Hardware detection and parameter tuning method for speed control system of PMSM

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Abstract. In this paper, the development of permanent magnet synchronous motor AC speed control system is taken as an example, aiming to expound the principle and parameter setting method of the system hardware, and puts forward the method of using software or hardware to eliminate the problem.

1. Introduction

In AC servo speed control system, it has been the focus of many electrical engineers or researchers. The permanent magnet synchronous motor (PMSM) with its high torque inertia ratio, high energy density and high efficiency, etc., in the development of small and medium power drive range, has caused more and more attention to [1-3]. And scientific research in the development of speed control system is not only software, hardware testing and parameter tuning are critical, but also to the development of the subsequent success plays a decisive role.

AC speed control system of permanent magnet synchronous motor is composed of three phase voltage inverter, permanent magnet synchronous motor, DC motor, three phase adjustable transformer, controller and voltage current detection part [4]. Development work is generally divided into two major parts, hardware and software parts. For many engaged in software development, and intelligent control of the scientific research personnel, mostly to research support staff completed preliminary hardware debugging work, in order to put the main work that chases the frontiers of science. In the actual work, conflicts are often occurring between the researchers and the auxiliary staff because of research and development issues and contradictions. For example, someone of the researchers designed a new type of permanent magnet synchronous motor, then the new PMSM will be tested and experimented by the researcher himself or others. Before that, the auxiliary staff would prepare all needed experimental tools well including inverter. However, when encountering problems with traditional AC control methods like the conventional field oriented control, maximum torque control and weak magnetic control, the researcher often put the blame on the speed control system of hardware facilities, especially on the inverter. And researchers in the preparation of software debugging process, often need the auxiliary staff to complete the test of the hardware facilities firstly, in order to ensure the correctness of software debugging.

As an example, the basic working principle and parameter setting method of system hardware is described in this paper, and the method of using software is put forward to realize the rapid development of scientific research personnel.

2. PMSM coordinate system mathematical model

Since the current vector control PMSM is used, the mathematical model of PMSM rotor reference frame is presented firstly as follow:

Voltage equation:

\[ u_d = R_s \cdot i_d + p \cdot \varphi_d - \omega \cdot \varphi_q \]  \hspace{1cm} (1)
\[ u_q = R_s \cdot i_q + p \cdot \varphi_q + \omega_n \cdot \varphi_d \] (2)

or expressed as a matrix form:

\[
\begin{bmatrix}
    u_q \\
    u_d
\end{bmatrix} =
\begin{bmatrix}
    R_s & 0 \\
    0 & R_s
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} +
\begin{bmatrix}
    p & -\omega_n \\
    \omega_n & p
\end{bmatrix}
\begin{bmatrix}
    \varphi_d \\
    \varphi_q
\end{bmatrix}
\] (3)

Flux linkage equation:

\[ \varphi_d = L_d \cdot i_d + \varphi_f \] (4)

\[ \varphi_q = L_q \cdot i_q \] (5)

Electromagnetic torque equation:

\[ T_{em} = \frac{3}{2} P_s \cdot (\varphi_d \cdot i_q - \varphi_q \cdot i_d) \] (6)

Which \( u_d, u_q \) and \( i_d, i_q \) are the voltage and current respectively; \( L_d, L_q \) and \( \varphi_d, \varphi_q \) are the inductance and flux linkages on the \( d, q \) axis respectively; \( \varphi_f \) is permanent magnet flux linkage; \( p = \frac{d}{dt} \) is differential operator; \( P_s \) is permanent magnet pole number; \( \omega_n \) is the rotor angular speed; \( T_{em} \) is electromagnetic torque.

2.1. Principle of system operation

As shown in Figure 1, in the permanent magnet synchronous motor AC speed control system development, the main circuit is composed of a three-phase transformer with 0-380V power supply; and the three-phase voltage inverter can be converted into frequency in 0-1000 Hz and 0-415V in the voltage change of the power supply, the main switch device using IGBT, control signal by DSPACE PWM I/O; variable frequency power supply by A2, B2, C2 connected to the salient pole permanent magnet synchronous motor IPMSM motor, with parameters of table I; EN encoding for rotor position detection of rotor, each turn output 4000 Hz high level pulse, and connected to the DSPACE encoding plate interface; DC motor load controller used as a test; using DSP as the core technology of DSPACE1104, and a desktop computer connected to complete the visual software programming and IPMSM closed-loop control; phase current, after testing through the coaxial cable is connected to the DSPACE ADC1 and ADC2 port, to complete conversion from analog signal to digital signal. Detection tools need to be prepared: DC constant voltage constant current source, multi-meter, oscilloscope, tachometer and wire number.

![Figure 1. Speed control development system of PMSM](image-url)
3. Hardware initialization test analysis

Table 1. Parameters of IPMSM

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Phase resistance 5.8-7.8Ω | d-axis inductance 0.0448H |
|                           | q-axis inductance 0.1027H |
| Moment of inertia 0.001329 kg m² | Rated speed 4000 rpm |
|                           | Permanent magnet flux 0.533 wb |
|                           | Pole pair 2            |

3.1. Initial installation angle between rotor and incremental encoder

Unlike DC motor and asynchronous motor, before the start we need to know the accurate rotor initial position of permanent magnet synchronous motor (PMSM), to complete the coordinate transformation realization of vector control strategies. We usually use the incremental encoder to obtain the rotor position, and incremental encoder generally provide 3 group of pulses, A, B, and Z, the A and B combined pulse rotor speed and positive & negative information can be obtained, and also when the rotor to rotate a circle with A\ Z pulse. After the encoder is actually installed to the rotor shaft, there is a certain angle between the initial angle of the rotor and the mechanical position of the Z pulse, which is called the initial installation angle. Only when the initial installation angle is accurate, can the position of the rotor be acquired in the condition of standstill or rotation.

Through the DC to the DC motor rotation, and drag the PMSM, through the oscilloscope or DSPACE 1104 control window to observe the counter electromotive force waveform and Z pulse waveform. Then adjusting the two waveform, the Z pulse down along with the anti electromotive force waveform zero crossing alignment, can be observed in the Z pulse ahead of the rotor N pole (the highest point of the back EMF) point of view. Due to the PMSM of the rotor pole number is 2, so the angle between the two Z pulses is 360°*2 electric angle.

3.2. Detection and Elimination of the Error of Phase Current Detection

Because the current sensor has a certain nonlinear, the output voltage of the inverter is zero, the current signal is not zero, and sometimes even to achieve the 0.5A error, as shown in Figure 2. And the initial error of the current is too large, which has great influence on the flatness and smoothness of the PMSM three-phase current, which leads to the precision control of the performance and even the failure. And different current sensor board, the detection error is not the same size, so developers usually use the software method to eliminate the initial error of current detection. Since the load is generally three-phase symmetrical load, so we can measure currents $i_a$, $i_b$, and get the $i_c = -i_a - i_b$. In Figure 2, $i_c$ is about to 0.45 amperes or so, we can subtract that value in the software in advance, for the same, you can make the initial value of three-phase current is close to zero, error is generally in the range of 0.05A, the system control performance had little effect.

![Figure 2. Initial detection error of three phase current](image)

3.3. Phase current and voltage scaling factor

Since the voltage and current sensor signal is generally small voltage signals, and in the PMSM control software programming, in order to make the program voltage and current variables value and the actual measured values are equal, we must to measure voltage, current sensor of the linear range and calculate the corresponding proportion coefficient. For example, table 2 shows, using a wire along
the current sensor in the direction of the arrow, the DC current source 1A, 3A, 5A were input to a fixed resistors, and get the value of the corresponding current sensor, which can calculate the current sensor in the actual circuit in the proportion coefficient is 10, pay attention to the positive and negative are key here. And the use of a universal table for simple voltage measurement can get the voltage scaling factor.

3.4. Test for inverter operating frequency and voltage
Voltage inverter in high precision speed control of PMSM control system plays an important role. Therefore, it is necessary to tests were carried out under different conditions on the inverter, especially of high frequency and high voltage stage, current waveform can maintain good sine degree directly affects the weak magnetic speed control strategy. In order to prevent the high frequency, the inverter main switch device in the course of a short circuit, the inverter protection, control system can not work properly.

![Figure 3. Load current curves when input voltage is DC 100V and output frequency is 100Hz](image)

![Figure 4. Load current curves when input voltage is DC 100V and output frequency is 500Hz](image)

Therefore, the dead time must be set according to the performance of the main switch device, which is generally 2-4us. Figure 3 shows the voltage inverter in the input DC voltage is 100V, AC output voltage and frequency is 100Hz load current waveform curve; Figure 4 for the inverter output frequency is 500Hz load current waveform. Compared to the two can be seen, the inverter in frequency 500Hz began to appear current waveform distortion.

4. Software program test

4.1. Software program test for PMSM open-loop drive
As shown in Figure 5, in order to complete the FOC system PMSM closed-loop control method, we first need to carry out the system open-loop control program debugging, in which the load can be used RL load instead of permanent magnet synchronous motor. The purpose of this is to test whether the
current loop program is correct in the open loop control, and whether the current response can follow the input control signal correctly. As shown in Figure 6, the current control commands by the three-phase three-phase ABC coordinate conversion into DQ reference instruction, which id-ref is set to 0, the iq-ref set as unit step step curve, when the q-axis current IQ can quickly follow the control signal iq-ref prove current loop control parameters and procedures correctly, open-loop commissioning work is completed.

![Diagram](image)

**Figure 5.** Open-loop vector control flow based on SV-PWM

| 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| -3 | -2 | -1 | 0 | 1 | 2 | 3 |

**Figure 6.** Response curves of q axis current following command

### 4.2. Test and analysis of PMSM drive based on closed loop control

![Diagram](image)

**Figure 7.** PMSM drive closed loop vector control block diagram
As shown in Figure 7, the permanent magnet synchronous motor vector control system by the inner current loop and the outer loop velocity loop together to complete the double closed loop control, and in the front part has set by the open loop control completed the current loop control software program testing, so here only of speed loop completion of the program is compiled and debugged and PI control parameters of the manual debugging, and through the motor testing a, B and C three-phase current symmetric peace sliding and steady speed to judge whether the drive system of the basic testing. As shown in Figure 8 for the permanent magnet synchronous motor three-phase B, A, C output current curve, it can be seen that the three-phase current has a good symmetry and smooth, the entire motor drive system to complete the basic closed-loop vector control requirements.

5. Conclusion
In this paper, the permanent magnet synchronous motor AC speed control system as an example, detailed description of the working principle of the system hardware and software and testing methods, and aiming at some hardware inherent problems put forward to eliminate the detection error and the ratio of voltage and current sensor tuning method using the software, the rotor and the incremental encoder initial installation angle detection switch the dead time setting device, these problems and solving methods have important reference value in engineering practice and scientific research in the development process, the rapid completion of PMSM closed loop vector control test of scientific research personnel, for the next step to continue to carry out further scientific research or to achieve rapid product development to provide a strong guarantee, so this paper has a positive promotion of scientific research and development work.

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