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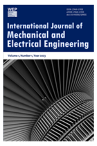

Research Review on Sensorless Measurement Technology of Permanent Magnet Synchronous Motor

Xinkai Zhao *

College of mechanical engineering, Tianjin University of Technology and Education, Tianjin, China
* Corresponding Author: Xinkai Zhao

ABSTRACT

Permanent magnet synchronous motor (PMSM) has the advantages of high torque/inertia ratio, high power factor, fast dynamic response speed and high reliability, and has been widely used in various high-precision AC drive systems. Incremental encoders are usually used to achieve high precision position feedback information for permanent magnet synchronous motors. The use of sensors leads to cost increase, volume increase and reliability reduction. Therefore, the sensorless measurement technology of permanent magnet synchronous motor is more and more concerned and applied by industry and research fields. In this paper, the related literature of sensorless measurement technology of permanent magnet synchronous motor is investigated, and the sensorless measurement technology is comprehensively reviewed. This paper introduces in detail the basic principle of various sensorless measuring techniques, the accuracy of position measurement and the application in the type of permanent magnet synchronous motor. In this paper, the concept of speed pole logarithm ratio is proposed to divide the speed region, and the initial rotor position, low speed and medium speed non-inductive measurement methods are described and compared. Finally, the non-inductive measurement accuracy of permanent magnet synchronous motor is summarized.

KEYWORDS

Permanent Magnet Synchronous Motor; Contactless Measurement; Sliding Mode Observer; Model Reference Adaptive System.

1. INTRODUCTION

Permanent magnet synchronous motor is a rotating motor driven by the electromagnetic force between the magnetic field generated by the rotor permanent magnet and the electric field of the stator coil[1]. Its structure is simple, no mechanical commutator, brush, excitation device and so on. In addition, permanent magnet synchronous motor also has high power factor, high power density, low noise, high torque/inertia ratio, high efficiency, fast dynamic response and other advantages[2]. Therefore, permanent magnet synchronous motor is widely used in electric transportation, aerospace and other high-tech fields[3].

There is a close correspondence between the rotor speed and the stator voltage frequency of permanent magnet synchronous motor. By controlling the stator voltage frequency, the motor speed can be adjusted and controlled [4]. According to the application requirement of the actual speed region, this paper puts forward the method of dividing the speed region into three sections. When the logarithm ratio of the speed pole is greater than or equal to 0 and less than 75, it is divided into zero low speed interval. When the ratio of logarithm of speed poles is greater than or equal to 75, it is divided into medium-high speed intervals. In short, the sensorless control method can be divided into zero low speed and medium high speed according to the concept of speed pole logarithm ratio[5]. Finally, the precision of rotor position measurement of all sensorless control methods of permanent magnet synchronous motors is summarized.

In this paper, the sensorless measurement technology of permanent magnet synchronous motor is comprehensively reviewed. The rest of the article is arranged as follows: The sensorless measurement method of zero low speed is discussed in section 2. The sensorless measurement method of medium and high speed is introduced in section 3. The sensorless measurement accuracy of rotor position is summarized in Section 4.

2. ZERO LOW SPEED

When the permanent magnet synchronous motor is at zero speed, the initial position detection of the rotor is a problem that must be considered in sensorless technology, which needs to accurately detect the initial position of the motor, which determines whether the motor can start and run normally. The rotor initial position detection is accurate, which can effectively improve the performance of the system. If there is a large error in the initial position measurement, the motor is likely to have abnormal conditions such as vibration and inversion, which will cause the motor and its equipment to fail and cause the motor to fail to start normally. In the model-based sensorless control method, the reverse electromotive force voltage is used as the reference signal. However, due to the influence of noise, sampled signal and motor parameters, the rotor position measurement error may be large at zero low speed[6]. In order to deal with this problem, researchers have proposed rotating high frequency signal injection method, pulsating high frequency signal injection method, and other zero low speed sensorless control methods.

2.1. Rotary High Frequency Signal Injection Method

When the motor is at rest, a high-frequency rotating voltage signal is injected into the stator winding of the two-phase stationary reference system to induce high-frequency current in the stator winding, as shown in Fig. 1 [7]. When the injected high frequency rotating voltage signal matches the rotor position, the current in the stator winding reaches its maximum value. Through the correlation analysis of voltage and current, the initial position of the rotor can be determined. The rotary high frequency injection signal is stable, and the rotor position measurement does not depend on the motor parameters, which is suitable for the built-in permanent magnet synchronous motor[8]. The high frequency current response of the motor, including positive sequence and negative sequence carrier current components, is detected by a bandpass filter. After the fundamental wave current, inverter switching frequency harmonic current and low frequency harmonic current are filtered, the positive sequence carrier current component is filtered by a synchronous shafting high-pass filter. Only the position signal can be extracted from the phase of the negative sequence carrier current component. Finally, the position and velocity information of the rotor are obtained by using heterodyne demodulation[9].

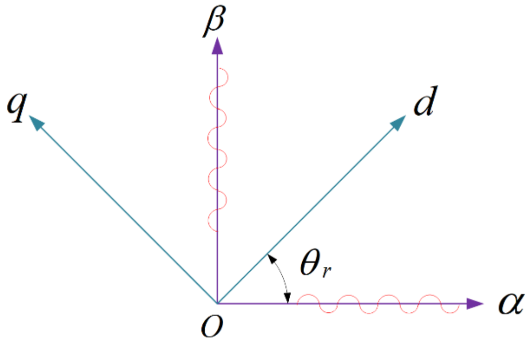

Figure 1. Rotating high frequency signal injection into the rest coordinate system diagram

Currently, in zero-speed sensorless control methods. Wang et al. proposed a rotor position detection method with rotary high-frequency voltage signal injection[10]. According to the relationship between the high frequency current response and the rotor position Angle, the rotor position Angle is obtained by using the arctangent trigonometric function and linear formula, and the maximum error of the rotor position is less than 5°. In contrast to the injection of rotating high-frequency signals into the stationary coordinate system, Li et al. proposed that injecting rotating high-frequency signals into the synchronous reference system can avoid the problems caused by filters and can be applied in the scenario of pumped storage power stations, with the actual position measurement error of about 2°[11]. Xiang et al. proposed an improved rotary high-frequency signal injection method, which adopted NPC three-level exchanger for the main circuit, which could effectively reduce the influence of harmonics and improve the measurement accuracy of the rotor position of low-speed high-power motor[12]. Through simulation and actual experiment, the position measurement error is within ±3°. S. Medjmadj et al. designed a simple estimator structure and reduced the three filters of the traditional method to one. The simulation results show that the measurement error of the rotor position in steady state is less than 2°[13].

2.2. Pulsating High Frequency Signal Injection Method

Pulsating high frequency signal injection method is to inject a high frequency signal into the d^* axis of the virtual synchronous coordinate system. It's a better choice for injecting high frequency signals. The schematic diagram of signal injection under synchronous rotating coordinate system is shown in Fig. 2 [14]. After coordinate transformation and motor mathematical model processing, a corresponding high frequency current response signal is generated. By detecting this high-frequency current response signal and conducting specific signal processing, by detecting the high-frequency current response caused by the salient pole of the rotor and decoupling the position error signal, zero-speed and low-speed rotor position measurement and speed observation can be realized [15].

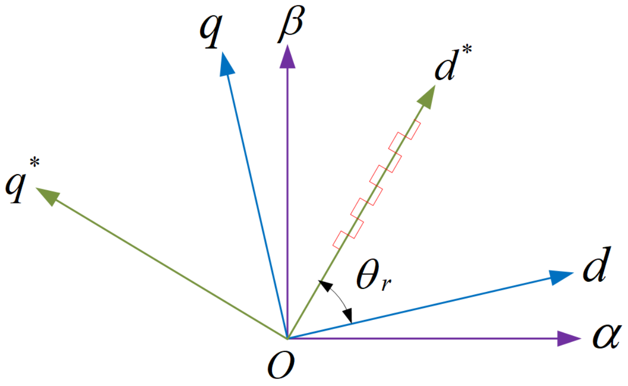

Figure 2. Pulsating high frequency signal injection synchronous coordinate system diagram

The pulsating high frequency signal injection method adopted is based on the significant tracking of the rotor. It may face the problems of long convergence time, weak system robustness and the effect of filter on the system bandwidth. To solve these problems, scholars have put forward some solutions. Bi et al.proposed a pseudo-random square-wave voltage injection method, which can judge magnetic polarity while extracting position information, and the measurement error of rotor position is 3°[16]. Han et al. combined the carrier frequency method with pulsating high frequency voltage signal injection to measure the initial position error of the rotor of a surface mounted permanent magnet synchronous motor within 2°[17]. On the basis of pulsating high-frequency signal injection, Mai et al.proposed an improved position error signal extraction strategy based on amplitude observer[18]. In the case that speed reversal or load step cannot guarantee the accuracy of rotor position measurement, the method based on adaptive observer position error signal extraction is adopted, and the rotor position measurement error is about 3°. Scicluna et al.proposed a rotor position measurement method for real-time search and debugging based on pulsating high-frequency signal injection[19].

Through the method of generating data and looking up tables, the steady state operation of the closed-loop loop is completed, and the measurement accuracy of the rotor position is less than 1.6°.

2.3. Other Zero Low Speed Method

Although the high frequency signal injection measurement method works well in the low speed range, the injected high frequency signal can produce more losses and greater torque ripple [20]. The frequency and amplitude of the debugging injection signal affect the accuracy and interfere with the control system, increasing the complexity of the control system and the accuracy of the motor parameters. In addition, it is difficult to apply sensorless control to non-significant surface mount permanent magnet synchronous motor [21]. To solve these problems, many researchers have proposed other sensorless control methods suitable for permanent magnet synchronous motors at zero low speed. Lin et al.proposed a fast method of single sequence pulse injection, which solved the problem of magnetic polarity judgment without increasing the calculation amount of the system[22]. A four-stage search algorithm is used to measure the initial position of the rotor, and each stage is optimized and adjusted to ensure that the maximum position measurement error is less than 3.6°. Fu et al.analyzed the vibration response signal induced by torque pulsation, which did not require the precise parameters of the motor and improved the robustness of the system[23]. The method is simple and easy to implement, and the rotor position measurement error is ±1.7°, which is suitable for the built-in permanent magnet synchronous motor.

3. MEDIUM AND HIGH SPEED

In sensorless control method of permanent magnet synchronous motor in medium and high speed region, the estimation of back electromotive force generated by the voltage model of permanent magnet synchronous motor performs well in the range of medium and high speed. Because the amplitude of the electromotive force is proportional to the rotor speed, the non-inductive measurement method is convenient and reliable in the range of medium and high speed [24]. Sensorless control methods mainly include Flux Observer (FO), Extended Kalman Filter (EKF), Sliding Mode Observer(SMO), Model Reference Adaptive System(MRAS) and other sensorless control methods.

3.1. FO Method

Based on the mathematical model of PMSM in the two-phase stationary coordinate system, FO measures the voltage and current of PMSM to calculate the flux linkage of the motor, and measures the rotor position by integrating the flux linkage [25]. Compared with closed-loop FO controller, open-loop FO is simple in computation, fast in dynamic response and easy to implement. However, the precision of stator resistance and inductance parameters is relatively high in the process of implementation. These parameters may change with the change of motor operating conditions, which will lead to large errors in rotor position observation. Therefore, this method is only suitable for application in scenarios where control accuracy is not required [26].

The traditional FO method needs to use pure integrator for rotor position measurement, which leads to DC drift of sampling current and DC bias resulting in pure integrator saturation and filter function reduction, which affects rotor position measurement accuracy. To solve these problems, Yu et al. proposed a compensation strategy based on the linear extended state observer, and designed a new low-pass filter, which mainly eliminated the position measurement errors caused by the low-pass filter and PLL[27]. The experimental results show that the error of rotor position measurement is 10° by the traditional FO method, while the error of rotor position measurement is about 4° by the proposed method. The traditional FO method is mainly used for fans, compressors, etc., and is suitable for surface mounted permanent magnet synchronous motor.

3.2. EKF Method

EKF is a generalized form of Kalman filter applied to nonlinear systems. This algorithm is used to describe linear dynamic processes[28]. Kalman filter does not retain the used data, when new data is measured, the recursion formula is used to recalculate the estimator. This method performs well in minimum covariance error estimation and is used for state prediction and correction evaluation [29]. EKF is an optimal estimator in the sense of least squares, which can linearize the estimation of nonlinear systems and then carry out Kalman filtering, roughly divided into two stages of prediction and correction [30].

Based on the sensorless EKF method used by PMSM, Yang et al. constructed the compensation controller of EKF[31]. The performance of the closed-loop controller is enhanced by optimizing the tracking error, and the precision of motor state estimation is improved. In addition, the position measurement of PMSM by parallel EKF method is realized on a single field programmable gate array chip. Chen et al. proposed a sensorless PMSM method based on adaptive EKF. The covariance calculation is innovatively designed and used in Kalman gain calculation[32]. The experimental results show that this method can significantly reduce the position measurement error, and can be applied to the complex environmental conditions of Marine electric propulsion system. Quang scholars proposed a reduced order extended Kalman filter based on the parallel field programmable gate array, which not only improves the operational accuracy of the system, but also simplifies the iterative process and reduces the use of resources[33]. In the experiment, the error of rotor position measurement is about 3°.

3.3. SMO Method

SMO is a dynamic system designed to infer estimates of state variables based on measured values of system input and output variables. Sliding mode control is a special nonlinear control system [34]. The key element of sliding mode regulation is to determine the appropriate sliding mode surface function and the effective sliding mode gain. In this process, we must clearly select the expected equation of the sliding mode surface, so that the trajectory of the state variable of the observer can follow the law of the sliding mode surface. More importantly, SMO has shown significant advantages in simple structure, robustness and high stability in the non-inductive measurement of PMSM [35]. The structure of SMO is shown in Fig. 3. When the observer converges, accurate extended back electromotive force observations can be obtained, from which the position information of the rotor can be extracted [36].

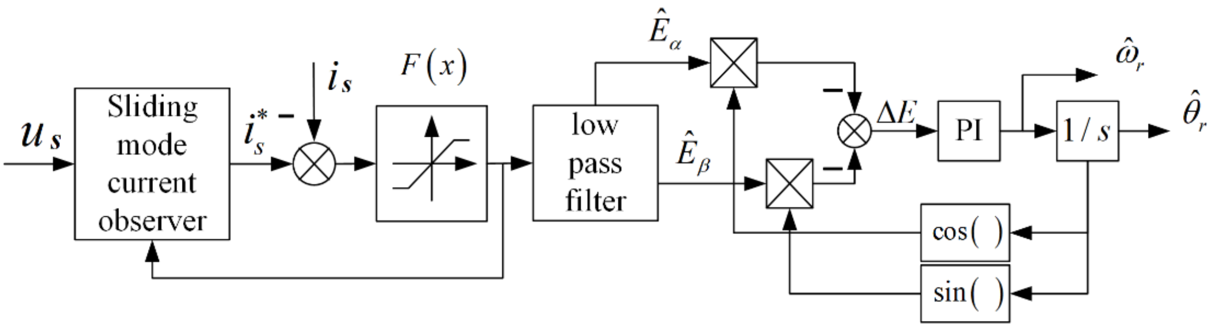

Figure 3. SMO structure diagram

In traditional SMO, a low-pass filter is often used to extract the back electromotive force from the sliding mode switching function. This introduces a delay problem, which reduces the accuracy of position and speed measurements. In addition, traditional SMO also has buffeting phenomenon and high order harmonics. To solve these problems, scholars in related fields have put forward some methods. Gong et al. proposed a delay suppression sliding mode observer, which uses a new hyperbolic function as a switching function, which can remove the low-pass filter and eliminate the delay problem[37]. The position measurement accuracy can be calculated by the proposed current pre-compensation strategy, and the maximum position measurement error is 2.6°. Ye et al. proposed a sensorless scheme based on the iterative flux sliding mode observer. The feedback matrix was used to replace the low-pass filter, and the observer gain was adjusted by the flux SMO for multiple iterations[38]. The experimental results show that the method can suppress the chattering phenomenon and improve the dynamic response ability, and the maximum position measurement error is 1.6°.

3.4. MRAS Method

The basic idea of MRAS is to build two models with exactly the same goals, one of which is a reference model with no unknown parameters preset for us, and the other is an adjustable model with parameters to be observed [39]. As the motor body, the reference model has nothing to do with the speed information of the motor. The stator voltage equation of the adjustable model contains parameters to be estimated. The input values of the two models are voltage and current components, so that the difference between the output values of the reference model and the adjustable model is close to zero state, then it is necessary to select a suitable adaptive law for adjustment. When the adaptive system estimates accurately, the estimation parameters of the tunable model can track the upper reference model. MRAS structure diagram [40], as shown in Fig. 4.

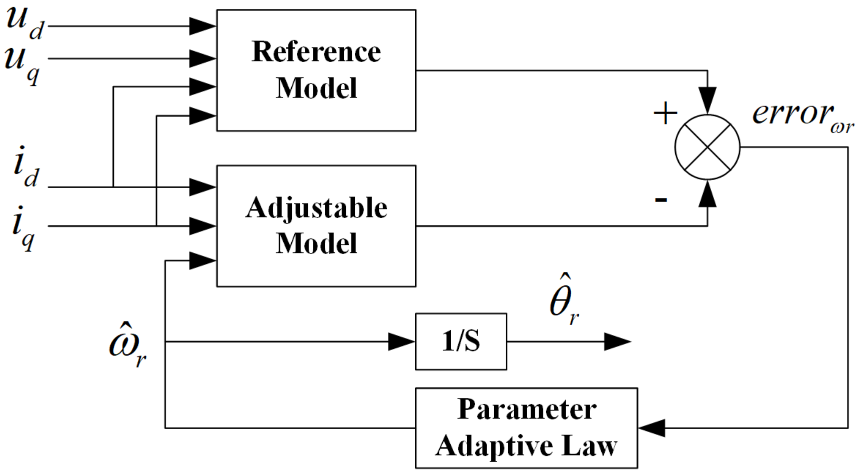

Figure 4. MRAS structure diagram

The use of traditional MRAS pure integrators will cause problems such as error accumulation and DC offset. In addition, the fluctuation and interference of each parameter will affect the measurement accuracy of the rotor position of the adaptive system. In view of the existing problems, scholars have carried out relevant research. Zhou S et al. proposed a PMSM velocity identification method based on MRAS[41]. The stator flux observer based on voltage model is redesigned, and the rotor position measurement error is about 1.2°. Kashif et al. proposed an improved active model reference adaptive system[42]. In the design of adaptive law, the main parameters such as PMSM permanent magnet flux linkage and armature resistance are constantly updated. Finally, the rotor position measurement error is about 1° when measured on the prototype.

3.5. Other Medium and High Speed Method

In addition, some scholars have studied other methods applicable to the sensorless control of PMSM. Shi Tingna et al. proposed a position sensorless method based on radial basis function neural network[43]. Radial basis function neural network is trained by the supervised learning mechanism based on stochastic gradient descent method. The PMSM rotor position can be measured with a maximum rotor position error of ±6°. M.Cacciato et al. proposed a sensorless control method of

Romberg observer[44]. Experimental results show that the proposed method is robust to parameter changes. Henwood et al. proposed a robust nonlinear Romberg observer to estimate rotor position and magnetic flux[45]. The experimental results show that the phase estimation error remains unchanged at constant speed, but increases proportionally with the speed. The measurement error of rotor position is about 3° under steady speed.

4. SUMMARY

Table 1. Summary of Rotor Position Measurement Accuracy

Measure Speed	Method	Test Speed Frequency (Hz)	Speed Pole Log Ratio	Positional Accuracy (°)
Zero-Speed	Rotating HF Signal	0	0	2
	Pulsating HF Signal	0	0	2
	Vibration Detection	0	0	±1.7
Low Speed	Rotating HF Signal	5	34	2
	Pulsating HF Signal	3	5	1.6
Medium-High Speed	Flux	50	187.5	4
	EKF	60	225	3
	SMO	16	240	1.6
	MRAS	29	430	1
	ANN	20	75	±6
	Luenberger	50	334	3

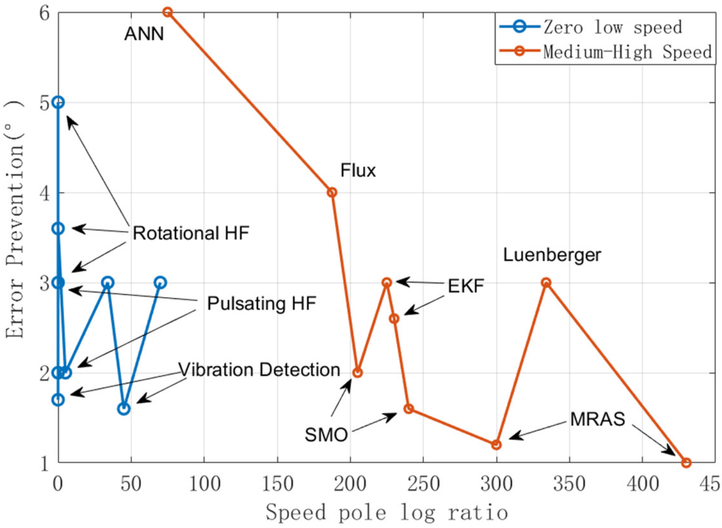

Figure 5. Speed pole logarithm ratio and position error precision diagram

In this paper, the application status of sensorless measurement method in permanent magnet synchronous motor is reviewed. The non-inductive measurement accuracy of the rotor position of the permanent magnet synchronous motor at static, low speed and medium and high speed is summarized, as shown in Table 1. According to the concept of speed pole logarithm ratio proposed, the measurement accuracy diagram of speed pole logarithm ratio and rotor position is drawn, as shown in Fig. 5. At present, sensorless measurement technology has made remarkable achievements in permanent magnet synchronous motor. However, there are still some challenges, such as rotor position estimation delay, load disturbance resistance and full speed control. Future research directions will focus on solving these problems and further improving the accuracy and reliability of sensorless measurement techniques.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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