A Review of Sensorless Control Methods for AC Motor Drives

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(Invited)

***Abstract*—In recent years, the application of sensorless AC motor drives is expanding in areas ranging from industrial applications to household electrical appliances. As is well known, the advantages of sensorless motor drives include lower cost, increased reliability, reduced hardware complexity, better noise immunity, and less maintenance requirements. With the development of modern industrial automation, more advanced sensorless control strategies are needed to meet the requirements of applications. For sensorless motor drives at low- and zero-speed operation, inverter nonlinearities and motor parameter variation have significant impact on the stability of control system. Meanwhile, high observer's bandwidth is required in high-speed region. This paper introduces the state of art of recent progress in sensorless AC motor drives. In addition, this paper presents the sensorless control strategies we investigated for practical industrial and household applications. Both advanced sensorless drives of induction motor (IM) and permanent magnet synchronous motor (PMSM) are presented in this paper.**

***Index Terms*—AC motor drives, low- and zero-speed, high speed operation, sensorless control.**

I. Introduction

IN advanced AC motor drive systems with high dynamic performance and efficiency, space vector control is mostly used, where accurate rotor position/speed is needed. Generally, mechanical position/speed sensor with high resolution is a prerequisite for excellent vector control, which also adds to the cost and complexity and impairs the reliability of drive systems. Therefore, vector control system without mechanical position sensors, or known as position/speed sensorless control of AC motors has been studied and applied increasingly in both industries and household appliances.

Induction motor (IM) has been widely used for its simple structure, low cost, high reliability and easy maintenance. The vector control-based IM drives have been proven as a kind of high performance control strategy.

Permanent magnet synchronous motors (PMSMs) have been widely used in industrial control systems and household appliances. These all due to their high power density, reliability, efficiency, control ability and wide speed range. In recent years, the penetration in semiconductor devices has enabled sensorless control methods applied in high quality control systems. Besides, improving the stability and robustness of PMSMs control have also been discussed intensively by researchers.

This paper will introduce the state of art of recent progress in position/speed sensorless control and present the position/speed sensorless control strategies we adopted in real industrial and household applications for AC motors. Both IM and PMSM drives will be presented. The IM is presented in the first part. Firstly, flux and speed estimation methods for IM are introduced. Then field weakening control strategies are presented. At last, special current loop control methods are discussed. As for PMSM, first, noise reduction HF signal injection methods for low-speed PMSMs drive are presented. Then, model based methods and some solutions to harmonics reduction are introduced, including ADLINE filter. Finally, low frequency ratio drive schemes are discussed.

II. Sensorless Control Methods for IM

Fig. 1 is the block diagram of typical IM vector control system. The whole control system includes control unit, rectifier and inverter unit, and a squirrel-cage IM. The rotor flux oriented vector control is applied as the basic control strategy. The double closed-loop structure is used, including current inner loop and speed outer loop. The flux and speed observer is adopted to estimate the motor speed and rotor flux angle. The three-phase alternating current is rectified into the direct current of DC-link, and then the direct current is inverted into the three-phase alternating current to drive the IM. This section focuses on the state of art and trend of vector control-based IM drives.

A. Flux and Speed Estimation

In general, the advantages of the sensorless drive system include: low cost driving system, less integrated parts of the system, small size, high reliability, and convenient maintenance. The disadvantages mainly include low load

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capacity, low speed accuracy and low speed range generation instability.

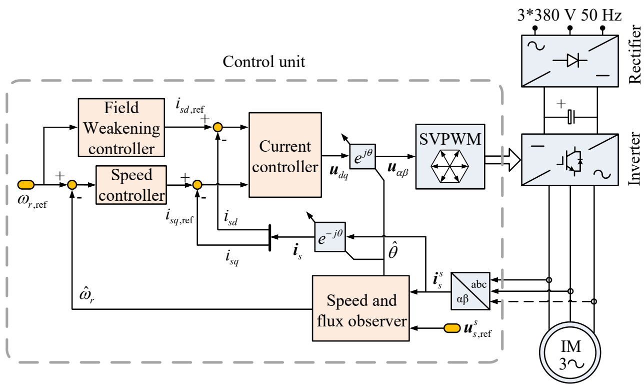

Fig.1. Block diagram of typical IM vector control system.

In recent years, a lot of researches have been done on flux and speed observer of IM sensorless drive system, mainly includes: low frequency signal injection method [1], high frequency signal injection method [2] and model reference adaptive system (MRAS) [3], full order flux observer [4], reduced order observer [5], sliding mode observer [6], neural network [7], and Kalman filter [8]. According to the characteristics of each method, the above can be divided into two categories:

(1) Signal injection-based flux and speed observer

By injecting signal, this kind of method uses rotor slot harmonic, saturated, and the leakage inductance to extract the rotor position information. It can guarantee the stability of IM operation at zero stator current frequency.

Two different high frequency current signal injection methods were proposed in [9]. Avoiding the injected signal current loop bandwidth limit, this paper directly injected the high frequency voltage signal into the output of current loop. Through sampling stator current, the low-frequency component is extracted as current loop feedback and the extract high-frequency response component to get rotor position. The nonlinear effect of the method is less than that of the dead zone time, but the current loop bandwidth cannot be set too high. The second kind of current injection method is to extract the high frequency component command voltage to calculate rotor position information. This method can guarantee a high bandwidth for speed loop, but it need complex signal processing method to overcome the effect of inverter nonlinear error. The high frequency signal injected based method can guarantee the sensorless IM running steadily under 150% rated load at zero speed or even zero current frequency. But due to the weak rotor anisotropy, the IM needs to be specially designed to extract the correct rotor position from the feedback current information, so this kind of method highly depends on the motor design.

A low frequency current signal injected based vector control method for sensorless IM control was presented in [10]. In this paper, the low frequency current signal was injected into the current loop, then the rotor position can be extracted from the current back EMF. Compared with high frequency signal injection based method, low frequency signal injection based method can guarantee the motor 150% output of the rated torque for a long time at zero speed and zero frequency without obvious anisotropy of magnetic field. However, the injected signal amplitude is larger than that of injected high frequency signal, and the torque ripple is more obvious. At the same time, the motor need to be special designed, so the low frequency signal injection based method has not been widely used yet.

A method for detecting rotor position with zero sequence current harmonic was discussed in [11]. This method used rotor leakage inductance due to the changes of motor saturation effect to estimate the rotor flux linkage angle according to the different voltage SVPWM vector on the zero-sequence current harmonic. This method can guarantee 100% rated output torque at zero speed and zero frequency without signal injection. But it is difficult to extract the rotor position information effectively by the leakage inductance effect in practical application due to the low signal noise ratio.

All methods above can guarantee stable operation of sensorless IM control system for a long time at zero frequency and zero speed. But this kind of methods for IM need obvious anisotropy of magnetic field, strongly rely on the motor design, and some problems such as torque ripple and noise make it hard to be widely used in industry [12].

(2) IM model-based flux and speed observer

Firstly, the mathematical model of IM is established, and then the rotor flux and rotor speed is estimated according to this model. The block diagram of full order observer is shown as Fig. 2.

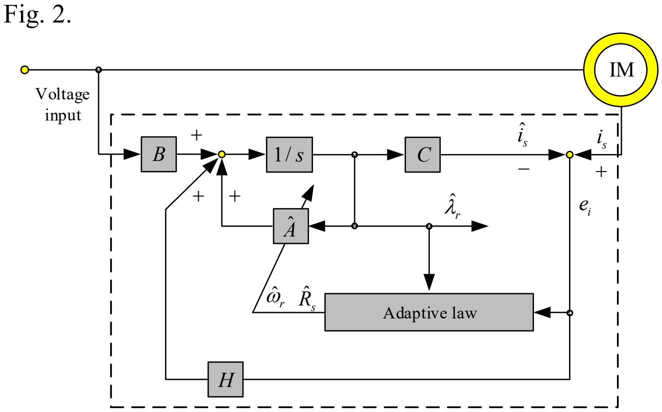

Fig.2. Block diagram of full order observer.

An observer equation that can be used to unify all the current observer into a form was discussed in [13]. Using the uniform equation, the problem caused by voltage error, current error and motor parameter error is analyzed in this paper. Finally, this paper proposed a unified equation method for voltage model and current model. Adjusting the unified equation coefficient, the observer is mainly run under voltage model when the motor running in high-speed region, or the current model when the motor running in low-speed region. This method could effectively take advantage of the voltage model in high speed and the current model in low speed to avoid the drawbacks of voltage model and current model and improve the flux observation accuracy, realize the smooth transition of the voltage model and current model. However, there was no attention on low speed generation and observer parameters robustness of sensorless IM. In addition, since this method was a model-based method, it cannot be carried on stable operation for a long time when the stator current frequency is zero.

A sliding mode observer for rotor flux observation was presented in [14] and [15]. The motor voltage equations and current equation were used to build up the full order sliding mode observer. The observer does not include the rotation speed variable, so the observer is not affected by the estimated speed error with strong robustness. In addition, the observer can effectively suppress the DC voltage deviation. Literature [16], based on MRAS system, replaced the traditional proportional-integral (PI) modulator by sliding mode adaptive method to estimate the speed. The improved speed adaptive law had strong anti-interference ability. But, based on the sliding mode observer, it was difficult to avoid the unstable problem at low speed, and the speed cannot be observed at the zero frequency. In addition, the system has a weak robustness to the motor parameters because the motor parameters were used in both flux and rotor speed estimation.

[17] proposed a robust Kalman filter observer. Firstly, a flux observer and a robust coefficient are designed to optimize the Kalman filter, which makes the system more immune to the variation of motor parameters. Then, a speed estimation adaptive law is designed according to the least square principle. Kalman filter-based speed and flux observation have strong robustness to motor parameters because the error of the motor parameters was considered at the beginning. However, the design of error coefficient matrix was relatively complex, and it did not consider the unstable problem of the speed estimation in low-speed generation and the inestimable problem at zero frequency.

In conclusion, strongly relying on motor design, the signal injection-based method has not been widely used yet. The researches on sensorless vector control method for IM mainly focus on stable operation at zero speed and zero frequency to improve the control performance and enlarge the sensorless vector control of IM in the field of industrial applications.

B. Field-Weakening Control Strategy

Common numerical control (CNC) system, locomotive traction and other applications have higher requirements for the high-speed operation of IM control system [18] [19]. Taking the application of CNC machine as an example, the important trend of the development of the world numerical control equipment is the high-speed machining technology. The specific requirements for the IM drive system are as follows:

(1) High speed operation. High speed processing technology can not only improve efficiency and reduce the cost when processing workpieces, but also help to improve the quality of the products. Ordinary CNC machine tools usually need to meet the stable operation of 6000-8000 r/min, while in the ultra-high-speed machining machine, the rotational speed can be as high as 20,000 to 40,000 r/min.

(2) Quick start-stop ability. The main frame of CNC system needs to be replaced frequently to adapt to different working condition, therefore, reducing the start-stop time of spindle motor can effectively reduce the time of replacement of cutting tools and other auxiliary operation time and improve processing efficiency. This requires the spindle drive system to have the maximum torque output capability in wide-speed range.

(3) High accuracy and high dynamic response. It is necessary to ensure that the spindle motor has high accuracy to deal with different cutting conditions. At the same time, it is necessary to make the spindle motor speed fluctuate less when the load changes and have good rigidity to ensure the surface finish and machining accuracy of the workpiece.

In view of the above high-speed driving requirements, it is necessary to carry out in-depth analysis and research on the field-weakening control strategy of IM. When the IM runs above the base speed, inverter output voltage will not be able to offset the motor back electromotive force (EMF). At this point, we need to reduce the back EMF by reducing motor magnetic field, so that the motor could have a further acceleration ability. At the same time, in order to ensure that the motor has a quick start-stop capability, it is expected to have the maximum torque output capability during the filed-weakening acceleration.

According to the voltage and current limitation of the inverter and the motor, the whole operation of the motor can be divided into three regions: the constant torque region, the constant power region and the constant voltage region, as shown in Fig.3. In the constant torque region, the motor runs below the base speed, where the excitation current of the motor is constant, and the maximum output torque is constant. In the constant power region, the motor speed is above the base speed, and the maximum output torque of the motor will be inversely proportional to the motor speed, while the motor power remains constant. As the speed increases further, the motor will enter the constant voltage region, and the maximum output torque and power of the motor will be reduced.

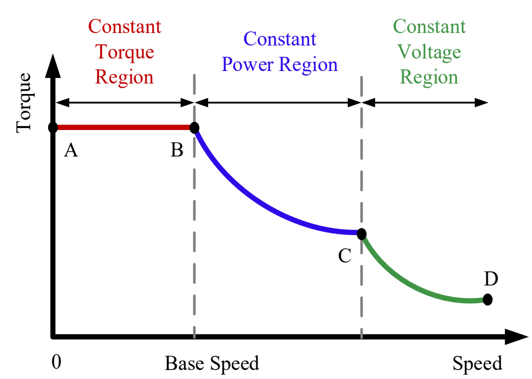

Fig.3. Torque-speed characteristic.

A large number of field-weakening control methods are proposed, and the starting points are consistent, namely the reasonable distribution of excitation current and torque current in field-weakening region to obtain the maximum torque output capacity. The main methods can be divided into two categories: the method of open-loop calculation of the motor model and the method based on the voltage limit closed-loop regulation.

(1) Field-weakening control strategy based on motor

model open loop calculation.

This method is based on the motor model and obtains the control strategy through open-loop calculation. The basic strategy is the "$1/\omega_r$" method [20], that is, when the motor speed is above the base speed, the excitation current is set to inversely proportional to the rotational speed. However, this method does not consider the influence of voltage and current limit on the system, so it will cause the higher magnetic field and cannot achieve the maximum torque output capability of the motor. According to the literature, the engineering correction method of "k/ω_r" is put forward, which improves the control performance by fitting the weak magnetic curve, but still cannot achieve the maximum torque output capability of the motor in the field-weakening field. In the literature [21] and [22], according to the motor model, voltage and current limit, the optimal excitation was obtained by the open-loop calculation, so the maximum torque output capability can be obtained theoretically. The literature [23] further pointed out the leakage effect, that is, under the same conditions, the smaller leakage inductance can output greater torque. Therefore, by considering the voltage and current limit of the stator resistance, the distribution strategy of the excitation current and torque current can be optimized to further improve the maximum torque output capability. Although the above methods can obtain the maximum torque output capability in theory, it seriously depends on the motor model, and when the motor parameters change, it will not achieve the theoretical performance. Literatures [24, 25] analyze the effects of parameter changes on the field-weakening control and improve the robustness of the algorithm and the parameter perturbation through the introduction of online identification, magnetic saturation compensation methods. Because of the essential open-loop based control, its dynamic and static performance is still limited.

(2) Field-weakening control strategy based on voltage limiting closed-loop regulation.

Different from the open loop calculation method, this kind of method constructs the voltage closed-loop to adjust motor magnetic field dynamically according to the system voltage. Therefore, the maximum torque output capacity is enhanced. Kim and Sul first used this idea in literature [26], a voltage close loop was first constructed to dynamically adjust the excitation current. At the same time, considering the current distribution of constant voltage area, another voltage regulator was given to adjust the limit of torque current reference, and the system block diagram as shown in Fig.4. This method can ensure the maximum torque output ability, and have strong robustness to motor parameters change, but it needs additional two regulators, which to some extent, increases the complexity of the system. Based on the literature [20], the current tracking performance of the system was further improved, and the robustness of the system was enhanced without the need of motor parameters. [27] used space vector modulation of zero voltage vector duration as input voltage loop to further expand the utilization of dc bus voltage, which improved the maximum torque output capacity. However, this method needs to look up the table, which affects the universality and robustness of the algorithm to some extent. Besides, scholars have proposed many other improved methods [25-28] to improve the torque output capacity and robustness, but these algorithms still exist such problems as complexity and limited dynamic performance.

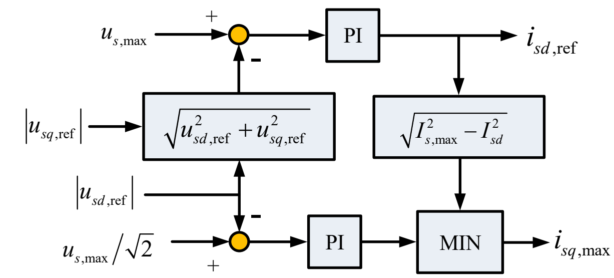

Fig.4. Block diagram of voltage loop-based field-weakening control strategy.

C. Current Loop Control Strategy

In the double closed-loop vector control system of IM, the current loop acts as the inner loop of the control system, which plays a key role in the overall system performance [29] [30]. The fast response current loop not only speeds up the current convergence but also guarantees the bandwidth enhancement of the speed loop, which is of great significance for applications such as CNC machine tools and high-speed drilling machines that require high dynamic performance. To this end, the academic community has proposed a variety of current loop control strategies as follows:

(1) Hysteresis control

Hysteresis control is an early widely used method for the control of IM current loops [31]. The basic principle is that three separate hysteresis comparators are used to control the three-phase stator currents, respectively. Eventually, the error between the stator current and the given value is limited to the set hysteresis bandwidth. The method has the advantages of simple, fast dynamic response, no steady-state error and not influenced by the change of the motor parameters. However, the structure of the hysteresis comparator determines the switching frequency is not fixed, especially in the case of large current changes, will produce high-frequency noise and harmonics. Coupled with its inherent randomness, it will further reduce system reliability. Aiming at the problem that the switching frequency of the hysteresis control is not fixed and generally large, the methods of hysteresis control of fixed switching frequency and adaptive hysteresis control were proposed in the literature [32]. However, these methods increase the complexity of the current loop and haven't been widely used.

(2) PI control in the stationary frame

PI control in the stationary frame [33] is also called ramp comparison control. Static frame PI control still uses the difference between the given current and the actual sampled current as the current controller reference signal. However, unlike hysteresis control, it uses three independent PI controllers to generate the inverter command voltage. By comparing the command voltage with the triangular wave, the PWM signal is modulated and finally the inverter is controlled. The advantage of this method is that the algorithm is easy to implement, and the switching frequency is fixed, so that the steady-state error tracking of the DC signal can be realized. Although this method performs well in the low-speed range of the motor, as the motor speed increases, the phase lag between the given current and the actual current increases and produces a steady-state error. This steady-state error can be compensated for by adding a feedforward compensation term or phase-locked loop, but this will also increase the complexity of the current loop.

(3) PI control in the synchronous rotating frame

PI control in the synchronous rotating frame [34] is the most widely used current loop control method. The system block diagram is shown in Fig.5.

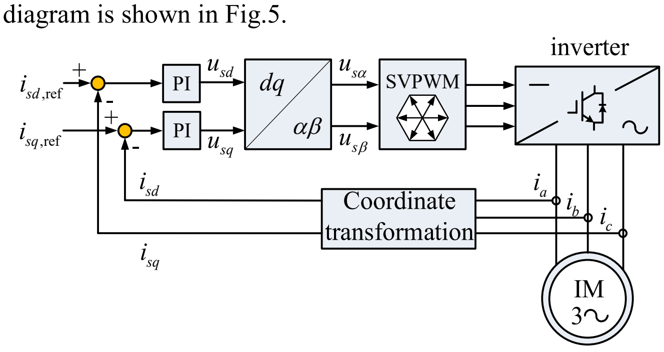

Fig.5. Block diagram of PI control in synchronous rotating frame.

The PI control in the synchronous rotating frame system converts the three-phase sinusoidal current of the motor into the direct current component of the two-phase synchronous rotating frame through the coordinate transformation, realizing the decoupling control of the torque current and the exciting current. Different from the PI control of stationary frame, PI control in the synchronous rotating frame uses the direct current as a reference value, so the steady-state current error of the motor during high-speed operation can be effectively avoided. In addition, PI control in the synchronous rotating frame system also has the advantages of clear structure, fixed switching frequency, high current control precision and easy analysis by linear control theory.

(4) Predictive control

In recent years, predictive control has been increasingly used in power converters. The basic idea of predictive control is to obtain the optimal control output by predicting the change of the control object based on the mathematical model of the control object and substituting the system information into the preset optimization rules. Predictive control has many advantages like: fast response, wide applicability, suitable for control constraints and nonlinear systems. The computational complexity is generally large. However, with the development of microprocessor technology, no hardware limitation exists in the predictive controller's online implementation. The different types of predictive control and their characteristics are as follows:

4.1 Hysteresis-Based Predictive Control

Hysteresis-based predictive control aims to limit the amount of system controlled to hysteresis bandwidth. The most typical controller is "bang-bang controller." Holtz and Stadtfeld proposed a "bang-bang controller" in [38] based on the fact that a circular error bound can be determined from a current reference vector, and the bound of the error will determine the switching timing of the controller. When the current vector reaches the circular error bound, the current vector trajectory for each possible switch state is calculated and the time that it reaches the circular error bound can be predicted. Finally, choose the switch state vector that can generate the maximum on time, so as to achieve optimal control and reduce the switching frequency.

4.2 Trajectory-Based Predictive Control

The goal of trajectory-based predictive control is to limit system variables to pre-programmed trajectories. Based on this principle, Flach proposed direct average torque control [39], and Baader proposed direct self-control [40]. At present, the predictive control algorithm is often used to directly control the stator current, torque or flux linkage of the motor, while the speed loop is superimposed on it as a control loop. The trajectory-based predictive control provides the possibility of directly controlling the system variables. According to trajectory-based predictive control, Mutschler proposed direct speed control, abandoned the traditional cascade control structure, and based on the speed deviation and time optimal principle to determine the inverter switching state, to control the motor speed tracking the desired point.

4.3 Model predictive control

Model predictive control first appeared in the late 1970s, mostly used in the field of petrochemical process control. The basic idea is based on the mathematical model of the controlled object, by selecting a specific objective function and make it optimal, and ultimately get control instructions. Model predictive control has three elements: model prediction, roll optimization, and feedback correction. With the development of microprocessor technology, model predictive control has been applied in power converter field more and more.

Model predictive control can be divided into continuous control set MPC (CS-MPC) and finite control set MPC (FS-MPC). In the actual control system, according to the specific conditions to select the sampling period, the objective function, the state constraints, the finite length of time and so on. Only when the control system chooses the reasonable constraints of input and state variables, can the system be scrolled and optimized according to the pre-set objective function to get the optimal control solution. In motor control systems, the problem of optimizing control over the state of a switch can be translated into a limited set of inverters switching states, and the FS-MPC can be used depending on the discrete control nature of the microprocessor. According to the prediction step, FS-MPC can be divided into single-step prediction and multi-step prediction. The single-step prediction and optimization process is simple and easy to implement, while the multi-step prediction and optimization process is complicated, but the system stability and precision are better.

4.4 Dead-beat predictive control

Dead-beat predictive control is another commonly used predictive control, the basic principle is based on the mathematical model of the controlled object, calculate the control needed for the next cycle in each sampling period instruction, so that the control object of deviation in the next update time is zero. This method has many advantages, such as low computational complexity, fast switching frequency and fast response. It has been successfully applied to network measurement converters, power factor correction [20], active filters, rectifiers, DC converter, motor drive and other occasions. The deadbeat predictive current control response is faster than the traditional PI control and provides the precondition for designing a high-bandwidth speed loop. Fig.6 is a block diagram of the IM control system based on deadbeat predictive current control.

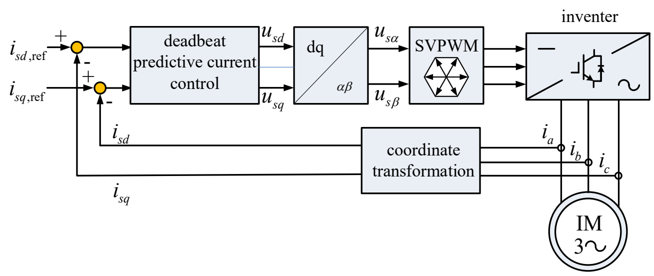

Fig.6. Block diagram of deadbeat predictive current control-based IM control system.

However, traditional deadbeat current control relies entirely on the motor model, so its stability is poor when the motor model mismatches. In the actual IM control system, the motor resistance and inductance will change with the changes of the external temperature and the saturation of the magnetic field, respectively, so that the motor model and the actual model in the algorithm do not match. The model mismatch will make the control system appear steady-state current error, when this error increases to a certain extent, the control system will become unstable. Therefore, how to improve the robustness of deadbeat predictive current control is the key to its application.

III. Sensorless Control Methods for PMSMs

Generally, sensorless PMSMs drives method are classified into two categories, i.e. high frequency signal injection (HFSI) methods applied in zero- and low-speed range and model-based methods applied in medium- and high-speed range. Different from the sensorless control for IM drives, the structural and saturation saliencies can contribute to position tracking for low- and zero-speed. However, acoustic noises restrict HFSI methods extended to area such as household appliances. Pseudo-random HFSI provides an alternative for the traditional methods [41-46]. For model based sensorless control methods, harmonics can adversely affect the estimated rotor position.The proposed adaptive linear neural (ADALINE)-network- based filter can help to improve the predicted rotor position [47-56]. To satisfy the demand for low frequency ratio control of PMSMs, the synchronous-frame full-order observer provides a good solution [57-68].

A. Low-Speed Sensorless Control Method

(1) *Development of Low-Speed Sensorless Control Method*

The low-speed position-sensorless control should be based on the voltage injection methods since the back EMF that contains rotor position information cannot be detected accurately. Since interior-PMSMs (IPMSMs) have anisotropy, also known as salient-pole features, injecting additional voltage signals into the stator can induce the currents that contain the rotor position information. High-frequency (HF) voltage injection methods are most applied to estimate the rotor position. By injecting HF voltage into the motor windings, the anisotropy of the motor can be reflected in the HF response current, and then the rotor position can be observed by signal processing technologies [45].

According to the types of injection signal, it is roughly categorized into rotating voltage injection [46], [69], pulsating voltage injection [70], and square-wave voltage injection [71-73]. Rotating HF voltage injection method was first used to detect the initial position of IPMSMs and then to sensorless control where the motor operates at low speed. The emergence of this method presents a new idea for low-speed sensorless control. The subsequent pulsating HF voltage injection method and square-wave HF voltage injection vibration method were evolved from this method. The digital filers used in signal processing were gradually reduced when the pulsating and square-wave HF voltage injection were proposed. Besides, the injection frequency was also increased, which definitely enhances the accuracy of the voltage injection-based sensorless control methods.

However, the audible noise pollution of the traditional injection methods has dramatically restrained the wide application of such methods. The noise generated during the operation of the motor is closely related to the motor current: the noise spectrum and the current spectrum contain the same frequency component. Traditional HF injection methods use the fixed-frequency voltages, making the induced current contain the single-frequency component. If the injection frequency was set in the human hearing range, the harsh noise pollution cannot be avoided. Therefore, audible noise reduction has been studied recently.

Adjusting injection amplitude or injection frequency can reduce the audible noise, while the sacrifice of detection accuracy, low dynamic performance or higher cost are unacceptable [41-44]. Therefore, the random HF square-wave injection is an available scheme that can reduce the audible noise pollution whilst ensure the estimation accuracy. In [74], the full-period-switch pseudo-random HF (FPS-PRHF) voltage injection method was firstly proposed. Fig. 7 is a typical diagram of FPS-PRHF method. Then, the comparison analyses of power density spectrum (PSD) with other two kinds of injection voltages, fixed-frequency HF (FFHF) and half-period-switch pseudo-random HF (HPS-PRHF) voltages, were discussed in [75]. The signal processing of the rotor position estimation is similar to the traditional square-wave voltage injection method [71].

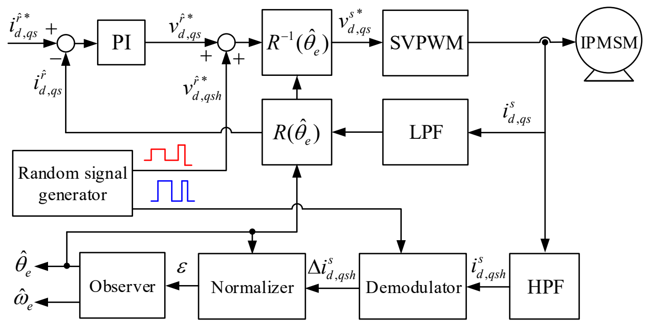

Fig.7. Block diagram of the FPS-PRHF square-wave voltage injection method.

(2) *Analyses of PSD for Different Injection Methods*

The selection of the injected voltages is quite important since it would affect the final performance of audible noise reduction. [42] compared the different performance in PSD of the induced HF currents of several injected voltages, including the FFHF voltage, and the HPS-PRHF voltage.

Fig. 8 shows the voltage, current and PSD waveforms of the FFHF voltage injection method, and the HPS-PRHF voltage injection method, respectively. The frequencies of the injected voltages are set as 7.5 kHz and 1.5kHz for the FFHF voltage injection method, and 750Hz and 1.5kHz for HPS-PRHF voltage injection methods.

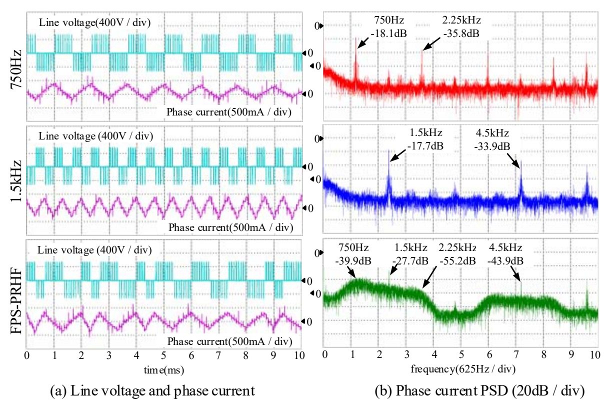

Fig. 8. Line voltage, phase current and PSD results.

It can be concluded that in the results of the FFHF voltage injection method shown in Fig. 8, the PSD of the excitation current only contains discrete spectrum appearing at the injection frequency and its odd harmonics. While the PSD of the HPS-PRHF voltage injection method only contains the continuous spectrum, and the total level of the PSD is lower.

In conclusion, the HPS-PRHF is the better choice of the injected voltages. The energy of the current distributes to the around spectrum that can make the audible noise reduced a lot. This novel voltage injection method with random square-wave voltages can mitigate the audible noise pollution effectively, which improves the practicability of the low-speed sensorless control for PMSMs.

B. Model based methods

(1) *Development of Mode Based Methods and Harmonics Reduction Methods*

The PMSM sensorless control block diagram based on the model-based methods is shown in Fig. 9. In normal conditions, as shown in Fig. 10, the estimated processes of the rotor position and speed which are based on the model-based methods can be divided into three parts: the observation of the back EMF or the flux-linkage information, the demodulation of the position error signal, and the tracker of the rotor position and speed [48]. According to the observed methods of the back EMF or the flux-linkage information, the model-based methods can be generally categorized as: model reference adaptive system observer, extended Kalman filter, flux-linkage observer, sliding-mode observer (SMO), state observer, and artificial intelligence-based estimation method, etc. [49]. The SMO can realize the convergence of position error signal with variable structure control, and has strong robustness to parameter variation. The state observer can realize the adaptability for various complex working conditions by designing feedback gain matrix structure reasonably. The position error signal has a uniform form in the steady state, and the d-axis voltage disturbance and the q-axis inductance uncertainty are the main cause of the position error in four different kinds of model-based methods [48]. After obtaining the back EMF or the flux-linkage information, the position error signal can be decoupled with simple algebra and trigonometric functions, and the PI tracker and the Luenberger observer are used to track the rotor position and speed [48].

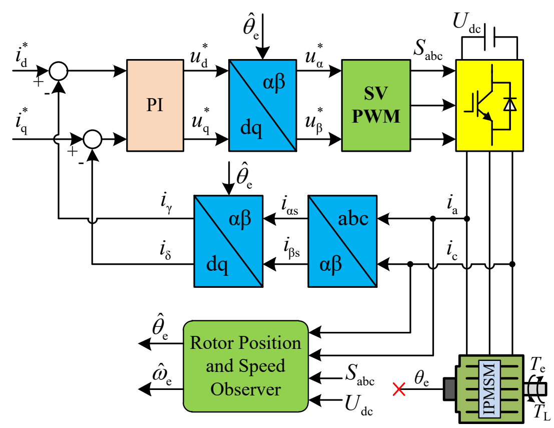

Fig. 9. Block diagram of general model-based sensorless drive system.

The rotor position information has coupling terms in the back EMF and inductance matrix for IPMSMs because of the saliency. Therefore, scholars have proposed numerous improvement strategies to enhance the robustness of the observer [76]. Boldea I et al. proposed a sensorless control scheme based on active flux model. The scheme can simplify the observer design of model-based methods for IPMSMs [77]. Chen Z et al. proposed a sensorless control scheme which is based on extended back EMF [78].

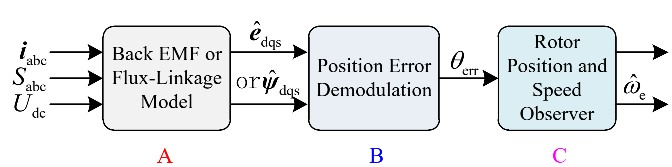

Fig. 10. Position and speed estimation procedure.

In general, the rotor position error includes a DC offset and a harmonic ripple in model-based methods. The DC offset is caused by parameter uncertainties, and the harmonic ripple is resulted from inverter nonlinearities and flux spatial harmonics [50]. In IPMSMs sensorless control systems, $(1 \pm 6k)$th harmonics appear in the back EMF estimation in the stationary frame because of the influence of inverter nonlinearities and flux spatial harmonics, resulting in $(6k)$th harmonic ripples in the estimated rotor position and speed further. The position error ripples can result in inaccurate orientation of the magnetic field, the torque and speed ripples, the increased loss, and the declined stability. In recent years, the methods of inverter nonlinearities compensation and position error ripples suppression have been proposed to improve the performance of the sensorless drive system. In [51], according to the result of current harmonics detection, an online compensation method for inverter nonlinearities with independent parameters was proposed. However, the method can only be applied to the stable operation conditions of motor. In [52], the fitted curve of the error voltage and current amplitude was obtained according to experimental results. However, the method is based on the accurate inverter nonlinearities model, resulting in poor universality. The position error ripples resulting from the flux spatial harmonics can be compensated by optimizing the PMSMs structure or improving control algorithm [53]. In control algorithm compensation strategies, the low pass filters (LPFs) are used to weaken the harmonic ripples in traditional methods. However, it is difficult to eliminate the influence of the flux spatial harmonics through the LPFs because the harmonic frequency is close to the fundamental. In [54], the IPMSMs flux spatial harmonics was modeled offline and the influence of the flux spatial harmonics was reduced with feedforward compensation. However, it is difficult to ensure the adaptability for high dynamic operation and the robustness for parameters variation of the flux spatial harmonics model.

(2) *Principle of Adaptive Linear Neural-network-based Filter Method*

An adaptive linear neural (ADALINE)-network-based filter was proposed for an EMF-model-based sliding mode observer (SMO)with an phase-locked loop (PLL) tracking estimator to reduce the harmonic ripples of the position estimation error [55]. As shown in Fig. 11, the ADALINE filter is a multi-input and single-output linear neuron structure based on adaptive cancellation principle. The ADALINE filter can achieve an optimal filtering effect through continuously self-tuning the filter weights [56]. The weight adaptive updating algorithms are the key link for ensuring the ADALINE filter convergence and dynamic performance. Least mean square (LMS) and recursive least-square (RLS) algorithms are the frequently-used weight adaptive updating algorithms for the ADALINE filter [79]. The LMS algorithm is simple and effective, and the resource occupancy rate is lower. Nevertheless, the LMS algorithm converges slowly. Compared with the LMS algorithm, the dynamic response of the RLS algorithm is much faster [80]. The ADALINE filter based on the LMS and the RLS algorithms can eliminate the specific harmonic components of the back EMF. Further, the harmonic ripples can be suppressed in model-based methods.

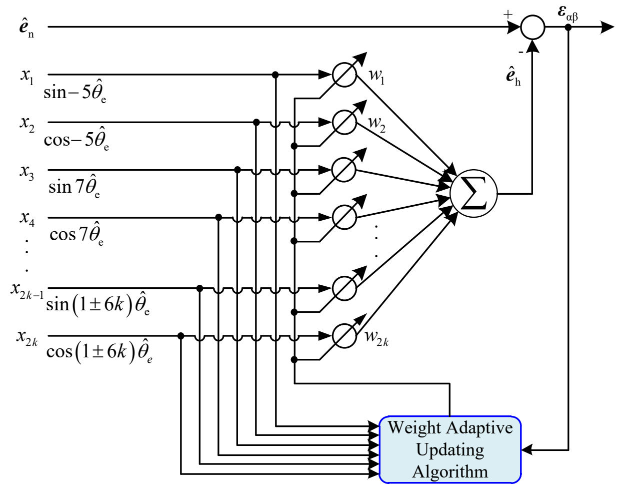

Fig. 11. Block diagram of the ADALINE-based filter.

Fig.12 (a) is the waveforms of the estimated rotor position, the position estimation error, and the back-EMF harmonic estimate without an ADALINE filter at 500 rpm and 50% rated load. Correspondingly, Fig. 12 (b) is the waveforms with an ADALINE filter at the same conditions. As can be seen from the experimental waveforms, the position estimation error is reduced from 9 degrees to 2 degrees, and the 6th position error ripples are eliminated effectively after using an ADALINE filter. Therefore, The ADALINE filter can eliminate the specific harmonic components of the back EMF and suppress the position error ripples.

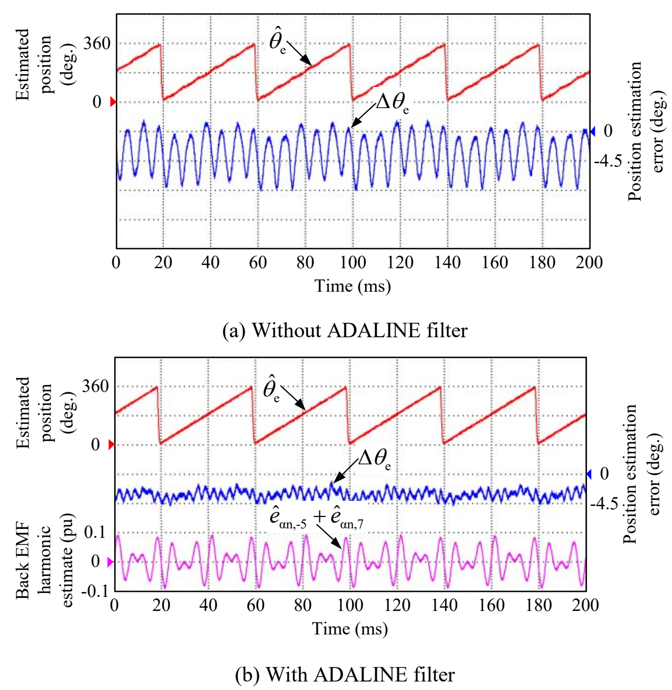

Fig. 12 Comparison of position estimation error and harmonic with and without ADALINE filter.

C. Synchronous-frame full order observer for sensorless IPMSM drive at low frequency ratio

With the development of sensorless control in middle- and high-power applications as well as high-frequency PMSMs drive, there is an increasing demand for the low frequency ratio f_{ratio}, which refers to the ratio of the pulsewidth modulation (PWM) frequency (f_{PWM}) to the fundamental frequency (f_{out}), i.e., $f_{ratio}= f_{PWM}/f_{out}$[57-68]. In middle- and high-power applications, the increase of the PWM frequency is limited by the switching loss, thus the frequency ratio is in limitation. As for high-frequency PMSM drives, which includes super high-speed motors and high-pole-pairs motors. The fundamental frequency can be even as high as 1 kHz, but the PWM frequency cannot increase infinitely in view of the switching loss. As a result, there is certain restriction on the frequency ratio. However, the low frequency ratio results in greater delay of the digital control system, which adversely affects the dynamic performance of the current loop and the position observation accuracy of the tracking observer. In view of this, it is necessary to research the discrete-time strategy at low frequency ratio f_{ratio}.

In order to improve the dynamic performance of the current loop at low frequency ratio f_{ratio}, a series of investigations have been carried out. A complex-vector PI controller with current prediction on active damping was developed to implement stabilization operation, and an error estimator was used to compensate for sampling error [61]. In [62], the complex vector AC machine model that contains the digital control delay in discrete-time domain was founded, based on which, it was verified that the direct-design complex-vector current regulator exhibited the better performance. In [63], an exact zero-order hold (ZOH)-equivalent model of PMSM was established. Further, the discrete-time two-degrees-of-freedom (2DOF) PI current regulator was proposed, and pole-placement method was employed for simplified parameter tuning. The dynamic performance and the robustness to the parameter variations were enhanced markedly.

The research on discrete-time flux and speed observation based sensorless control of IM at low frequency ratio was relatively earlier, and many achievements have been made. In [64], the optimal strategy of fuzzy-like Luenberger observer was proposed by utilizing genetic algorithms (GA), which realized the minimum convergence time of the estimated error. Besides, an optimized discrete-time model of IM based pole trajectory analysis was proposed and employed in the design of rotor flux observer to achieve a wide range of stability and less computational burden [65].

By comparison, the investigations on the low frequency ratio based sensorless PMSM drives relatively lagged behind. The discrete-time stator current and flux linkage observer were developed by taking the cross-coupled terms into consideration [66]. The dynamic estimation performance and the robustness to the parameter variations were improved significantly at both high and low sampling frequencies.

In [68], a speed-adaptive full-order observer is designed and analyzed in the discrete-time domain. The observer design is based on the exact discrete-time motor model, which inherently takes the effects of the ZOH and time delays inherently into account. The ratio below 10 between the sampling and fundamental frequencies is achieved in experiments with the proposed discrete-time design. On this basis, a complex-vector ZOH-equivalent mathematical model of interior PMSM (IPMSM) was established in discrete-time domain, and the current regulators were designed by direct discretization [67]. Furthermore, a synchronous-frame full-order observer as shown in Fig. 13 was presented based sensorless IPMSM drives to improve the stability and the dynamic performance. Fig. 14 shows the experimental results with a smaller f_{ratio} (4800 r/min, f_{ratio} = 2.5) at no load condition. The rotor position estimation error is limited within 0.02π such that a stable low-frequency-ratio sensorless control can be maintained.

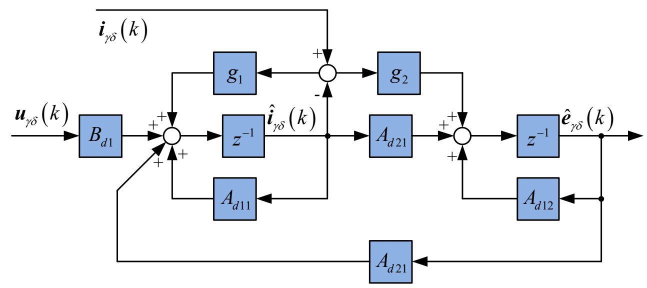

Fig. 13. Block diagram of synchronous-frame full-order observer in discrete-time domain.

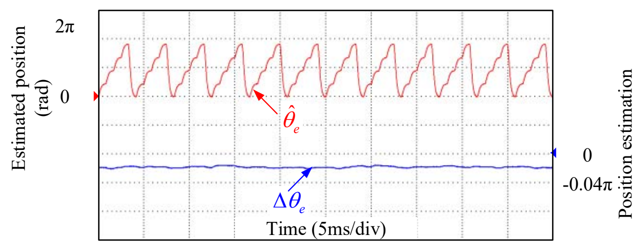

Fig.14. Experimental evaluation with a smaller frequency ratio (fratio = 2.5).

IV. Conclusion

This paper introduced the state-of-art of recent progress in position/speed sensorless control and presented the position/speed sensorless control strategies for AC motor.

For sensorless IM drives at low- and zero-speed operation, inverter nonlinearity and motor parameter deviation due to loads have the most significant impact on the stability of control system. This paper gives several approaches to solve these problems for robust low-speed sensorless IM control. In addition, to achieve maximum torque capacity in high-speed region, a robust field-weakening control strategy which can regulate the field current and the clamp of torque current is presented.

Sensorless PMSM drives have been studied since 1990s. Basically, there are two main types of sensorless PMSM control according to the operation frequency: one is model based method which detects the fundamental component of back EMF. The other injects additional excitation signal to utilize the asymmetrical effect of inductance in PMSM. The former works well in high-speed range but fails at low speed when the signal-to-noise ratio (SNR) of EMF is too small for observation. The latter, on the contrary, can derive position at low and even zero speed, but performs poor at high speed due to the limitation of observer bandwidth. To achieve whole-speed-range sensorless operation, hybrid position estimation strategy combining both methods at middle speed is adopted. The paper aims to introduce the technical knowledge from both academia and industry perspectives.

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