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An Improved Method to Estimate Initial Rotor Position for Surface-Mounted Permanent Magnet Synchronous Motors

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Abstract — Permanent magnet synchronous motors (PMSM) are widely used in servo systems, and many methods have been proposed to solve the critical problem of detecting the rotor position in real time. However, existing methods are not suitable for the detection of initial rotor position for surface-mounted permanent magnet synchronous motors (SPMSM). A simple and highly accurate method utilizing an incremental encoder is presented. By applying certain current vectors, monitoring the direction of motor's rotation, and changing the next applied current vectors, the initial rotor position can be obtained.

I. Introduction

With the development of power electronics and control theories, permanent magnet synchronous motors, which have many attractive characteristics such as high efficiency, high power density, fast dynamic response, wide speed control capability and accurate positioning, have been widely used in servo systems and high-performance speed regulating systems. To some degree, the precision of industrial servo systems represents the level of equipment manufacturing of a nation. Thus, a lot of attention has been attached to the development of high-performance PMSMs in our country. One critical factor is to detect the rotor position in a simple and accurate way, especially the initial rotor position, which has an impact on whether motors can start up with the largest torque and whether the rotor may reverse.

Many efforts have been made and many methods have been proposed, which can be divided into two categories: the mechanical sensor methods and the sensorless detection methods [1-7]. This paper reviews several rotor position estimation methods and some experiments were carried to see whether they are effective for initial rotor position estimation of the surface-mounted permanent magnet synchronous motor (SPMSM). On this basis, an improved and simple method is given for detection with better precision.

II. Review of Rotor Position Estimation Methods

A. Mechanical Position Sensors Method

Resolvers and encoders are usually used as mechanical position sensors in PMSMs. The principle of resolvers is based on the following equation:

$$u = kU_m \sin(\omega_0 t + \theta) \tag{1}$$

Where u is the output voltage of the resolver, ω_0 the angular frequency of the resolver's excitation signal, θ is the rotor position. The equation indicates that the output contains the rotor position information, but to obtain the information, the output needs to be demodulated, which requires complex algorithms and expensive decoders.

There are two kinds of encoders: absolute encoders and incremental encoders. The output of absolute encoders is a binary number, corresponding to the rotor position. However, because of the limited space on the code disk, the detection accuracy is lower than that of incremental encoders. Also, the output signal is usually transferred in a parallel way, requiring many wires and thus making the system very complicated. Incremental encoders, which have relatively simple structures and high accuracy, only have three output signals: pulse signal A, B and Z. With these signals, the rotor position and direction of rotation can be easily computed. However, the outputs are incremental signals, which cannot obtain the rotor position information at standstill. Although new incremental encoders with UVW hall signal outputs can position the stationary rotor, the maximum error is ±30°.

B. Sensorless Detection Method

1) Back Electromotive Force (EMF) Method

In a PMSM, the direction of the permanent magnet's flux linkage vector ψ_f is aligned with the d-axis of the rotor. When the permanent magnets rotate, the stator windings cut the magnetic field and a back EMF is generated, which changes with the rotor position [1]. The relation between them can be described as follows:

$$e_0 = e_\alpha + \mathrm{j}e_\beta = -\omega_r\psi_f \sin\theta + \mathrm{j}\omega_r\psi_f \cos\theta \ , \tag{2}$$

$$e_\alpha = u_\alpha - R_s i_\alpha - L_s \frac{di_\alpha}{dt} \ , \tag{3}$$

$$e_\beta = u_\beta - R_s i_\beta - L_s \frac{di_\beta}{dt} \ , \tag{4}$$

where e_0 is the back EMF, R_s the stator resistance, L_s the stator inductance, ω_r the rotor angular velocity and θ the rotor position, while e_α, e_β, u_α, u_β, i_α, i_β correspond to the components of back EMF, stator voltage and current in the α-β axis respectively. Based on these three equations above, the rotor position can be obtained by the following formula:

$$\theta = \arctan\left(\frac{-u_\alpha + R_s i_\alpha + L_s \dfrac{di_\alpha}{dt}}{-u_\beta + R_s i_\beta + L_s \dfrac{di_\beta}{dt}}\right) \tag{5}$$

This method does not need additional equipment and the algorithm is not complicated, and this has been proved to be

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effective on rotor position detection in the high-speed range. However, this method relies on parameters of the motor, so the robustness is weak. In addition, formula (2) shows that when the motor is in the low-speed range or at standstill, the back EMF is very small and cannot be accurately detected, leading to a failure on initial rotor position detection.

2) High-frequency Signal Injection Method

This kind of method injects high-frequency signals into the motor and utilizes the current response to estimate the initial position [2]. The stator voltage and flux equations of PMSM in an arbitrary $d'q'$ reference frame are shown as follows [3]:

$$\begin{cases} u'_d = Ri'_d + p\psi'_d - \omega'\psi'_q \\ u'_q = Ri'_q + p\psi'_q + \omega'\psi'_d \end{cases}, \tag{6}$$

$$\begin{cases} \psi'_d = [L+\Delta L\cos(2\theta-2\theta')]i'_d + \Delta L\sin(2\theta-2\theta')i'_q + \psi_f\cos(\theta-\theta') \\ \psi'_q = \Delta L\sin(2\theta-2\theta')i'_d + [L-\Delta L\cos(2\theta-2\theta')]i'_q + \psi_f\sin(\theta-\theta') \end{cases}, \tag{7}$$

where u'_d, u'_q, ψ'_d, ψ'_q, i'_d, i'_q are the stator d' and q'-axis voltage, flux linkage and current in the arbitrary $d'q'$ axis, respectively, L is the average inductance, ΔL the amplitude of the spatial modulation of the inductance defined as

$$L = (L_q + L_d)/2 \quad \Delta L = (L_q - L_d)/2, \tag{8}$$

p the derivative operator, ω' the angular velocity of d′-axis and θ′ the angle between d′-axis and α-axis. The relation between the coordinate systems is shown in Fig. 1 [3].

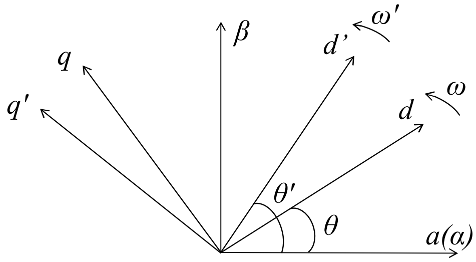

Fig. 1 The relation between coordinate systems.

If ω' and θ' are both zero, then the equation is built in the $\alpha\beta$ reference frame. Injecting high-frequency voltage signals ($u_\alpha = u_\beta = U_m\cos\omega_h t$) into the stator windings, the expressions of the stator α and β currents are:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{U_m\sin\omega_h t}{(L^2-\Delta L^2)\omega_h}\begin{bmatrix} L-\sqrt{2}\Delta L\cos(2\theta-\pi/4) \\ L-\sqrt{2}\Delta L\sin(2\theta-\pi/4) \end{bmatrix}, \tag{9}$$

The amplitudes of the high-frequency currents contain the rotor position information θ. And the current amplitudes I_α, I_β can be obtained through modulation and low-pass filters.

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} LPF(i_\alpha\sin\omega_h t) \\ LPF(i_\beta\sin\omega_h t) \end{bmatrix} = \frac{U_m}{2(L^2-\Delta L^2)\omega_h}\begin{bmatrix} L-\sqrt{2}\Delta L\cos(2\theta-\pi/4) \\ L-\sqrt{2}\Delta L\sin(2\theta-\pi/4) \end{bmatrix} \tag{10}$$

Subtracting the DC offset and comparing the absolute value of $I_{\alpha\theta}$ and $I_{\beta\theta}$, the rotor position can be obtained.

$$\begin{bmatrix} I_{\alpha\theta} \\ I_{\beta\theta} \end{bmatrix} = k\begin{bmatrix} -\cos(2\theta-\pi/4) \\ -\sin(2\theta-\pi/4) \end{bmatrix} \qquad k = \frac{\sqrt{2}U_m\Delta L}{2(L^2-\Delta L^2)\omega_h} \tag{11}$$

A rotor position detection system was built as shown in Fig. 2 and some experiments were carried out to verify whether this method is suitable for SPMSMs.

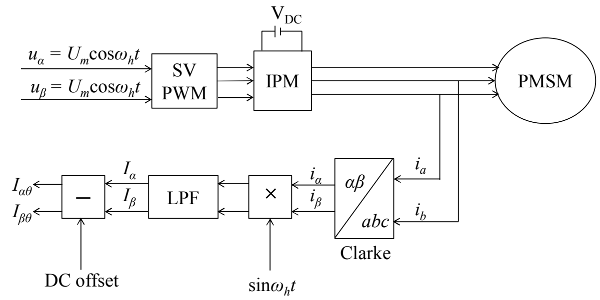

Fig. 2 Block diagram for the high-frequency signal injection method.

It should be noted that to reduce the rotor's vibration, the injected signals' amplitude should be low and frequency should be high. Meanwhile, to obtain large amplitude of the resulting current, the injected signals' amplitude should be high and frequency should be low. Hence, a balance must be made. We found out the appropriate voltage amplitude and frequency, and set them in the simulation. The results are shown in Fig. 3 and Fig. 4.

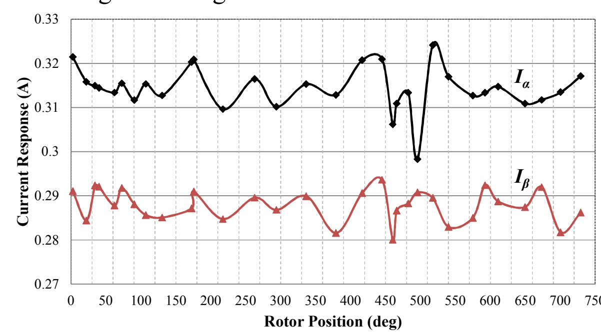

Fig. 3 Amplitudes of the resulting high-frequency currents.

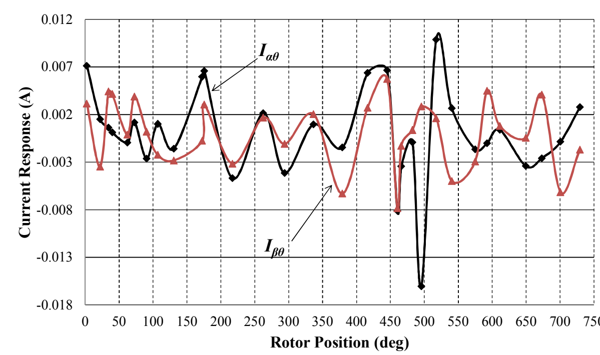

Fig. 4 Resulting high-frequency currents after subtracting the DC offset.

As Fig. 3 shows, I_α and I_β have different DC offsets. As Fig. 4 shows, the plots of both $I_{\alpha\theta}$ and $I_{\beta\theta}$ are very complicated, which indicates that this approach needs current sampling circuits with high-precision. Moreover, the amplitudes are less than 0.015A which is relatively small. In the experimental SPMSM, the d-axis inductance is 22.46 mH and the q-axis inductance is 23.05 mH, so the ΔL is almost close to zero, which is not significant enough to extract the position information. Therefore, the high frequency signal injection method is not suitable for initial rotor position detection of SPMSMs.

3) Magnetic Saturation Voltage Injection Method

The magnetic saturation voltage injection method is based on the nonlinear magnetization characteristics of stator cores. The closer a part of a stator core is to the magnetic pole of a permanent magnet, the more the part of stator core is magnetized, and in turn the smaller its inductance is due to magnetic saturation [4]. Moreover, if a stator winding is close to a magnetic pole of the rotor, then for the same applied voltage amplitude, the amplitude of current flowing in the magnetizing direction is larger than that flowing in the demagnetizing direction. Applying different voltage vectors to the stator windings, when the induced current reaches its maximum possible value, the direction of the applied voltage vector is along the direction of a magnet's magnetization direction.

The estimation method consists of two processes. In the first process, 12 voltage vectors are applied to the motor in the order 0, 1, 2, … , 11, as shown in Fig. 5. For each voltage vector, the corresponding d-axis current is measured. Comparing all the measured currents, we can get I_{d_max1} and θ_{m1}.

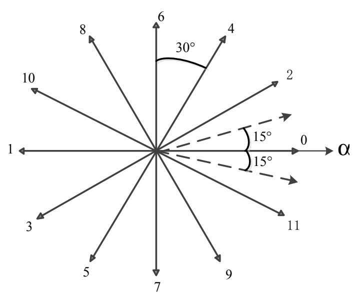

Fig. 5 Voltage vectors applied in the first process.

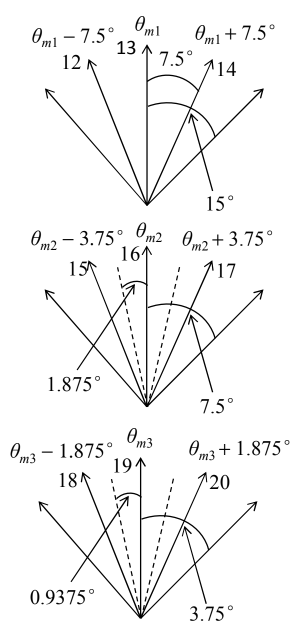

Fig. 6 Voltage vectors applied in the second process.

In the second process, three new voltage vectors whose angles are θ_{m1} - $\Delta\theta$, θ_{m1} and θ_{m1} + $\Delta\theta$ are applied to the motor. For each voltage vector, the corresponding d-axis current is still measured to obtain I_{d_max2} and θ_{m2}. Then repeat the second process to get a new I_{d_max2} until voltage vector 21 is applied to the motor. In this process, the initial value of $\Delta\theta$ is 7.5, and for every new round, $\Delta\theta$ is halved, as shown in Fig. 6. The flow chart of this method is shown in Fig. 7.

To avoid influence on current measuring, all the gate signals of the inverter are turned off for a period of T_{off} between two adjacent injections to ensure each phase current attenuates to zero. In addition, during every injection, the d-axis current is only sampled in the last several milliseconds instead of the whole time period.

As Fig. 8 shows, most estimation results are close to actual initial rotor positions, except two estimated angles which are 180° ahead of their actual position. The average error over the whole range is 20.32 electrical degrees, which is still big for practical position estimation. Since the saliency ratio of SPMSM is small and it is hard to distinguish N/S poles by the detected currents, this method entails a very precise device for current measurement.

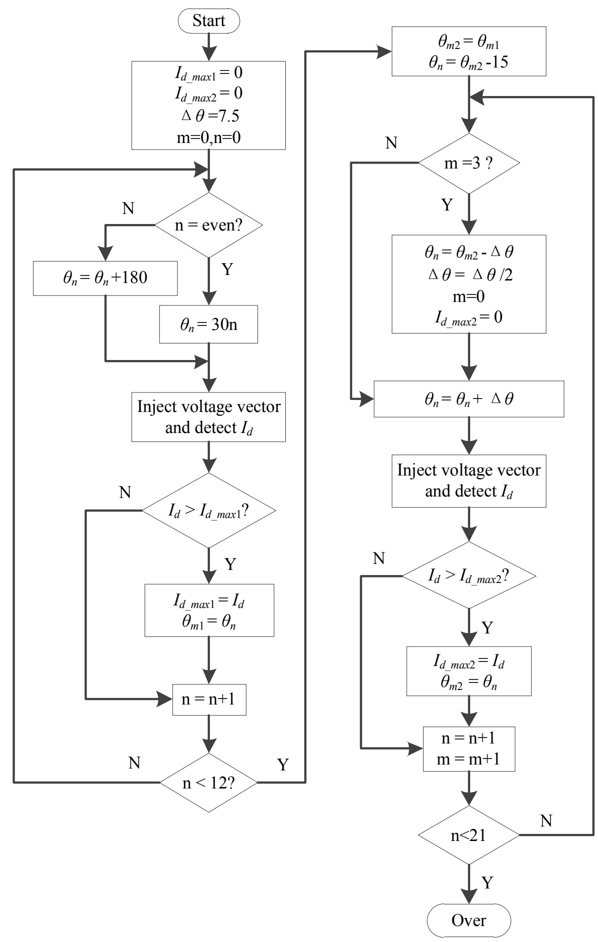

Fig. 7 Flow chart of magnetic saturation voltage injection method.

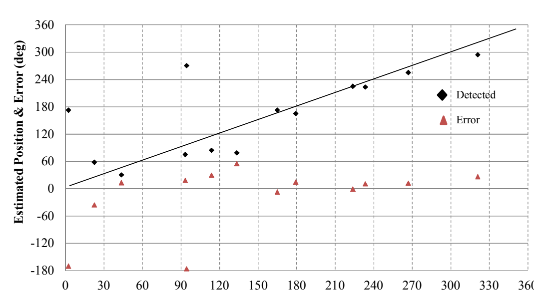

Fig. 8 Results of estimated initial rotor positions and errors.

III. An Improved Method for Initial Rotor Position Estimation

Incremental encoders are commonly used in SPMSMs, but they cannot detect initial rotor positions. However, the incremental encoder method can obtain relatively highly accurate results in rotor position detection, thus it is recommended to be extended to initial rotor position estimation. The experimental SPMSM control system is illustrated in Fig. 9. Unlocking the system from the speed loop, we can set *dq*-axis current references i_{dref}, i_{qref} and an angle θ_n; hence a specified current vector I_s is applied to the motor windings to produce a corresponding flux linkage ψ_s. The direction of ψ_s is aligned with the current vector's direction. When the angle of stator flux linkage ψ_s is not aligned with permanent magnet flux linkage ψ_f, the rotor tends to rotate.

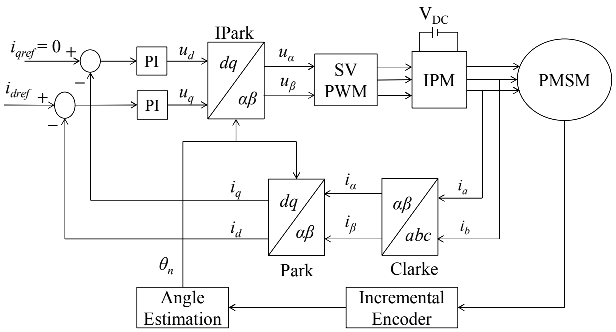

Fig. 9 Block diagram of encoder-coordinated current injection method.

When the output of the encoder changes, block all the PWM outputs, and the rotor position is almost unchanged. According to the output, the rotor's rotation direction can be identified. The rotation direction is used for stator current angle correction.

The principle of stator current angle θ_n correction is shown in Fig. 10. If the angle θ_n of the stator flux linkage is ahead of the initial rotor position θ_0, the rotor rotates in a counterclockwise direction, and the count value of the encoder increases. Then the angle of the next applied current vector should be reduced.

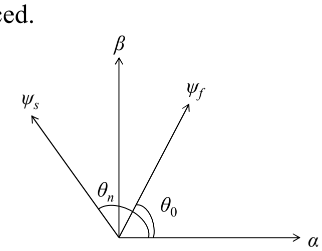

Fig. 10 Relation between stator and rotor flux linkage on forward.

If the motor rotates in a clockwise direction, which indicates that the stator flux linkage ψ_s lags ψ_f as shown in Fig. 11, the angle θ_n should be increased.

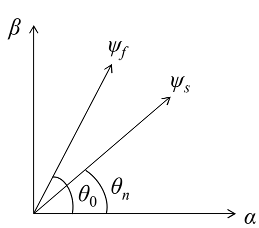

Fig. 11 Relation between stator and rotor flux linkage on reversion.

We repeat the process until the rotor does not rotate when a current vector is applied. The direction of the current vector is the initial rotor position.

IV. Experimental Results and Comparative Analysis

The main parameters of the experimental SPMSM are shown in Table I. The pulse count value rather than the direction signal was selected as the basis for angle correction during experiment, because the change of the direction signal is not stable. It should be noted that if the current amplitude is very small, the pulse count value does not change, which may lead to a wrong estimated angle. On the other hand, if the amplitude is very large, the rotor will rotate substantially. Hence, a compromised current amplitude should be selected. Similar balance should also be made for the time interval to apply the current vector I_s. On one hand, if the time interval is very short, the PI regulators do not work. On the other hand, if the time interval is very long, the rotor will rotate substantially before the application of the first current vector is finished. Thus, in order to have recognizable encoder outputs and keep the motor almost at standstill, the current amplitude and the time interval should be selected cautiously. The estimation flow chart is shown in Fig. 12, where "timer" is the time interval of applying I_s, "Counter" is the pulse count value and θ_n is the estimated initial rotor position.

TABLE I
The main parameters of the experimental SPMSM

Power (W)	750	Voltage (V)	220
Current (A)	5.8	Torque (N·m)	11.4
Speed (r/min)	3000	R_s (Ω)	4.5
L_d (mH)	22.46	L_q (mH)	23.05

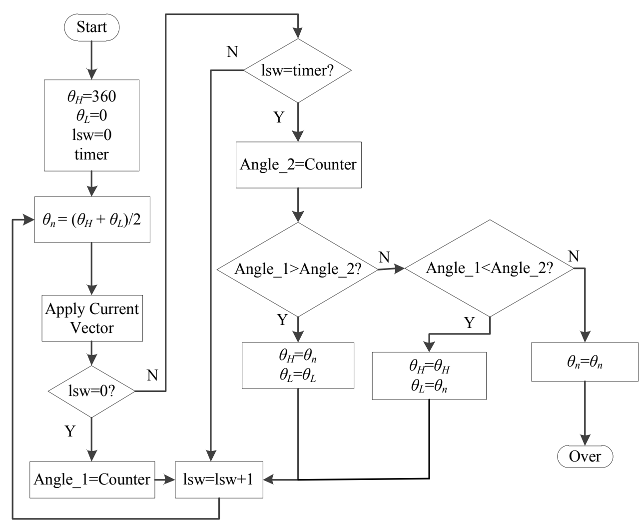

Fig. 12 Flow chart of initial position estimation using incremental encoders.

After several trials, the current vector amplitude was selected to be 0.2A and the time interval was selected to be 0.4ms (corresponding to timer =100). Fig. 13 shows one initial rotor position estimation process when the real position was 53.4°. The angle of the first applied current vector was 180°, which was ahead of the actual position, and the rotor tended to rotate in a counterclockwise direction. When the first injection process was over, "Counter" increased. The next angle was reduced to 90°, which was still ahead of the real position, causing "Counter" to increase. When the third angle was 45°, which lagged the real angle, the rotor tended to rotate in a clockwise direction, causing "Counter" to decreases. The next stator current vector angle was 67.5°. The process was repeated until "Counter" did not change anymore. Finally, the estimated result was 56.60° and the error was only 3.2 electrical degrees. All the experimental results are shown in Fig. 14, and the data demonstrate that the estimation error was about 6 electrical degrees.

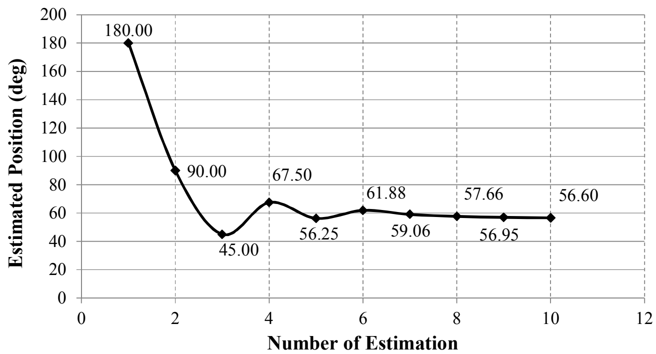

Fig. 13 Estimated results corresponding to the real angle 53.4°.

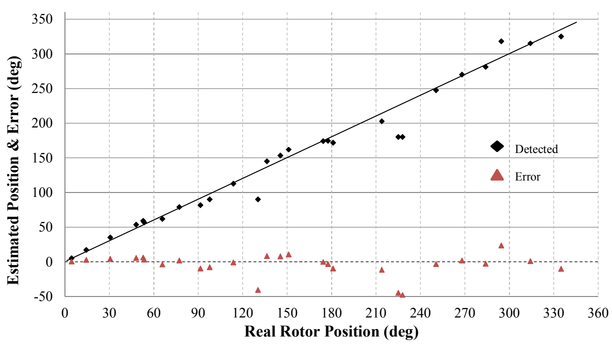

Fig. 14 Estimated initial rotor position and errors.

Compared with the estimation methods mentioned in Section II, the advantages of this method are as follows:

a. Unlike the high-frequency signal injection method, this method does not need a low-pass filter or other complex calculation.

b. Unlike like the back EMF method, this method does not rely any on the motor's parameters, so its robustness is good.

c. This method uses the pulse output of an incremental encoder, which is very accurate and easy to obtain. Correcting estimated angles by pulse outputs rather than measured currents, which is used in the magnetic saturation voltage injection method, leads to much smaller estimated errors.

d. Utilizing existing resources in the market, this method not only reduces costs, but also makes up the shortage of incremental encoders.

V. CONCLUSIONS

Based on the comparison of existing rotor position estimation methods and some related experimental results, an improved initial rotor position estimation method for SPMSM is given in this paper, and estimation results show that this method can easily obtain initial rotor position without complex algorithms or high-precision measuring devices. This method utilizes the most commonly used incremental encoders in extant servo systems. Utilizing this method, when a motor starts up, its rotor will not reverse accidentally anymore. Furthermore, the UVW hall signal outputs can be removed to reduce costs since the estimation error is much smaller than that by method relying on UVW outputs. This method may find applications not only in technological research but also in industrial realms.

ACKNOWLEDGMENT

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