised, some technical difficulties are brought about on the premise of the system satisfying the other performance requirements. Based on the analysis of the traditional servo control system for industrial lockstitch sewing machine, the ac servo control system for PMSM based on the algorithm of Phase-locked loop and sliding mode observer is deeply analyzed and studied in the following sections.

2. The mathematical model for three-phase PMSM

The mathematical model for three-phase PMSM [3] is a strongly coupled and complex nonlinear system. This paper assumes that the three-phase PMSM is an ideal motor and meets the following conditions:

- Ignore the saturation of the motor core.
- Ignore the eddy current and the hysteresis losses of the motor.
- The current in the motor is a symmetrical three-phase sinusoidal one.

In order to facilitate the design of the relevant controller, the mathematical model of three-phase PMSM in the rotating coordinate system is usually selected, so as to realize order reduction and decouple for the mathematical model in the stationary coordinate system. Therefore, under the above ideal conditions, stator voltage equation for three-phase PMSM under the rotating coordinate system can be expressed as

$$\begin{cases} u_d = Ri_d + \frac{d}{dt}\psi_d - \omega_e\psi_q \\ u_q = Ri_q + \frac{d}{dt}\psi_q + \omega_e\psi_d \end{cases} \tag{2-1}$$

The stator flux equation is

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{2-2}$$

where u_d , u_q are the d-q axis stator voltage, respectively, i_d , i_q are the d-q axis stator current, respectively; ψ_d and ψ_q are the d-q axis stator magnetic flux, respectively; L_d and L_q are the d-q axis stator inductance, respectively; R is the stator resistance; ω_e is the electrical rotor speed; ψ_f is the rotor flux.

The electromagnetic torque is

$$T_e = \frac{3}{2}\rho_n i_q\left[i_d\left(L_d - L_q\right) + \psi_f\right] \tag{2-3}$$

where ρ_n is the number of pole-pairs of three-phase PMSM.

The mechanical movement equation of the motor is

$$\mathrm{J}\frac{\mathrm{d}\omega_m}{\mathrm{dt}} = T_e - T_L - B\omega_m \tag{2-4}$$

where ω_m is the angular velocity of the motor; J and B are the inertia and the friction coefficient of the motor, respectively; T_e and T_L are the electromagnetic torque and the load torque of the motor, respectively; equation (2-1) to (2-4) constitute the mathematical model of three-phase PMSM in the rotating coordinate system.

3. Traditional ac servo control system for PMSM

The traditional ac servo control system for PMSM used in industrial lockstitch sewing machine generally adopts the vector control method and the direct torque control method [4], which can meet the requirements of steady speed, precisely positioning and speed regulation in practical application.

3.1. The vector control method for PMSM

The vector control method for PMSM is based on the coordinate transformation theory. Firstly, the stator current is represented by the rotating coordinate system, and then its magnitude and direction are controlled. The system using vector control method for three-phase PMSM usually includes position control loop, speed control loop, current control loop and PWM control algorithm. Among them, The function of the position control loop is to accurately position rotor when the motor is running; the function of the speed control loop is to control the motor to meet the requirements of speed regulation; the function of the current control loop is to accelerate the dynamic adjusting process of the system, so that the stator current of the motor could better approach the given value. In this way, the control objectives of the ac servo system are achieved.

3.2. The direct torque control method for PMSM

The direct torque control method for PMSM is a relatively new and high-performance alternating frequency conversion technique. The three-phase PMSM's control system using direct torque control method also includes four main parts which are the same as the control system using the vector control method. In direct torque control method, the amplitude of the torque and flux linkage can be calculated by using the stator voltage and current of the motor. Then, the calculated amplitude of torque and the flux linkage are compared with corresponding given values in order to obtain the deviations, and then the amplitude of the torque and stator flux linkage are controlled by using the deviations. Therefore, the target of direct control of flux linkage and torque is realized.

To sum up, the traditional ac servo control system for PMSM, which uses either vector control method or the direct torque control method, has position control loop and speed control loop. In these traditional ac servo control systems, the actual position and speed of the rotor follow the corresponding given value through these two loops. In order to meet the actual requirements and simplify the structure of control system, the ac servo control system for the PMSM based on the algorithm of sliding mode observer and phase-locked loop is studied below.

4. The algorithms of phase-locked loop and sliding mode observer

The algorithm of sliding mode observer [5] is a kind of control algorithm for sensorless PMSM, which is a special nonlinear and robust control algorithm. For the traditional servo control system mentioned above, it is generally necessary for the mechanical sensors to obtain accurate position and speed of rotor. The addition of mechanical sensors in the system not only has strict requirements on the environment but also increases the size, weight and cost of the system. The ac servo control system for the PMSM based on the algorithms of Phase-locked loop and sliding mode observer [6] not only has high performance, but also reduces the number of sensors and simplifies the system structure. Therefore, this control system represents the development direction of the ac servo control system for three-phase PMSM.

4.1. The algorithm of sliding mode observer

4.1.1. The sliding mode observer model

According to the mathematical model of three-phase PMSM expressed in the rotating coordinate system, the dynamic equation of stator current is

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_d}(-Ri_d + u_d + L_q\omega_e i_q - E_d) \\ \frac{di_q}{dt} = \frac{1}{L_q}(-Ri_q + u_q - L_d\omega_e i_d - E_q) \end{cases} \quad (4-1)$$

where $E_d \; and \; E_q = \omega_e \psi_f$ are the d-q axis induced electromotive force, respectively. In order to obtain the values of induced electromotive force in equation (4-1), the sliding mode observer is built as

$$\begin{cases} \frac{d\hat{\imath}_d}{dt} = \frac{1}{L_d}\left(-R\hat{\imath}_d + u_d + L_q\omega_e\hat{\imath}_q - V_d\right) \\ \frac{d\hat{\imath}_q}{dt} = \frac{1}{L_q}\left(-R\hat{\imath}_q + u_q - L_d\omega_e\hat{\imath}_d - V_q\right) \end{cases} \quad (4-2)$$

$$\begin{cases} V_d = k \cdot sgn(\hat{\imath}_d - i_d) \\ V_q = k \cdot sgn(\hat{\imath}_q - i_q) \end{cases} \quad (4-3)$$

where $\hat{\imath}_d$ and $\hat{\imath}_q$ are the d-q axis current observations for the stator in the rotating coordinate system; k is the sliding mode gain; sgn is a sign function.

The state equation of current error can be obtained by subtracting the equation (4-1) from the equation (4-2).

$$\begin{cases} \frac{d\tilde{\imath}_d}{dt} = \frac{1}{L_d}(-R\tilde{\imath}_d + L_q\omega_e\tilde{\imath}_q - V_d + E_d) \\ \frac{d\tilde{\imath}_q}{dt} = \frac{1}{L_q}(-R\tilde{\imath}_q - L_d\omega_e\tilde{\imath}_d - V_q + E_q) \end{cases} \quad (4-4)$$

$\tilde{\imath}_d = \hat{\imath}_d - i_d$ and $\tilde{\imath}_q = \hat{\imath}_q - i_q$ are the observation errors of current in the rotating coordinate system.

The equation (4-4) is rewritten as a vector form

$$\dot{\tilde{\boldsymbol{\imath}}} = \boldsymbol{A}\tilde{\boldsymbol{\imath}} + \boldsymbol{B}(-\boldsymbol{V} + \boldsymbol{E}) \quad (4-5)$$

where $\tilde{\boldsymbol{\imath}} = [\tilde{\imath}_d \quad \tilde{\imath}_q]^T$, $\mathbf{V} = [V_d \quad V_q]^T$, $\mathbf{E} = [E_d \quad E_q]^T$, $\mathbf{A} = \begin{bmatrix} -\frac{R}{L_d} & \frac{L_q}{L_d}\omega_e \\ -\frac{L_d}{L_q}\omega_e & -\frac{R}{L_q} \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}$.

The sliding mode observer is used to estimate the rotor speed. The function of sliding mode surface is defined as

$$\tilde{\boldsymbol{\imath}} = [\tilde{\imath}_d \quad \tilde{\imath}_q]^T = \mathbf{0} \quad (4-6)$$

The sliding mode observer begins to enter the sliding mode when the equation (4-7) is satisfied.

$$\tilde{\boldsymbol{i}}^T\dot{\tilde{\boldsymbol{i}}} < 0 \qquad (4-7)$$

When the sliding mode gain is large enough, the equation (4-7) is established. The system enters sliding mode and the observation errors gradually approach zero, and there is

$$\tilde{\boldsymbol{i}} = \dot{\tilde{\boldsymbol{i}}} = \boldsymbol{0} \qquad (4-8)$$

Substituting the equation (4-5) into the equation (4-8) yields

$$\mathrm{E} = \left[k \cdot sgn(\hat{\imath}_d - i_d) \quad k \cdot sgn(\hat{\imath}_q - i_q)\right]^T \qquad (4-9)$$

It can be seen from equation (4-9) that E contains discontinuous high-frequency signals, these discontinuous high-frequency signals should be removed by a low-pass filtering, yielding the equation (4-10)

$$\mathrm{E} = \begin{bmatrix}[k \cdot sgn(\hat{\imath}_d - i_d)]_{eq} \\ [k \cdot sgn(\hat{\imath}_q - i_q)]_{eq}\end{bmatrix} = \begin{bmatrix}0 \\ \omega_e\psi_f\end{bmatrix} \qquad (4-10)$$

When the condition given by equation (4-7) is reached according to the sliding mode, the expression of the gain k can be calculated by using equation (4-11).

$$\mathrm{k} = \check{\mathrm{n}} \cdot \max\left[\frac{E_d}{L_d} sgn(\tilde{\imath}_d) - (\frac{R}{L_d} + \frac{L_d}{L_q}\omega_e)|\tilde{\imath}_d| \quad \frac{E_q}{L_q} sgn(\tilde{\imath}_q) - (\frac{R}{L_q} + \frac{L_q}{L_d}\omega_e)|\tilde{\imath}_q|\right] \qquad (4-11)$$

where $\check{n}$ is a positive adjustment constant. Normally, when $\check{n}=2$ the condition of sliding mode $\tilde{\boldsymbol{i}}^T\dot{\tilde{\boldsymbol{i}}} < 0$ can be satisfied.

Therefore, the sliding mode observer can obtain estimated value of the component of induced electromotive force in the rotating coordinate system. It is known from equation (4-10) that E is equal to $\omega_e\psi_f$. Comparing equation (4-1) with equation (4-2), $E_q = V_q$ is established, so the estimation of rotor speed $\widehat{\omega}_e$ is

$$\widehat{\omega}_e = \frac{V_q}{\psi_f} \qquad (4-12)$$

4.1.2. The rotor position estimation based on Phase-locked loop

Because the ψ_f is not a constant due to the influence of temperature, load and other factors during actual operation, the position angle of rotor obtained by integrating from the equation(4-12) is not accurate one, therefore, the position estimation of rotor deviates from its actual value, which will affect the dynamic performance of the whole system. In order to obtain better dynamic performance, the phase-locked loop [7] is introduced to realize position estimation of rotor.

Since the winding of the motor is symmetrical, it is assumed that the phase voltage of the three-phase winding for the motor is

$$\begin{cases} u_a = u \cdot cost\omega_e t \\ u_b = u \cdot cos\left(\omega_e t - \frac{2\pi}{3}\right) \\ u_c = u \cdot cos\left(\omega_e t + \frac{2\pi}{3}\right) \end{cases} \qquad (4-13)$$

where u is the amplitude of phase voltage; let $\theta_e = \omega_e t$ and $\omega_e = \pi\rho_n n/30$; θ_e is the electrical angle; ρ_n is the number of pole-pairs of the motor; n is the mechanical speed of the motor.

According to the coordinate transformation theory, the transformation matrix [8] that transforms the three-phase voltage in the stationary coordinate system to the rotating coordinate system is

$$\mathrm{T}(\hat{\theta}_e) = \frac{1}{3}\begin{bmatrix} cos\hat{\theta}_e & \cos(\hat{\theta}_e - \frac{2}{3}\pi) & \cos(\hat{\theta}_e + \frac{2}{3}\pi) \\ -sin\hat{\theta}_e & -\sin(\hat{\theta}_e - \frac{2}{3}\pi) & -\sin(\hat{\theta}_e + \frac{2}{3}\pi) \end{bmatrix} \qquad (4-14)$$

where $\hat{\theta}_e$ is the estimation of the electrical angle and$\hat{\theta}_e = \widehat{\omega}_e t$.

Substituting the transformation matrix $\mathrm{T}(\hat{\theta}_e)$ into the equation (4-13) and by proper simplification, the equation (4-15) in the rotating coordinate system can be obtained.

$$\begin{bmatrix}V_d \\ V_q\end{bmatrix} = \begin{bmatrix}u \cdot sin(\hat{\theta}_e - \theta_e) \\ u \cdot cos(\hat{\theta}_e - \theta_e)\end{bmatrix} \qquad (4-15)$$

Define $\tilde{\theta}_e = \hat{\theta}_e - \theta_e$ as the estimation of the error for phase-locked loop. Adjust $\tilde{\theta}_e$ appropriately to zero, so that the position estimation of rotor converges to its actual value. Equation (4-15) shows that the estimation of the actual position of rotor is obtained when phase-locked loop tells V_q equals to u.

To sum up, the control block diagram [9] for sensorless three-phase PMSM based on phase-locked loop and sliding mode observer can be obtained, which is shown in Figure 1. This control system adopts the strategy of $i_d = 0$. In the speed feedback loop, the phase voltages obtained from the sampling which is transformed by rotating coordinate system are used as the input of the sliding mode observer, and $\theta^*{}_e$ and $\omega^*{}_e$ are the output of sliding mode observer, which are the estimations of phase angle and the speed of rotor, respectively. $\omega^*{}_e$ is transformed proportionally and becomes the speed feedback signal. The current feedback control loop takes the phase current obtained from the sampling which is transformed by static coordinate and rotating coordinate system as the current feedback signal.

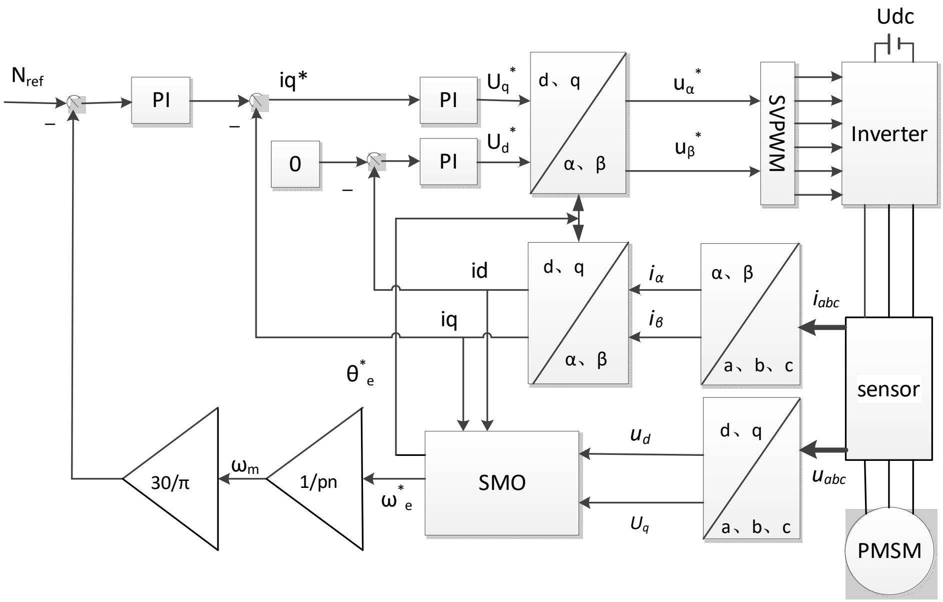

Figure 1 The control block diagram of the control system for sensorless three-phase PMSM

5. Simulation verification

Because the simulation effects of the ac servo system for PMSM using traditional vector control method and the direct torque control method are basically the same, so that the vector control method is selected for simulation. Matlab/simulink is used to build the simulation models of ac servo control system for PMSM based on the vector control method and the algorithms of phase-locked loop and sliding mode observer, respectively. The simulation results are compared to verify the feasibility of the servo control system based on the algorithms of phase-locked loop and sliding mode observer. The simulation parameters of the two control methods are set according to the actual requirements. The simulation results are shown as follows.

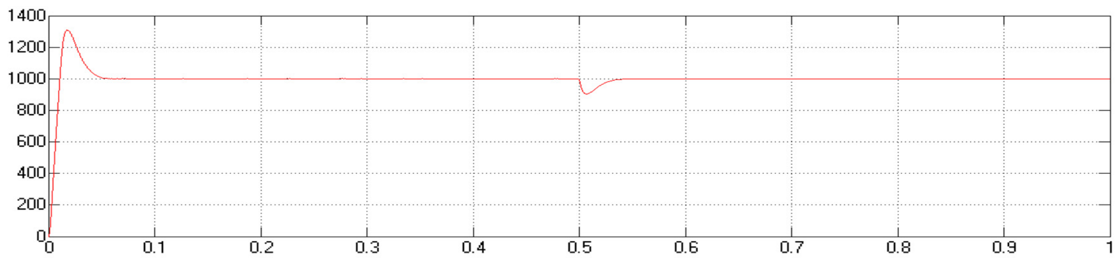

Figure 2 The speed-time curve of the motor, where the vertical axis is the speed and the horizontal axis is the time

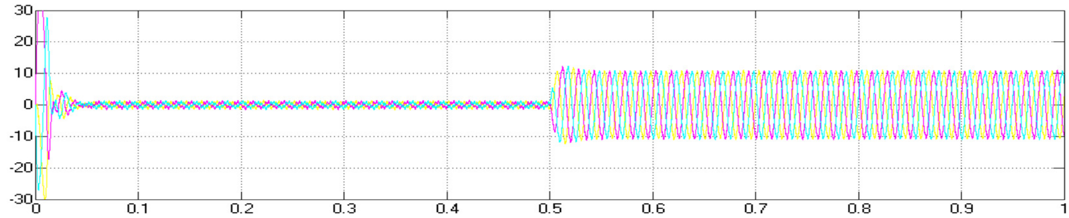

Figure 3 The curve of three-phase current i_{abc} , where the vertical axis is current and the horizontal axis is time

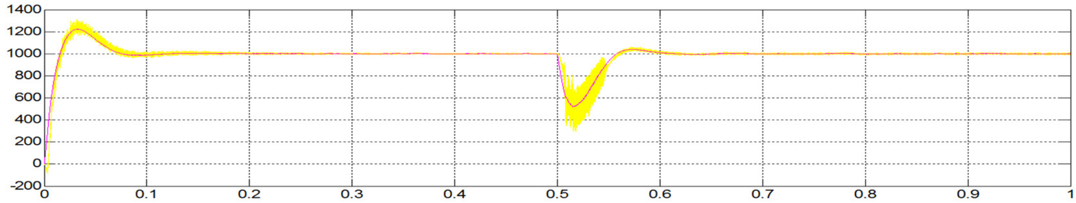

Figure 4 The speed-time curve of the motor, where the red is the actual speed value and the yellow is the estimated value of the speed; the vertical axis is the speed and the horizontal axis is the time.

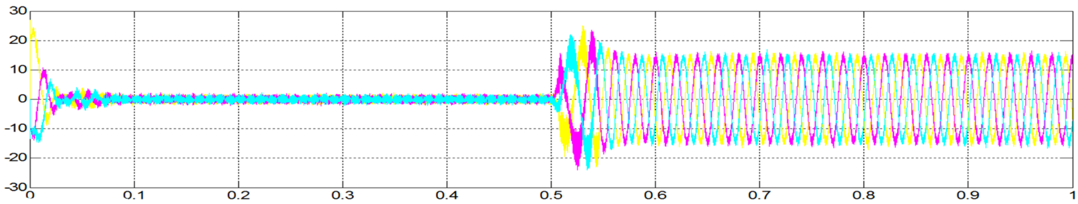

Figure 5 The curve of three-phase current i_{abc} , where the vertical axis is current and the horizontal axis is time

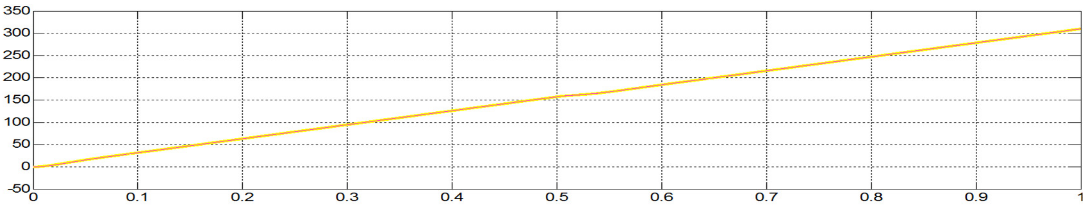

Figure 6 The curve of the estimation of position error for rotor, where the red is the actual value and the yellow is the estimated value; the vertical axis is the angle and the horizontal axis is the time

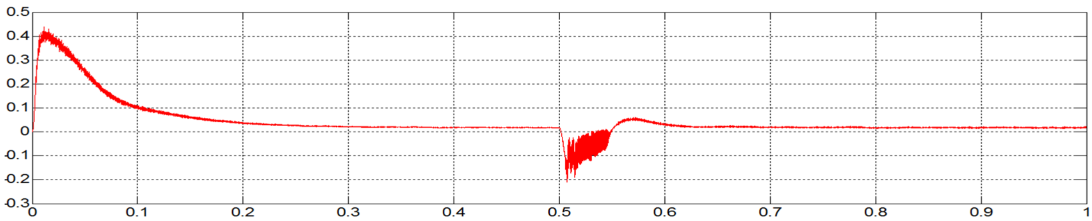

Figure 7 The e curve of the estimation of position error of rotor, where the vertical axis is value of the estimated error and the horizontal axis is the time

In the above simulation results, the Figure 2 and 3 are the simulation waveforms of system using vector control method, and Figure 4 to 7 are the simulation waveforms of system based on the algorithms of phase-locked loop and sliding mode observer. As can be seen from Figure 4 and 5, when the motor speed rises from zero to the reference speed of 1000r/min, although the motor speed has a certain overshoot at the beginning, it has a fast dynamic response speed. The load is introduced suddenly at 0.5s, the actual speed of the motor can quickly restore to the given speed, and both the actual value and the estimated value of speed and the actual value and the estimated value of rotor position can be well fitted. Compared Figure 2 to 3 with Figure 4 to 5, the simulation results of the vector control method and the control method based on the algorithms of phase-locked loop and sliding mode observer are basically the same.

6. Conclusion

This paper studies the ac servo control system of industrial lockstitch sewing machine. The simulation results show that the ac servo control system based on the algorithms of phase-locked loop and sliding mode observer not only has almost the same control performances as the traditional control system, but also reduces the number of sensors, simplifies the system structure and improves the system adaptability to the environments. Therefore this ac servo control system is feasible and has high performance-price ratio. It is an ideal ac servo control system for industrial lockstitch sewing machine.

Acknowledgments

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