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Review Article

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Sensorless Control Techniques of Electric Vehicle Motor Drives: A Review

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Keywords

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motor,
electric vehicle,
control strategies.

Abstract

Considering the problems of conventional mechanical position or speed sensors in electric vehicle motor drives, such as high manufacture cost, occupies large space, inconvenient installation, and low reliability, sensorless control technology is widely application in the motor control filed. This paper gives an overview of the main sensorless control technologies. They are divided into four categories based on the motor running process under different operating conditions of electric vehicles: start-up control strategies, low-speed control strategies, mid-high-speed control strategies and full-speed control strategies. The basics of these strategies, the advantages and disadvantages of the control algorithms and their application for different types of permanent magnet synchronous motors are detailed. Finally, it is concluded that the stable start-up, the parameter sensitivity problem and the smooth switching technology are the development trends of the sensorless control techniques of electric vehicle motor drives.

Introduction

With the growing deterioration of the global environment and energy supply constraints, new energy vehicles have become an important direction of modern automotive development. Countries around the world have introduced support for new energy development programs, it is expected that China's new energy vehicle market share in2030 to reach 40%.[1] Electric vehicle is an important component of new energy vehicles. It uses electrical energy as the source of all or part of power, and motor is used to convert electrical energy into mechanical energy for propulsion. The development of electric vehicles is therefore an important part of the solution to environmental and energy problems.

Permanent Magnet Synchronous Motors (PMSMs) are characterized by the small size, high efficiency, low weight, and high power density, making them the best choice for the drive motors of electric vehicles.[2-3]The PMSM control system is evolving rapidly with the development of high performance magnetic materials, electronic and microelectronic technologies, and modern control theories. Reliable sensors and accurate detection techniques are essential for high-performance PMSM control systems, such as field-oriented control (FOC) and direct torque control (DTC).which can accurate measure the rotor position. But the conventional mechanical sensors (e.g., photoelectric encoders, resolvers, etc.) consist the problems of high manufacture cost, occupies large space, inconvenient installation, and low reliability, it is limit the accuracy and response speed of PMSM control. [4-5]

This paper reviews the literature on sensorless control techniques of electric vehicle motor drives. Section 2 introduces the characteristics and classification of PMSM. Section 3 presents the sensorless control methods of PSMS under start-up, low-speed, medium-high speed and full-speed operating conditions based on the motor running process. Section 4 compares the application of different types of PMSM in terms of their control methods. Section 5 proposes research hotspots and the direction of development of sensorless control techniques of PMSM.

Classifications of Electric Vehicle Motor Drives

Due to advances in inverters, AC motor drives have grown steadily since the 1950s and are widely used in industry. Currently, the most commonly used AC motor drives for electric vehicles include induction motor (IM), permanent magnet synchronous motor (PMSM) and reluctance synchronous motor (SRM). Table 1 compares the difference performance of the three motors drives. IM is extensive use for medium-high power due to nonlinearity.[6] The advantages are simple structure, low cost, low raw material price fluctuation, self-starting, wide application and durability. PMSM is mainly used for high speed applications, which have better speed control and torque characteristics, but require a more complex motor control algorithm. [7] Overall, the best performance is achieved by PMSM.

Table 1 Comparison of the difference performance of motor drives

	PMSM	IM	SRM
Power density	High	normal	normal
Speed-torque	Best	good	better
Speed range	4000-15000rpm	9000-15000rpm	>15000rpm
Peak efficiency	90%-97%	94%-95%	90%
Operability	best	Good	Good
Reliability of running	good	good	Good
Robustness of the structure	good	good	Good
Cost	high	high	Low
Space scale	small	normal	Small
Mass	light	normal	Light
Efficiency of 10%load	90%-92%	79%-85%	78%-86%
Performance evaluation	best	good	better

PMSM is classified into surface-mount permanent magnet synchronous motor (SPMSM) and interior permanent magnet synchronous motors (IPMSM) according to the different mounting forms of the permanent magnets in the rotor,[8] as shown in Figure 1. Motors with permanent magnets mounted on the rotor steel surface, called SPMSM or non salient pole rotor. Since the permeability of the permanent magnets is basically the same as the air, the inductance in the closed path of the magnetic circuit is the same whether it is in the direct axis or in the quadrature axis, i.e. $L_d = L_q$. SPMSM always use $I_d = 0$ control method. Motors with magnets embedded in the steel backing, called IPMSM or salient pole rotor. IPMSM always use maximum torque per ampere (MTPA) control method.[9-10]

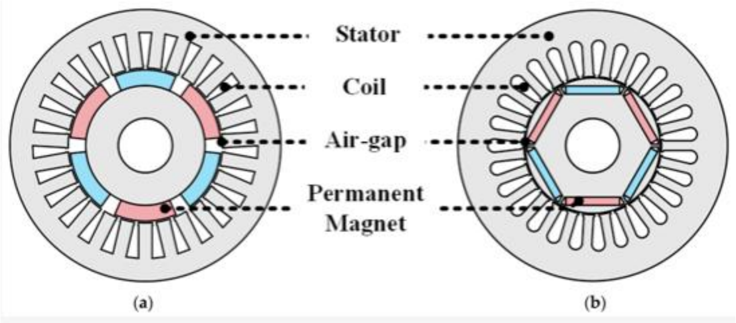


Figure 1 Classification of PMSM: (a) SPMSM,(b) IPMSM[11]

Types of Sensorless Control Methods

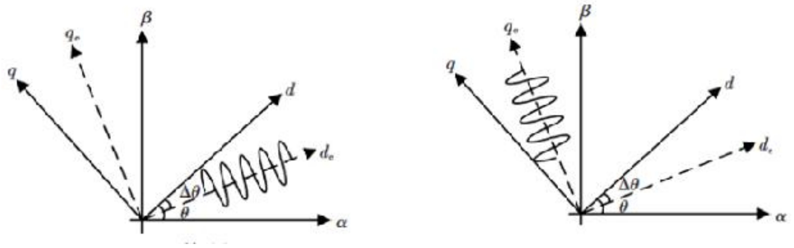
Most of PMSM sensorless techniques estimate the rotor position by the back- electromotive force (back-EMF). However, back-EMF tends to zero when the motor speed is zero or low, the position of rotor pole is difficult to estimate accurately or even impossible. Therefore, it is necessary to use the salincy effect to get the rotor position information. Joachim Holtz proposed the classification method of sensorless control techniques of PMSM: Model-based sensorless control techniques which estimates the rotor position and rotational speed based on the fundamental wave model of the motor, and it is mainly applicable for the mid-high speed stage. The other is saliency-based sensorless control techniques which extract the rotor position by injecting voltage or current signal. This method is independent of motor parameters and it is suitable for zero-low speed stage. [12] This paper reviews the main sensorless control technologies, which are classified into four categories based on the motor running process under different operating conditions of electric vehicles: start-up control strategies, low-speed control strategies, mid-high-speed control strategies and full-speed control strategies.

(1) Start-up Control Strategies

Signal Injection Methods

Signal injection methods refers to injecting the signal at the initial stationary state of PMSM. By injecting a voltage signal into the stator, the rotor position information can be isolated by the detected response current. According to the different ways and types of injecting voltage signals, signal injection methods are classified into pulsating high-frequency voltage injection method, rotating high-frequency voltage injection method, and pulse injection method.

The pulsating high-frequency voltage injection method is always implemented in a rotating frame (including d-axis and q-axis).After a pulsating high-frequency voltage signal is injected into its d-axis or q-axis, the rotor position angle is obtained from response current by phase-locked loops or other algorithms. Literature [13] presents the high-frequency voltage inject into the q-axis as shown in Figure 2(a), and literature [14-15] presents the injection of high-frequency voltage into the d-axis as shown in Figure 2(b). The results show that q-axis injection introduces additional pulsations and has a inferior static performance compared to d-axis injection which is mostly used in practical applications. Literature [16] adopts injecting the square wave signal into the d-axis of the rotor and decoupling the position error information by using the filter carrier signal separation method, which effectively improves the convergence speed of the algorithm; and magnetic pole polarity discrimination is achieved by accumulating the d-axis high-frequency current amplitude, which improves the reliability of the initial position detection of PMSM.



(a) (b)

Figure 2 The high-frequency pulsating voltage injection method: (a)d-axis injection;(b)q-axis injection[13-15]

The rotating high-frequency voltage injection method injects a rotating high-frequency voltage signal with the electrical angle into the stationary frame (including α-axis and β-axis), as shown in Figure 3. Since the rotor position angle information is contained by the negativesequence response current, it can be extracted directly. This method is more versatile and it can be applied to a variety of control algorithms. However, the difficulty lies in the high requirements for current acquisition accuracy by using high performance filters.Due to the saliency effect in IPMSM, the locus of the carrier current response is an oval whose macro axis reflects the position of the rotor, while the negative pole direction is observed by the offset of the locus.[17] It can be seen that the rotating carrier signal injection method robust to the motor parameters and it can estimate the rotor position and speed when the motor is stationary, while the whole system requires high precision of the hardware, and the implementation is complex.

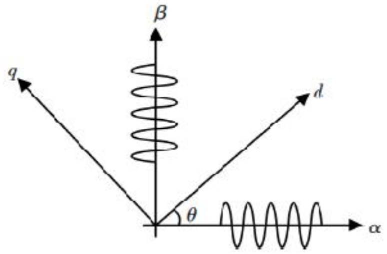


Figure 3 The rotating high-frequency voltage injection method

The pulse injection method is used to obtain the rotor position and speed from the response current by injecting a specific pulse voltage vector signal into the motor windings. Literature [18] and [19] provide the harmonics pulse injection method based on pulse width modulation (PWM), and literature [20] presents a method to inject special voltage test vectors vector pulse width modulation (PWM) excitation sequence in standard fundamental wave space. The harmonic pulse injection uses conventional PWM, which is easy to implement, but the hardware requires high accuracy and speed of sampling, and is more suitable for low inductance PMSM. The vector test voltage pulse injection methods generally requires special voltage vectors, and have large current biases which require special algorithms for processing. Literature [21] detects the current response by injecting pulse equal width voltage vector, and obtains the initial rotor position with 1.875° accuracy of electrical angle.

Inductance Matrix Measurement

A linear independent voltage vector is applied twice to the winding in the inductance matrix measurement method. The inductance matrix, which contain rotor position information can be calculated by the instantaneous response current.[22] This method is only applicable to IPMSM due tothe difference inductance between q-axis and d-axis.

If

$$L_1 = \frac{L_d + L_q}{2}, L_2 = \frac{L_d - L_q}{2} \#(1)$$

The inductance matrix is

$$\begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} = \begin{bmatrix} L_1 - L_2\cos(2\theta_e) & L_2\sin(2\theta_e) \\ L_2\sin(2\theta_e) & L_1 + 2\cos(2\theta_e) \end{bmatrix} \#(2)$$

The instantaneous response current$i_{\alpha 1}, i_{\beta 1}, i_{\alpha 2}, i_{\beta 2}$ are tested when injecting twice test voltage$u_{\alpha 1}, u_{\beta 1}, u_{\alpha 2}, u_{\beta 2}$into stator winding, then, the inductance matrix is

$$\begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} = \begin{bmatrix} u_{\alpha 1} - Ri_{\alpha 1} & u_{\alpha 2} - Ri_{\alpha 2} \\ u_{\beta 1} - Ri_{\beta 1} & u_{\beta 2} - Ri_{\beta 2} \end{bmatrix} \begin{bmatrix} \frac{di_{\alpha 1}}{dt} & \frac{di_{\alpha 2}}{dt} \\ \frac{di_{\beta 1}}{dt} & \frac{di_{\beta 2}}{dt} \end{bmatrix}^{-1} \#(3)$$

The electrical angle of the rotor position is obtained in a close step as

$$\theta_e = \frac{1}{2} arctan \frac{L_{12} + L_{21}}{L_{11} - L_{22}} \#(4)$$

Literature [23] uses inductance matrix measurement to estimate the max error of initial rotor position less than 6°. Although this method is simple to calculate, it is sensitive to parameter variations.

(2) Low-speed Control Strategies

High-frequency Rotating Signal Injection Method

The block diagram of high-frequency rotating signal injection method is shown in figure 4, which is consistent with the high-frequency rotating signal injection method at standstill introduced before. When a high-frequency voltage signal is injected to the stationary frame, a response current including the rotor position and speed information is generated. This method is taking advantage of the saliency effect which is more obvious in IPMSM. The injected high-frequency voltage signal is as

$$\boldsymbol{u}_{inj} = \begin{bmatrix} u_{\alpha_h} \\ u_{\beta_h} \end{bmatrix} = U_{rot_h} \begin{bmatrix} \cos(\omega_h t) \\ \sin(\omega_h t) \end{bmatrix} \#(5)$$

Where U_{rot_h} is the amplitude of the injected high-frequency rotating voltage.

The response current vector is as

$$\underset{i_{in}}{\rightarrow} = i_{\alpha in} + j \cdot i_{\beta in} = I_{cp} e^{j\left(\omega_{in} t - \frac{pi}{2}\right)} + I_{cn} e^{j\left((-\omega_{in} + 2\omega_e)t + pi/2\right)} \# \quad (6)$$

Where $I_{cp} = \frac{V_{in}}{(L_1^2 - L_2^2)\omega_{in}} L_1, I_{cn} = \frac{V_{in}}{(L_1^2 - L_2^2)\omega_{in}} L_2$ are the amplitudes of the positive and negative carrier response current. It is clear that the second part of equation (6) contains the rotor position information. Therefore, it is necessary to use appropriate signal processing techniques such as observers or phase-locked loop (PLL) to extract rotor speed and position information.

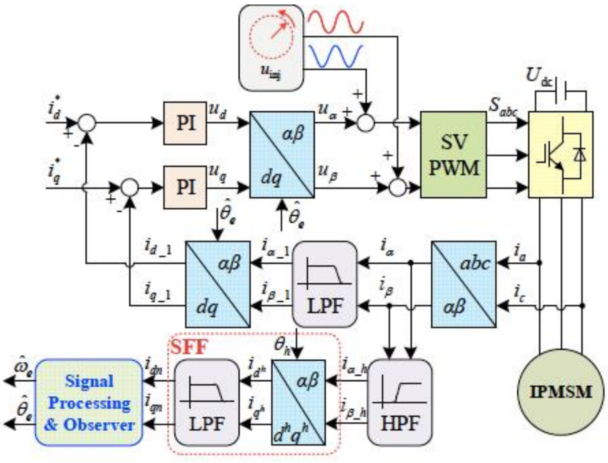


Figure 4 The block diagram of high-frequency rotating signal injection method[24]

Conventional high-frequency rotating signal injection methods estimate an inaccurate rotor position because of system delays, stator resistance and inverter non-linearities. Literature [25] proposes a new sensorless rotor position estimation strategy. The rotor position estimation deviation can be divided into stator resistance phase deviation (SRPD) and high frequency phase deviation (HFPD), the new sensorless rotor position estimating strategy can eliminate HFPD caused by the nonlinearity of the control system and reduce HFPD caused by the stator resistance. The results improved the accuracy of the estimated rotor position at low speed range. Literature [26] proposes a bi-directional rotating high-frequency carrier signal injection strategy, which effectively solves the phase deviation by simultaneously injecting two high-frequency carrier voltages with different rotational frequencies and directions, and thus obtains more accurate rotor position information.

High-frequency Pulsating Signal Injection Method

Unlike the high-frequency rotating signal injection method mentioned above, the high-frequency pulsating injection method only injects one signal into the d-axis in the rotating frame. The block diagram of high-frequency rotating signal injection method is shown in figure 5. The injected signal which generates a pulsating voltage vector in space is expressed as

$$\boldsymbol{u}_{inj} = \begin{bmatrix} u_{\hat{d}_h} \\ u_{\hat{q}_h} \end{bmatrix} = U_{pul_h} \begin{bmatrix} \cos(\omega_h t) \\ \sin(\omega_h t) \end{bmatrix} \#(7)$$

Where $U_{pul_h}$is the amplitude of the injected high-frequency pulsating sinusoidal voltage, and“^” means the estimated rotating frame.

If defined $\Delta\theta_e = \theta_e - \hat{\theta}_e$, and suppose $\Delta\theta_e$is small enough, the high-frequency response current in the stationary frame as

$$\begin{bmatrix} i_{\alpha_h} \\ i_{\beta_h} \end{bmatrix} = \frac{1}{L_d} \begin{bmatrix} \cos(\theta_e) \\ \sin(\theta_e) \end{bmatrix} \cdot \int \boldsymbol{u}_{inj}\, dt \#(8)$$

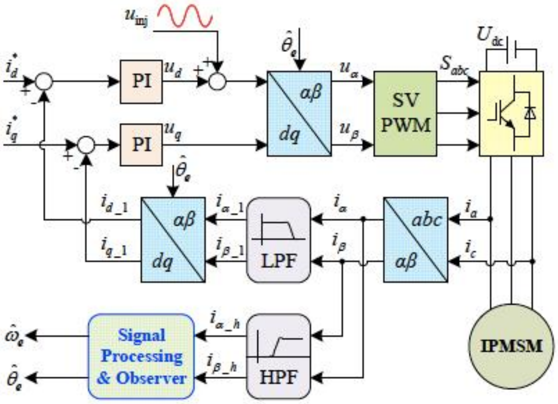


Figure 5 The block diagram of high-frequency pulsating signal injection method[24]

The high-frequency pulsating signal injection method has no requirement for saliency, so it can be used to both IPMSM and SPMSM. This method has a better response to variations in motor parameters and load disturbances, but there are some problems such as poor system dynamics, narrow stability range and slow convergence.[26] Literature [27] proposed that to inject high-frequency pulsating sinusoidal signals into stationary frame can improves the stability of the observer and simplifies the process of demodulating the signals. Literature [28-29] proposes to inject the high-frequency pulsating signal into a three-phase ABC frame and a fixed-frequency rotating frame to improve the convergence speed and system stability.

Except high-frequency sinusoidal signals, also high-frequency square waves and triangular waves can be injected. The advantages of injecting the high-frequency square wave voltage signals are the absence of noise and the ease of processing the signal and more accurate positional estimates.[30]The literature [31] employs the periodic positive and negative injection of high-frequency square wave voltages to evaluate the position information. Since the injected high-frequency voltage vectors are same magnitude and opposite directions, the average current and dead time voltage errors at positive and negative injection can be considered equal. Subtracting the two current integrations minimizes the error without any compensation. Although some bandwidth of the current loop is decreased, it is still higher than the bandwidth of high frequency sinusoidal injection voltage. The method is robust to voltage errors s meanwhile has less fluctuation in the position estimation error.

(3) Mid-High-Speed Control Strategies

Back-EMF Method

Back- EMF method also called flux estimation method can be used in both open-loop and close-loop.[32] The key to the FOC of PMSM is to obtain accurate rotor flux linkage vectors. Depending on the stator and rotor voltage equation and flux equation of PMSM in the stationary frame, the integral or inverse trigonometric operations are performed on the rotor position and speed.[33] flux vector is simply calculated from

$$\boldsymbol{\psi}_f = \boldsymbol{\psi}_s - \boldsymbol{L}_{\alpha\beta}\boldsymbol{I}_s = \int (\boldsymbol{U}_s - R_s\boldsymbol{I}_s)\,dt - \boldsymbol{L}_{\alpha\beta}\boldsymbol{I}_s \#(9)$$

Where $\boldsymbol{\psi}_f$ is the vector of flux, $\boldsymbol{\psi}_s$is the vector of stator flux, $\boldsymbol{U}_s$is the vector of stator voltage, $\boldsymbol{I}_s$is the vector of stator current, $\boldsymbol{L}_{\alpha\beta}$ is the inductance matrix in stationary frame.

The rotor position angle is obtained as

$$\theta_e = arctan\frac{\psi_{f\beta}}{\psi_{f\alpha}} \#（10）$$

$\psi_{f\alpha}$,$\psi_{f\beta}$is the components of $\psi_f$on the stationary frame.

Back-EMF method is easy to implement and fast to dynamic response. However, the initial value of the integral, voltage and current measurement noise, inverter non-linearity and other factors result in integral drift and make the motor unstable operation in practice.[34-35] When the PMSM is operarion at a low speed (less than 5% of the rated speed), the back-EMF is too small to affect the accuracy of the estimation results. Instead of pure integrators, integrators with low-pass filtering are often used to suppress or eliminate integral drift. This way can improve the rotor position observation accuracy.[36]Based on the traditional low-pass filter (LPF), an improved algorithm combining the zero-drift correction and the LPF with bias compensation is proposed in the literature [35]. The algorithm can completely eliminate the DC bias and the estimation error is less than 1.5% compared with the measurement result by sensor control system. The second-order general integrator (SOGI) has the advanced filtering capabilities and it can effectively avoids amplitude degradation and phase shift. Literature [37] designed two new types of flux observers based on SOGI, which effectively eliminate direct current (DC) bias and harmonics without additional parameter identification and compensation. These two flux observers improve the steady state performance and capacity of resisting disturbance, and expand the speed regulation range.

It is not easy to calculate the rotor position directly from the back-EMF of IPMSM. Literature [38] proposes the concept of extended back-EMF. The voltage equation of PMSM is expressed as

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R_s + pL_d & \omega_e(L_d - L_q) \\ -\omega_e(L_d - L_q) & R_s + pL_d \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \varepsilon \#(11)$$

$$\varepsilon = \left[(L_d - L_q)(\omega_e i_d - p i_q) + \omega_e \psi_f\right] \begin{bmatrix} -sin\theta_e \\ cos\theta_e \end{bmatrix} \#(12)$$

The extended back-EMFε contains information about the position of EMF and stator inductance. The extended back-EMF is obtained by a perturbation observer, and then obtained the rotor position information by adaptive estimation speed algorithm. The stability of the system were verified based on Popov hyperstable theory, and the experimental results showed that the maximum position error was about 1° electrical angle. Literature [39] proposes a cross-coupling compensation method, which achieve independent control of the d - q axis without interference. This method not only reduces the error between the actual current and the reference current, but also reduces the rotor position error.

Sliding Model Observer

The sliding model observers (SMO) is designed using variable structure control theory of sliding mode to obtain the rotor position and speed. The estimation error between observed and actual currents reaches a sliding surface, and then slides along this surface, eventually to zero. Block diagram of conventional SMO method shows as Figure 6. Back-EMF is estimated to the voltage and current measured in the PMSM control system, which is used to design the sliding mode surface. And then, the rotor position and speed is obtain by back-EMF. SMO is a discontinuous control algorithm based on the current equation in stationary frame, which is insensitive to parameter and to external disturbances.[40] SMO is used to SPMSM and IPMSM.

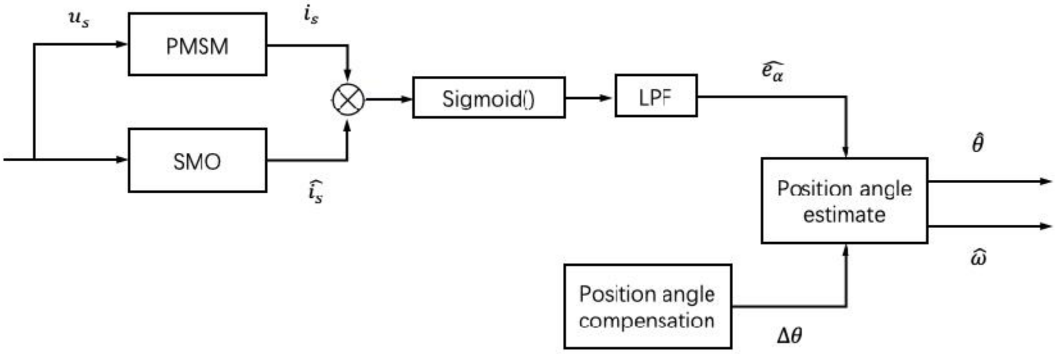


Figure 6 Block diagram of conventional SMO method[41]

The advantages of SMO is fast response, strong robustness and easy implementation.[42-43]Since variable structure control of sliding mode is controlled by discontinuous sign function, it produces the chattering, which can cause relatively large torque pulsations especially at low speed. Therefore, the most pressing problems of SMO are the elimination of chattering and the improvement of control accuracy under the stronger robustness of the system. Therefore, the research on the improvement control strategy of SMO mostly focuses on the sliding mode surface selection, the switching function selection and the phase compensation.[44-45]

Literature [42] uses the system function to replace the sign function, which reduces the chattering and improves the accuracy of rotor position estimation. At the same time, it constructs an back-EMF observer to compensate phase shift by the low-pass filter, but this control system has a complicated hardware design and slow response speed. SMO combined with PLL can effectively reduce the high-frequency chattering and improve the observing accuracy.[46-48] Literature [49-50] use the adaptive notch filter to observe the rotor position, which can effectively reduce pulsation error of the rotor position observation. This method has the faster convergence speed, and better control effect in the steady state and dynamic process.

In the literature [51], Kalman filter SMO is designed according to the stability theory of Lyapunov, which is adopted sigmiod function of the SMO combining with the Kalman filter. The result shows the rotation speed and position angle are extracted by using the back-EMF observer, which avoids the phase delay and improves the tracking effect.

Model Reference Adaptive System

The block diagram of model reference adaptive system (MRAS) shows as figure 7. The principle is that put the mathematical model containing the estimated parameters (such as current equations, flux equations and voltage equations) as the adjustable model, and the PMSM model with parameters as the reference model. The output is the difference between these two models. By designing suitable adaptive laws to achieve the tuned model tracks with the reference model, and thus estimate rotor position and speed.[53] MRAS is a parameter identification method based on Popov hyperstability theory, and its estimation accuracy is related to the reference model. The choice of adaptive law and ensuring the stability and robustness of the system while improving the convergence speed are the research focuses currently.

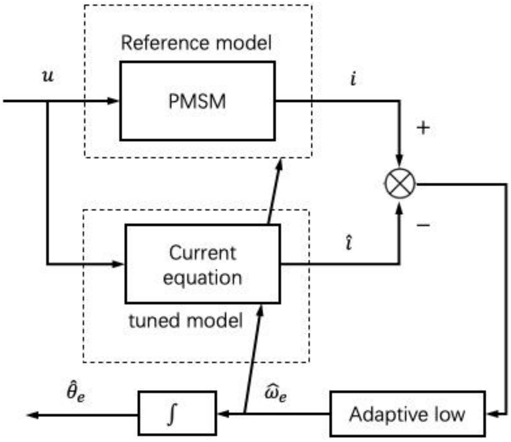


Figure 7 The block diagram of model reference adaptive system[52]

Literature [54] combines the SMO with MRAS to construct a sinusoidal saturation function with variable boundary layer, which reduces the chattering caused by the SMO. Meanwhile, in order to improve the stability of the sliding mode switching, the sigmoid function has been introduced. Due to the traditional digital integration defects caused by the reference model calculation accuracy degradation in the MRAS, Literature [55] proposes a digital integration method based on the prediction-correction system. By predicting the next integral value to correct the error of the rectangular formula, the influence of digital integration error on the accuracy of the algorithm is greatly reduced, and the estimation accuracy of the rotor position and speed is improved.

Extended Kalman Filters

Kalman filters is a linear random observer using the optimal prediction estimation method. The principle is through the voltage and current signals at the two ends of the motor stator to obtain the rotor position information with recursive calculations of the voltage and mechanical equations in the fundamental wave model. The filter gain can be automatically adjusted with the environment, and then optimized with the sampled signals to provide more accurate rotor position information. This method attenuates the effects of random disturbances and measurement noise.[56-57] but the PMSM control system is nonlinearly, so it can be used Extended Kalman Filter(EKF) and Unscented Kalman Filter (UKF).

Literature [58] proposes an inertia compensation method with extended Kalman filter to obtain the rotor position information. The method through a load disturbance observer to establish online identification and compensate the disturbance inertia. Literature [59-61] proposes to combine the Kalman filter algorithm with SMO algorithm so as to achieve the online estimation of rotor position and speed. Literature [62] compares the estimation performance between UKF and EKF about position and speed of PMSM. The simulation results show that the estimation accuracy in the steady state of UKF is 2.4 times of EKF, but EKF performs better in the start-up and dynamic processes. The disadvantage of the EKF is the complex algorithm and the high computational performance of the controller, Therefore, at present, field programmable gate array (FPGA) is widely used to implement observe the rotor position of EKF, which can improve the response speed and operational precision.[63]

Luenberger Observer

The block diagram of Luenberger observer (LO) shows as Figure 8, the principle is to construct an observer model using the PMSM mathematical model and to correct the state variables based on the deviation feedback signals. When the observed current is following the actual current, the rotor position information can be calculated from the observed back-EMF, forming a tracking closed-loop estimation.[65] The LO effectively avoids the chattering and getsthe high speed dynamic response and high estimation accuracy. However, the selection of feedback gain is the key to influence the estimation speed, and it is more sensitive to the motor parameters variable.

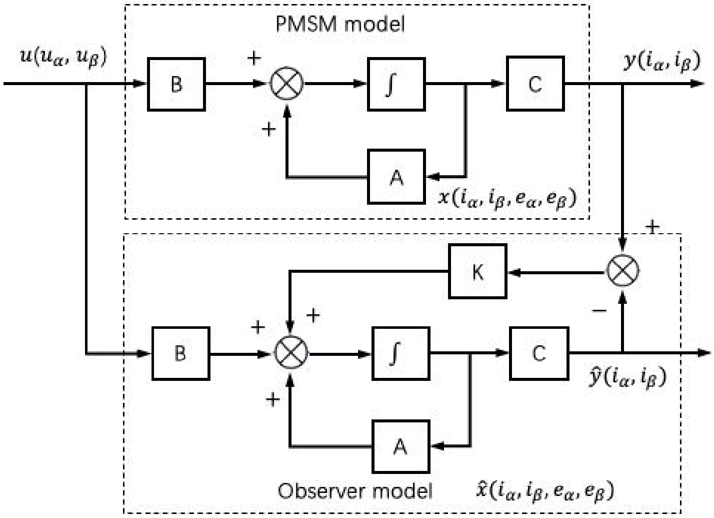


Figure 8 The block diagram of Luenberger observer[64]

In order to improve the robustness of the control system, literature [66] proposes a robust nonlinear LO to estimate the rotor position and flux with currents and voltages as only measurements. The robustness to the mechanical load and physical parameters of the machine estimate both the rotor position and the flux of a SPMSM in a robust way. When the given speed is constant, the estimation error remains constant. Literature [67] proposes a linear reduced dimensional LO constructed by stator current and speed equations. The method employs a back stepping control strategy to design the speed and current controllers, so that the system has few regulation parameters and also good at speed tracking and torque response.

Artificial intelligence method

With the development of computers and modern control theory, artificial intelligence control methods began to be used in the 1990s, which mainly includes artificial neural network (ANN), fuzzy control, expert systems, genetic algorithms and other intelligent algorithms with self-learning, self-adaptation and self-tuning capabilities.[68] Literature [69] proposes a sensorless control method of PMSM based on ANN, and proves the stability of velocity and position adaptive observer. Literature [70-71] propose radial basis function (RBF) neural network, which used stochastic gradient descent (SGD) to train and optimize the network parameters online. This sensorless control system is good at dynamic response and regulating ability. In order to reduce the chattering, literature [72] combines fuzzy control with SMO to determine the magnitude of the gain. The result shows that the chattering is restrained at low speed, so the position detection accuracy and static and dynamic performance are improved. Currently, artificial intelligence methods are not very mature and still in the theoretical research stage.

(4) Full Control Strategies

Currently, there is not one method to achieve sensorless operation control of PMSM over the full speed range.The general solution is to switch smoothly between different control methods in different speed ranges, or to combine a position detection method based on back-EMF with other start-up techniques that can detect the rotor position in a wider speed range.

The difficulty in the design of good composite control methods is how to achieve smooth switching between the two different types of methods. The direct switching method and the weighted average switching method are the most adopted. Literature [73] proposes to combine the high-frequency signal injection method in the low-speed stage with the SMO method in the high-speed stage according to the current decreasing slope switching method. so as to realize to the sensorless control of PMSM in the full speed range. In order to solve the problems of position estimation hysteresis in the low speed stage and the large influence of model parameters in the high speed stage, literature [74] proposes a composite control algorithm that combines the MRAS with the high-frequency pulsating voltage signal injection method. through the weighted average algorithm, the smooth switching between these two methods is achieved.

Applications of Sensorless Control Methods

Each control method has its own adjustable speed range and applicable motor drive. The choice depends on its advantages and disadvantages. Especially for the sensorless control technology of PMSM in the full speed range, multiple methods can be used to play their respective advantages and remedy the insufficiency of single control method. Thus, the accuracy and robustness of system control can be improved. Table 2 summarizes the characteristics of the control methods and the applicable motors.

Table 2 Characteristics of the control methods

Methods		Characteristic	Motors
Star-up	rotating	no acoustic noise; independent of motor parameter;	IPMSM
	pulsating	small effect on inverter non linierities; magnitude modulated	SPMSM, IPMSM
	inductance	simple; insensitive to parameter variation	IPMSM
Low-speed	rotating	independent of motor parameter; response delay	IPMSM
	pulsating	no saliency; bad stability; low convergence rate	SPMSM, IPMSM
Mid-high-speed	Back-EMF	DC bias and harmonics; bad performance in the low-speed range; independent of motor parameter	SPMSM, IPMSM
	SMO	guaranteeing no mistakes; very reliable; independent of motor parameters; Ineffective at rest and at slow speeds	SPMSM, IPMSM
	MRAS	A fail-safe machine model; high-velocity adaptation; Struggle with a wide range of motor characteristics	SPMSM, IPMSM
	EKF	less influence of noise; low computational time; Weak low-speed performance	SPMSM, IPMSM
	LO	Convergence is certain all across a large chunk of the possible states; convergence times are completely arbitrary; sensor noise issue much worse	SPMSM, IPMSM
	AI	excellent self-learning ability; fast self-adjusting ability; strong robustness; in the stage of theoretical research	SPMSM, IPMSM

Discussion

Sensorless control techniques of motor drives is superior to sensor control when it comes to overall system reliability and cost. This paper discusses the state of the art of position sensorless control techniques. The saliency based methods are used in low speed range, the model based methods are used in mid-high speed rang and the composite control methods are used over the full speed range. Based on the research reviewed of the sensor less control techniques, there are areas for potential research and development:

(1) Initial position detection at standstill and low-speed operation control relies on the saliency effect, or injects the voltage/current signals. These methods is independence of motor parameters, but the signal process is complicated. So it needs to be simplified to improve the start-up performance.

(2) With the increase of rotational speed, the injection signal cause more chattering and loss. Therefore, in the middle and high speed range, the control mainly base on fundamental wave model and various observers are used to estimate the rotor position.

(3) Composite control methods combining the complementary strengths of the various methods enables sensorless operation control of PMSM over the full speed range. The key is the smoothness of the switching process.

(4) As AI technology matures, future research will focus on composite AI sensorless control methods which have high estimation accuracy, robustness and the ability to directly realize the full speed range.

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