Review of Position Estimation Methods for Permanent Magnet Synchronous Motors

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Abstract: *This paper presents a review regarding the techniques used for estimation of position and speed of sensorless permanent magnet synchronous motor drives .Permanent-magnet synchronous machines (PMSMs) are widely used in industrial applications due to their distinctive advantages, such as high efficiency, high power density, and wide constant power region. Most of the times, accurate rotor position information is measured by rotary encoders or resolvers to achieve high-performance field oriented control. However, the use of these sensors increases the cost, size, weight, and wiring complexity and reduces the mechanical robustness and the reliability of the overall PMSM drive systems. Hence sensorless methods have gained much attention. In this Paper Sensorless Control Methods including Indirect Methods based on magnitude of back EMF, some model based methods like Flux linkage based estimation, Non-linear observers and extended kalman filter and high frequency signal injection based methods are described.*
Keywords: *back EMF, estimators, high frequency signal injection, PMSM, Sensorless.*

I. Introduction

Permanent Magnet Synchronous Motors provide an excellent power density (compactness), a high energy efficiency and a high torque to inertia ratio. In the last years the price of rare-earth magnet material decreased significantly. The main drawback of a PM-Machine is the position sensor, which is vulnerable for electromagnetic noise in hostile environments and has a limited temperature range. Thus the elimination of the electromechanical sensors reduces the hardware costs, reduces the installation complexity of the system (because of associated cabling), decreases the system inertia, increases the robustness and the reliability and reduces obviously the noise sensitivity of the electrical drive. PM-Machines can be divided in two categories which are based on the assembly of the permanent magnets (PM's). The PM's can be mounted on the surface of the rotor (surface permanent magnet synchronous motor - SPMSM) or inside of the rotor (interior permanent magnet synchronous motor - IPMSM). These two configurations have an influence on the shape of the back electromotive force (back-EMF) and on the inductance variation. Subsequent only the IPMSM machine with a sinusoidal excitation is examined. The rotor position/speed estimation methods can be classified into three major categories:

1. Indirect position sensing methods in which the rotor position information is obtained indirectly from the sensed position-related quantities, e.g., back EMF components or third harmonic back EMF.
2. Model-based methods in which the fundamental-frequency model of PMSM, measured stator currents, and measured or commanded stator voltages are utilized to estimate the rotor position information.
3. Saliency-based methods in which the rotor position information is extracted from the position-dependent machine saliency and an HF excitation is usually required.

II. Indirect Position Estimation Methods

The basic idea of this category of methods is to obtain the rotor position information indirectly from the instantaneous magnitude of the back EMF, which is a function of rotor position. These methods were firstly applied to the brushless DC (BLDC) motors, which have trapezoidal back EMF waveforms, where the rotor position was obtained from the detected zero-crossing points on the back EMF [2], [3]. However, back EMF sensing does not work in low-speed operating conditions. To solve this problem, an open-loop starting procedure is needed. Moreover, the base speed is the maximum achievable speed using this method. Author in [4] proposed an indirect position sensing method based on the third harmonic component of the back EMF, which has a constant phase relationship with the rotor flux regardless of the machine operating mode. The third harmonic component is extracted from the stator phase voltages while the fundamental and other higher order harmonic components are eliminated via a simple summation of the three phase voltages. Compared to the aforementioned back EMF sensing methods, this method needs less filtering and has an improved capability to operate in a lower-speed region. an improved position estimation method was presented in [7] for a PMSM, which combined a third harmonic back EMF sensing method and a position observer. In this method, the integral of the third harmonic back EMF, which is the third harmonic flux linkage, was utilized as a reference.

The error between the estimated and reference third harmonic flux linkages was used to compensate the speed estimation error. The rotor position was then calculated based on the compensated rotor speed. This method has been reported to achieve better position estimation accuracy than the previous work.

III. Model Based Methods

The Methods based on the fundamental-frequency PMSM models are most widely used for rotor position and speed estimation. These model-based methods are especially effective for medium- and high-speed applications. They can be generally grouped into two different categories: open-loop calculation and closed-loop observers. The open loop position/speed estimation methods are straightforward and easy to implement. These methods behave like real-time dynamic models of the PMSMs. They receive the same control inputs and run in parallel. Based on the dynamic model of a PMSM, the states of interest, e.g., back EMF, rotor flux, or stator inductance, can be calculated, from which the rotor position and speed information can be extracted.

In a closed-loop observer, both the control inputs of the plant and the output tracking error, i.e., the error between the outputs of the plant and the observer, are often used as the inputs to the observer. The observer gains are designed to force the observer output to converge with the plant output. Thus, the estimated values of the states of interest are forced to converge to their actual values. From this aspect, the closed-loop observer can be viewed as an adaptive filter, which has a good disturbance rejection property and good robustness to the variations of machine parameters and the noises in current/voltage measurements. In this review paper, many observers have been proposed for rotor position/speed estimation, such as disturbance observers, sliding-mode observers (SMO), extended Kalman filters (EKF), etc.

3.1 Back EMF-Based Methods

Based on the machine model, the PMSM stator phase currents measured, and measured or commanded stator voltages,the EMF components can be calculated. For example, in [8], the EMF components were calculated as:

$$L\frac{di_\alpha}{dt} = -i_\alpha R - e_\alpha + v_\alpha \tag{1}$$

$$L\frac{di_\beta}{dt} = -i_\beta R - e_\beta + v_\beta \tag{2}$$

$$e_\alpha = -\lambda_0\,\omega\,\sin\theta \tag{3}$$

$$e_\beta = \lambda_0\,\omega\,\sin\theta \tag{4}$$

Then the rotor position can be calculated as $\theta = \tan^{-1}(e_\alpha/e_\beta)$. This method presented in [8] can be applicable to both salient-pole and nonsalient-pole PMSMs. This method is simple, fast, and straightforward without using complex observers. However, the performance of this method is subjected to the accuracy of the sensed current/voltage and machine parameters.

3.2 Flux Linkage-Based Methods [40], [41]

At steady state, where $di_\alpha/dt \approx 0$ and $di_\beta/dt \approx 0$, the stator and rotor flux vectors rotate synchronously. Therefore, if the position angle of the stator flux can be calculated, the rotor flux angle can also be determined, which is the same as the rotor position angle. The voltage and current components in the stator stationary reference frame can be used to compute the stator and rotor flux linkage as follows:

$$\tag{5}$$

$$\tag{6}$$

$$\tag{7}$$

$$\tag{8}$$

where $\Phi s\alpha$ and $\Phi s\beta$ are the stator flux linkages, and $\Phi r\alpha$ and $\Phi r\beta$ are the rotor flux linkages. Then the rotor position can be calculated as $\theta = \tan^{-1}(\Phi r\beta / \Phi r\alpha)$. The accuracy of the flux based methods highly depends on the quality and accuracy of the voltage and current measurements. Since integrators are needed in this method, the initial condition of the integration and current sensor DC offset are problems that should be properly handled. In addition, this method may work well in the steady state, but the transient performance is usually unsatisfactory

3.3 Inductance-Based Methods [42]

The basic idea for this type of methods is that the spatial distribution of the phase inductance of a PMSM, especially for the PMSM with a significant difference between Ld and Lq, is a function of the rotor position. The phase inductance can be calculated from the measured voltage and current information. Then the rotor position can be found based on the calculated phase inductance. In a PMSM control system, if the switching frequency is high enough, the values of the phase inductance and back EMF can be viewed as constant during a switching period. Under this assumption, the dynamic voltage equation for phase α of a PMSM can be expressed as:

$$v\alpha = -i\alpha R - e\alpha + Ls\alpha \frac{di\alpha}{dt} \qquad (9)$$

where all of the variables are phase a quantities, va is the terminal phase voltage, ia is the phase current, Lsa is the synchronous inductance, R is the phase resistance, and ea is the back EMF. The rotor position can be obtained from a lookup table, which was created offline to store the relationship between the rotor position and phase inductance. The accuracy of the inductance-based methods also highly depends on the quality and accuracy of the voltage and current measurements. Since the current and position derivatives need to be calculated in every switching cycle, the rotor position is subjected to a high level of measurement noise. In addition, this type of method requires that the PMSM has a high saliency ratio, e.g., $Lq/Ld > 2.5$; and the performance will be poor for non salient-pole PMSMs.

3.4 Nonlinear State Observers

An SMO is an observer whose inputs are discontinuous functions of the errors between the estimated and measured outputs. When the trajectories of the desired states reach the well-designed manifold, the sliding mode will be enforced. The dynamics of the desired states under the sliding mode depend only on the surfaces chosen in the state space and are not affected by system structure or parameter accuracy. Advantages such as high robustness to system structure and parameter variations make the SMO a promising solution for the rotor position estimation of PMSMs. In the literature, the SMOs were usually designed based on the PMSM models in the stationary reference frame and were rarely designed based on the PMSM models in the rotor reference frame. For an SPMSM a typical SMO [12] was compared with conventional signum function.

$$Ls \frac{d\hat{i}\alpha}{dt} = -\hat{i}\alpha Rs + v\alpha - sign\left(\hat{i}\alpha - i\alpha\right) \qquad (10)$$

$$Ls \frac{d\hat{i}\beta}{dt} = -\hat{i}\beta Rs + v\beta - sign\left(\hat{i}\beta - i\beta\right) \qquad (11)$$

In this case, the sliding surface is designed as $S = [\hat{i}\alpha - i\alpha \quad \hat{i}\beta - i\beta] = 0$. Many variations of Equation (10) and (11) can be found in the literature, e.g., using the saturation function [13] or the sigmoid function [14] to replace the sign function to mitigate the chattering problem. The design of the sliding surface can also be different. In addition, several online machine parameter adaption schemes [15] have also been proposed to improve the observer robustness to machine parameter variations.

3.5 Extended Kalman Filter-Based Methods

As an extension of the Kalman filter, which is a stochastic state observer in the least-square sense, the EKF is a viable candidate for the online estimation of the rotor position and speed of a PMSM. In the EKF algorithm, the system state variables can be selected in either the rotor reference frame [16] or the stationary reference frame [17]. A standard EKF algorithm contains three steps: prediction, innovation, and Kalman gain update. Due to the stochastic properties of the EKF, it has great advantages in the areas of robustness to measurement noise and the inaccuracy of machine parameters. However, tuning the covariance matrices of the model and measurement noise is difficult [16]. In addition, the EKF-based algorithms are computationally intensive and time consuming. This drawback makes the EKF hard to implement in industrial drives.

IV. Saliency Based Methods

The fundamental frequency model-based rotor position/speed estimation techniques for PMSMs are reviewed. These methods are capable of providing highly accurate position/speed estimations for the vector control of PMSMs in medium and high-speed regions. However, these methods will have poor performance or even fail in the low-speed region and at standstill due to low signal-to-noise ratios (SNRs) of the position-related system states. To overcome this limitation and improve the low-speed operation capability, rotor position/speed estimation methods using machine saliency tracking [18], [19] have been extensively studied. In these methods, an HF excitation, whose frequency is much higher than the fundamental frequency, is usually utilized. Using the measured response of the PMSM under the HF excitation, the position-related saliency signal can be obtained.

4.1 High-Frequency Models of PMSMs

The HF model of a PMSM, i.e., the dynamics of a PMSM under an HF excitation, can be derived based on the fundamental frequency model of the PMSM expressed in a *dq* rotor reference frame. Considering that the HF voltage signals, *vdh* and *vqh*, whose frequency is sufficiently higher than the electrical rotating frequency of the PMSM, are injected into the PMSM stator windings, HF currents, *idh* and *iqh*, will be generated. To reduce extra losses, vibration, and acoustic noise caused by the HF excitation during normal operation of the drive system, the amplitudes of the injected voltage signals are usually much smaller than those of the fundamental stator voltages, such as the induced currents. However, due to the high frequency, the derivatives of the induced currents can be quite large. Therefore, when considering the HF components while the PMSM is operating in the low-speed region or is at standstill, the off-diagonal cross-coupling terms are much smaller than the diagonal terms and, therefore, can be ignored. Similarly, in the low-speed region or at standstill, the back EMF term can also be neglected.

4.2 Methods of High-Frequency Excitation

The methods of HF excitation can be generally classified into two major categories: continuous and discontinuous. Due to the highly accurate position estimation and the capability of continuous position estimation, the continuous excitation is the dominant method for the HF excitation. However, discontinuous excitation methods, e.g., "Indirect Flux Detection by On-line Reactance Measurement (INFORM)" [22], were investigated during the past two decades. This method can be implemented in a low-cost DSP, which leads to an economic drive solution. The basic idea of the INFORM method is to measure the current response to the voltage space phasors applied in different directions. This method can be implemented by using a PWM pattern modification and needs additional *di/dt* sensors. The position estimation accuracy of the INFORM method is in the range of 3–15 electric degrees, which is not acceptable for high-performance drives. The accuracy could be improved by using the optimized INFORM method [20].

For continuous HF excitation, the carrier signal injection-based methods are the most widely used. Both HF voltage and current signals can be injected. However, due to the utilization of VSIs and the limited control bandwidth of current regulators, the HF current injection-based methods [21] are rarely used. In the HF voltage signal injectionbased methods, a sinusoidal or square-wave voltage vector can be injected into either the estimated rotor reference frame or the stationary reference frame.

V. Conclusion

A review of prior work in the field of control of PMSM drive, especially techniques using the stator voltages or currents and flux- or back-EMF based position estimators has been presented in this paper. It can be noted that no method for controlling is perfect. Some of the methods are suitable for low speed region while others are not. For achieving the performance control, observers based on sliding mode have simple structure, good robustness. The chattering in that case can be reduced by using smooth sliding surface. Techniques that use digital signal processors are provides easy control and a good effectiveness.

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