Speed identification technology in speed sensorless machine drive systems

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Abstract. Speed control system based on speed sensorless system is a research and project which is widely concerned by the international electric drive industry. The researchers found that the speed sensorless system has better rotation rate measurement, which is no longer affected by temperature, humidity, and other environments. However, there are higher requirements for the accuracy and speed of revolution measurement and feedback adjustment of the speed sensorless control mechanism. Therefore, the research topic of this paper is how to use a speed sensor to measure speed more efficiently. The research methods of this dissertation are as follows: second-order synovial observer, rotor tooth harmonic signal, and feedforward decoupling control are used to explore and analyze. It is found that the design of a second-order synovial observer can achieve better control performance in a high-speed range. Rotation speed can be obtained by using the harmonic signal of the rotor and current filter. At the same time, the rotation speed can be determined by the current Ideal model of an electromagnetic chain. Finally, the author makes a comprehensive comparison of the three methods, finds the problems of the three methods, analyses the causes, and puts forward possible solutions.

Keywords: Speed sensorless machine drive systems; second-order sliding mode observer; rotor tooth harmonic method; feedforward decoupling control method; Clark transform; Park transform.

1. Introduction

The speed sensorless control technology begins with the speed measurement and feedback system of conventional speed sensors. Some engineers use the speed sensor based on the photoelectric code disk to measure the velocity of the motor, and also need retroaction on the speed signal to form a closed loop. Such a design is very cumbersome, and the cost of the system is greatly increased. There may be concentricity problems in the installation of the code disk on the motor. Therefore, more and more scholars and scientists have focused their research on the speed sensorless control system. After 13 years of hard research, R. joetten et al. [1] combined speed sensorless systems and vector control for the first time. This achievement greatly promoted the innovation of speed sensorless systems and scientists' recognition of its prospects. However, as far as the current situation is concerned, the research on speed sensorless variable frequency speed regulation in China started late, and there is a big gap with foreign countries. There are still some substantive problems with the speed sensorless system. For example, in the development of clean energy, electric vehicle, and hybrid oil-electric vehicle, there are a lot of difficulties in the engine design and use environment. Environmental factors such as humidity and low temperature often lead to encoder disconnection, pulse signal loss, and other failures. This leads to the failure of the vector control system [2]. This paper introduces three methods of second order synovial devices, the frequency component of the harmonic signal of rotator teeth related to speed, the current model of rotator magnetic chain, and an improved voltage model to solve some speed identification problems in the speed-sensorless system.

2. Rotor tooth harmonic method

In the process of measuring the speed of the motor, some speed sensors have high requirements on the size of the parameters in the motor, such as efficiency, frequency, starting current, etc. If these parameters cannot be accurately measured and brought into the formula, the speed cannot be obtained. Therefore, many scholars have found and used the frequency components related to the rotation speed

in the rotor tooth harmonic signal to extract the rotation speed. This method takes into account the magnetic circuit saturation, hysteresis lag and vortexing, and skin collecting effect.

There will be cogging between the rotor and stator of the induction motor, and the air gap is tooth-shaped, not smooth, and uniform, so a harmonic magnetic field will be generated in the air gap of the motor. As shown in Fig. 1, when the motor rotates, because the winding magnetic potential curve is not sinusoidal, the harmonic magnetic field will generate harmonic voltage and current on the coil of the stator winding. Through the analysis of the obtained voltage and current, the harmonic quantity of the tooth slot can be obtained, and the magnitude of the rotational speed n can be deduced through the relationship between the harmonic quantity and the rotational speed [3]. This method mainly uses data signal processing, Fourier transforms and other technologies.

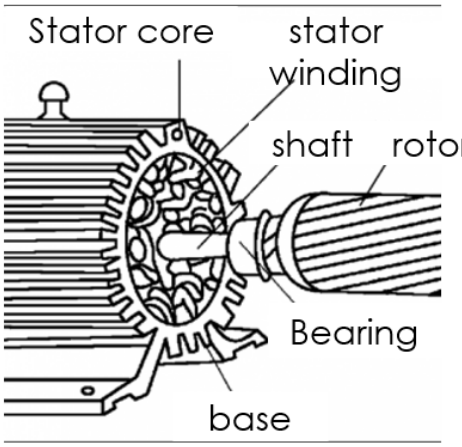


Fig. 1 Diagram of rotor and stator of three-phase asynchronous motor [4].

Rotor tooth harmonic frequency:

$$f_{sh} = \frac{z_r}{P} f \pm f_1 \tag{1}$$

Bring the speed n (2) into (1):

$$n = \frac{60f}{p} \tag{2}$$

It can be concluded that:

$$n = \frac{60}{z_r}(f_{sh} \pm f_1) \tag{3}$$

where z_r is the number of slots without rotor; f_1 is the fundamental frequency; f is the electric motor frequency; p is the number of pole pairs; f_{sh} is the harmonic frequency of rotor teeth [3].

3. Conventional sliding mode observer for speed measurement

When using vector control, it is necessary to obtain the position information of the rotor first. It is very important to analyze and feedback on the position information to control the operation of the motor. The operating environment is usually bad. vibration, humidity, high temperature, and other environmental factors often lead to encoder pulse signal loss and other failures. and then lead to vector control system operation failure [5]. Therefore, this paper mainly uses the fundamental wave back EMF observation method to measure the rotor speed. Although this method can not guarantee high accuracy when the motor is in a low-speed motion state, it can maintain high-speed measurement accuracy and rotor position positioning in a high-speed motion state [6]. This method is now recognized by many scholars.

A sliding pattern observer can be constructed to observe the reverse electrodynamic force (EMF) and estimate the rotor position. In the document [7], a second-order synovial observer is designed to effectively control the sensor system. p represents the differential operator $p\hat{i}_\alpha$ $p_{\hat{i}_\beta}$ can be calculated in (4).

$$\begin{cases} p\hat{\imath}_\alpha = -\frac{R_s}{L_s}\hat{\imath}_a + \frac{u_\alpha}{L_s} - \frac{1}{L_s}s_a \\ p_{\hat{\imath}_\beta} = -\frac{R_s}{L_s}\hat{\imath}_\beta + \frac{u_\beta}{L_s} - \frac{1}{L_s}s_\beta \end{cases} \tag{4}$$

i_a and i_β are axis α and β components of stator galvanic current and electric tension of permanent magnet synchronous motor (PM motor) respectively. $\hat{\imath}_a$ and $\hat{\imath}_\beta$ in the formula are the estimated values of the current (estimated values should be reasonable and cannot be taken blindly). At the same time, s_a and s_β need to satisfy the formula (5).

$$\begin{cases} S_a = k\,sgn(\hat{\imath}_a - i_a) \\ S_a = k\,sgn(\hat{\imath}_\beta - i_\beta) \end{cases} \tag{5}$$

S_a and S_ρ has a lot of noise. To solve the noise problem, it can be considered to add a low-pass filter (LPF) to the external circuit of the motor. The LPF permits the signal under the cut-off frequency to pass, but the signal above the cut-off rate is unable to pass, which will lead to phase and amplitude errors.

Therefore, it is necessary to compensate for the phase and amplitude errors. According to references [8, 9], the concept of feedback here can be organically combined with the second-order synovium to solve the problem of compensation errors. Therefore, the new values of $p_{\hat{\imath}\alpha}$ and $p_{\hat{\imath}\beta}$ can be calculated in (6).

$$\begin{cases} p_{\hat{\imath}\alpha} = -\frac{R_S}{L_S}\hat{\imath}_a + \frac{U_\alpha}{L_S} - \frac{1}{L_s}\left(S_\alpha + l\hat{S}_{aeq}\right) \\ p_{\hat{\imath}\beta} = -\frac{R_S}{L_S}\hat{\imath}_\beta + \frac{U_\beta}{L_S} - \frac{1}{L_s}\left(S_\beta + l\hat{S}_{\beta eq}\right) \end{cases} \tag{6}$$

where l is the feedback gain, while $\hat{S}_{aeq}$ and $\hat{S}_{\beta eq}$ need to satisfy the relationship (7).

$$\begin{cases} \hat{S}_{aeq} = \frac{1}{Ts+1}S_\alpha \\ \hat{S}_{\beta eq} = \frac{1}{Ts+1}S_\beta \end{cases} \tag{7}$$

T is the time constant of LPF added to the external circuit of the motor, and its size cannot be too large, otherwise, the waveform passing through the filter will be greatly distorted.

This method can effectively improve the velocity sensorless accuracy by designing and reasonably adjusting the values of l, $\hat{S}_{aeq}$ and $\hat{S}_{\beta eq}$. In some harsh environments, many factors affect the performance of the sensor. At this time, unnecessary errors can be controlled by adjusting the parameters of the second-order synovium. This is a very effective control method.

4. Speed measurement of feedforward decoupling control method

The three stator current componentsi_a, $i_b$and i_c of the asynchronous motor in the stationary coordinate system are subjected to clark and park transformation to gain the current components $i_{s_\alpha}, i_{s_\beta}$in the stationary coordinate system. The rotor flux estimation value ψ_γ and the rotor flux phase andigammdigammas ϕ are obtained through cacalculationand then the three-phase stator voltage u_A, u_B, u_C are Clark transformed to obtain the component $u_{s_\alpha}, u_{s_\beta}$of the three-phase stator voltage in the stationary cooris dinate system. Thus, the rotor speed $\hat{\omega}$ is determined by using the current model of flux linkage and modified voltage model [10].

This theoretical method needs to estimate the angular velocity $\hat{\omega}$ of the rotor through the calculation of the formula (8).

$$\begin{cases} \frac{d\psi_r}{dt} = -\frac{1}{T}\psi_r + \frac{L_m}{T_r} i_{sm} \\ \omega_1 = \hat{\omega} + \frac{L_m}{T_r \psi_r} i_{st} \\ \varphi = \int \omega_1 \, dt \end{cases} \tag{8}$$

The parameters are described as follows: ω_1 is the synchronous angular velocity, φ is the rotation phase angle of the magnetic chain generated by the rotor, L_r, R_r are the inductance and resistance of the rotor, T_m is the electromagnetic time constant of the rotor, and the magnitude is the ratio of inductance and resistance (9).

$$T_m = \frac{L_r}{R_r} \tag{9}$$

To use the improved voltage model to estimate the speed of $\hat{\omega}$, an improved method is to add aanLPF to determine the magnetic chains ' magnitude ψ'_{sa} and $\psi'_{s\beta}$ of the stator (10).

$$\begin{cases} \psi'_{sa} = \frac{1}{s+\omega_c}(-R_s i_{s\alpha} + u_{s\alpha}) \\ \psi'_{s\beta} = \frac{1}{s+\omega_c}(-R_s i_{s\beta} + u_{s\beta}) \end{cases} \tag{10}$$

When an LPF is added to this model, The phase lag at the gain frequency traversal reduces the stability margin and brings instability to the control system. Therefore, the amplitude ψ'_{sa} and $\psi'_{s\beta}$ of the stator magnetic chain need to be added to compensate for $\psi_{s\alpha}$ and $\psi_{s\beta}$ (11).

$$\begin{cases} \psi_{ra} = \frac{L_r}{L_m}(\psi_{sa} - \delta L_s i_{s\alpha}) \\ \psi_{r\beta} = \frac{L_r}{L_m}(\psi_{s\beta} - \delta L_s i_{s\beta}) \end{cases} \tag{11}$$

ψ_{ra} and $\psi_{r\beta}$ are the components of the rotor magnetic chain on the α and β axis. The model with a low-pass filter produces a leakage sensation with a leakage coefficient of δ.

5. Comparison and Discussion

The principle of the rotor tooth harmonic method is relatively simple and easy to measure the speed directly. With the improvement of digital signal processing technology and spectrum analysis technology based on the harmonic generator, the accuracy of the rotor tooth harmonic method will be much higher. However, the harmonic signal measured by the stator is relatively strong, and it is difficult for the oscilloscope to capture a clear signal. To solve these problems and improve the accuracy of the signal and the robustness to noise, the harmonic detection method of stator current can be adopted. It mainly calculates the instantaneous active current and reactive current of the three-phase current [11].

The second method is to design a second-order sliding mode observer for a PM motor to realize speed sensor control. This method uses the first derivative of the sliding surface representing the rate of change of the system response to evaluate the system state. The defect is that the synovium is too noisy. It can be seen from the above that the method needs to add an LPF, and also needs to compensate for the phase and amplitude, so the operation steps will be cumbersome in real use. To solve this problem, literature [12] designed a new control method without a speed sensor for synovium. This method needs to collect the feedback signals $\hat{S}_{aeq}$ and $\hat{S}_{\beta eq}$ by using a state observer. The state observer is introduced to solve the problem that some state variables cannot be

observed when state feedback is applied. So that the use of a low-pass filter can be avoided. The operation steps are also relatively simple. At the same time, a large range of speed detection can be achieved.

The third method is based on Clark and Park transformations of the three-phase electric current and voltage of the motor. The rotator speed is estimated using the current model of the magnetic chain and the improved voltage model. The two transformations project a b c axis into the static coordinate system $\alpha\&\beta$ and the rotated coordinate system d&q respectively. Clark transformation is to project the three-phase current of the stator onto the straight and cross-axes with the rotation of the rotator, which diagonalizes the inductance matrix and facilitates the operation analysis of the PM motor. However, In the actual operation of the motor, the actual values of the motor parameters (stator resistance, stator inductance, magnetic chain amplitude of the permanent magnet) will deviate due to the influence of temperature change and whether the magnetic field is saturated [13]. This method is also computationally intensive and can be calculated with the help of simulation software on the computer.

The summary of the method comparison is presented in Table 1.

Table 1. Three Method comparing

	rotor tooth harmonic signal	Conventional sliding mode observer	feedforward decoupling control
Principle	Relationship between Harmonic Current, Voltage, Harmonic Frequency, and Rotation Speed	The first derivative of the sliding mode surface of the system response rate	Rotor magnetic chain model in rotating coordinate system, Improved voltage model
Technical requirement	Digital Signal Processing Technology, Fast Fourier Transform Chip	second-order sliding mode observer	Park and Clark transform
Detection parameters	$f_1,\ f_{sh},\ z_r$	$\hat{\imath}_a, \hat{\imath}_\beta,\ u_\alpha,\ U_\beta,\ L_s,\ T$	$i_{s_\alpha}, i_{s_\beta}, u_{s_\alpha}, u_{s_\beta} L_r, L_m, R_r, \psi_{ra}, \psi_{r\beta}$
Speed Range	Wide range	Wide range	Wide range
Control accuracy	High	Medium	Low
Technical difficulties	A harmonic signal is relatively strong.	Need to add a low-pass filter	Tedious calculation The parameters are affected by temperature.
Solutions	Stator‘s current harmonic detection method	Introducing a state observer	with the help of simulation software

6. Conclusion

There is still much room for the potential of speed-free sensors. Now many speed-free sensors rely mainly on the changes in electromagnetic fields to get signals, which can be further calculated by filters or theoretical formulas. Therefore, these sensors cannot detect the rotation speed in some strong magnetic fields. At the same time, the choice of materials for such sensors needs to be explored and discussed. These are application issues that future experts may need to consider.

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