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Review of Sliding Mode Observers for Sensorless Control of Permanent Magnet Synchronous Motor Drives

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ABSTRACT

Permanent magnet synchronous motors (PMSMs) are increasingly used in high performance variable speed drives of many industrial applications. PMSM has many features, like high efficiency, compactness, high torque to inertia ratio, rapid dynamic response, simple modeling and control, and maintenance free operation. Presence of position sensors presents several disadvantages, such as reduced reliability, susceptibility to noise, additional cost and weight and increased complexity of the drive system. For these reasons, the development of alternative indirect methods for speed and position control becomes an important research topic. Advantages of sensorless control are reduced hardware complexity, low cost, reduced size, cable elimination, increased noise immunity, increased reliability and decreased maintenance. The key problem in sensorless vector control of ac drives is the accurate dynamic estimation of the stator flux vector over a wide speed range using only terminal variables (currents and voltages). The difficulty comprises state estimation at very low speeds where the fundamental excitation is low and the observer performance tends to be poor. Moreover, the noises of system and measurements are considered other main problems. This paper presents a comprehensive study of the different sliding mode observer methods of speed and position estimations for sensorless control of PMSM drives

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1. INTRODUCTION

Permanent magnet synchronous motor (PMSM) drives are replacing classic dc and induction motors drives in a variety of industrial applications, such as industrial robots and machine tools [1-3]. Advantages of PMSMs include high efficiency, compactness, high torque to inertia ratio, rapid dynamic response, and simple modeling and control [4]. Because of these advantages, PMSMSs are indeed excellent for use in high-performance servo drives where a fast and accurate torque response is required [5, 6]. Permanent magnet machines can be divided in two categories which are based on the assembly of the permanent magnets. The permanent magnets 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. In general, there are two main techniques for the instantaneous torque control of high-performance variable speed drives: field oriented control (FOC) and direct torque control (DTC) [7, 8]. They have been invented respectively in the 70’s and in the 80’s. These control strategies are different on the operation principle but their objectives are the same. They aim both to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. The main advantages of DTC are: the absence of coordinate transformations, the absence of a separate voltage modulation block and of a voltage decoupling circuit and a reduced number of controllers. However, on the other hand, this solution requires knowledge of the stator flux, electromagnetic torque, angular speed and position of the rotor [9]. Both control strategies have been successfully implemented in industrial products. The main drawback of a PMSM is the position sensor. The use of such direct speed/position sensors implies additional electronics, extra wiring, extra space, frequent maintenance and careful mounting which detracts from the inherent robustness and reliability of the drive. For these reasons, the development of alternative indirect methods becomes an important research topic [10, 11]. PMSM drive research has been concentrated on the elimination of the mechanical sensors at the motor shaft (encoder, resolver, Hall-effect sensor, etc.) without deteriorating the dynamic performances of the drive. Many advantages of sensorless ac drives such as reduced hardware complexity, low cost, reduced size, cable elimination, increased noise immunity, increased reliability and decreased maintenance. Speed sensorless motor drives are also preferred in hostile environments, and high speed applications [12, 13].

2. PMSM MODEL

The PMSM model can be derived by taken the following assumptions into consideration,

- The induced EMF is sinusoidal
- Eddy currents and hysteresis losses are negligible
- There is no cage on the rotor

The voltage and flux equations for a PMSM in the rotor reference *(d-q)* frame can be expressed as [8]:

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega\psi_{qs} \tag{1}$$

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega\psi_{ds} \tag{2}$$

$$\psi_{ds} = L_d i_{ds} + \psi_r \tag{3}$$

$$\psi_{qs} = L_q i_{qs} \tag{4}$$

The torque equation can be described as:

$$T_e = \frac{3}{2}P\left[\psi_r i_{qs} - (L_q - L_d) i_{ds} i_{qs}\right] \tag{5}$$

The equation for the motor dynamic can be expressed as:

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_L - F\omega_r) \tag{6}$$

where the angular frequency is related to the rotor speed as follows:

$$\frac{d\theta}{dt} = \omega = P\omega_r \tag{7}$$

where P is the number of pole pairs, Rs , is the stator winding resistance, ωf is the angular frequency, vds, vqs and ids, iqs are d-q components of the stator winding current and voltage, ψdsand ψqsare d-q components of the stator flux linkage, Ld and Lq are d and q axis inductances, and ψris the rotor flux linkage. F is the friction coefficient relating to the rotor speed; J is the moment of inertia of the rotor; ωr is the electrical angular position of the rotor; and Te and TL are the electrical and load torques of the PMSM.

3. SPEED ESTIMATION SCHEMES OF SENSORLESS PMSM DRIVES

Several speed and position estimation algorithms of PMSM drives have been proposed [14]. These methods can be classified into three main categories. The first category is based on fundamental excitations methods which are divided into two main groups; non-adaptive or adaptive methods. The second category is based on saliency and signal injection methods. The third done is based on artificial intelligence methods. These methods of speed and position estimation can be demonstrated in Figure 1.

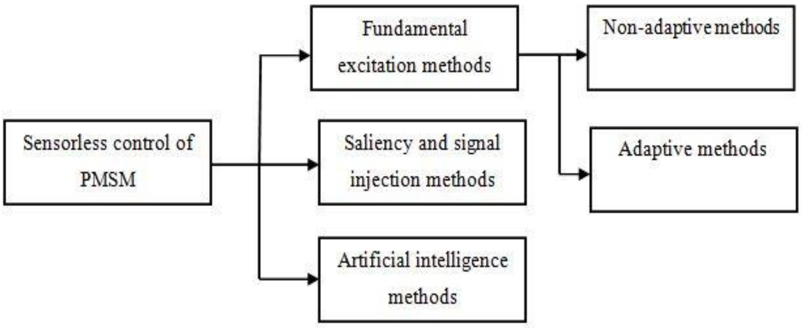

Figure 1. Speed estimation schemes of sensorless PMSM drives

3.1 Adaptive Methods

In this category, various types of observers are used to estimate rotor position. The fundamental idea is that a mathematical model of the machine is utilized and it takes measured inputs of the actual system and produces estimated outputs. The error between the estimated outputs and measured quantities is then fed back into the system model to correct the estimated values adaptation mechanism. The biggest advantage of using observers is that all of the states in the system model can be estimated including states that are hard to obtain by measurements. Also, in the observer based methods, the error accumulation problems in the flux calculation methods do not exist [15], but the limitation is poor speed adjustability at low speed, complicated algorithm and huge calculation [2]. Observers have been implemented in sensorless PM motor drive systems. The adaption mechanism based on the following three methods are super stability theory (Popov), kalman filter, and method of least error square [16]. Methods using the Popov are model reference adaptive system and luenberger observer.

3.1.1 Observer-Based Estimators

Observer methods use real model of the motor instead of the reference model . The observer is the adaptive model with a constantly updated gain matrix K which is selected by choosing the eigen values in a way, such that the system will be stable and transient response of the system will be dynamically faster than the PM machine [16]. Luenberger observer, reduced order observer and sliding mode observer fall under this category. Comparatively, sliding mode observer is widely used with the advantages that the parameter sensitivity of the mathematical model is less, control algorithm being simple, and robust when the motor parameters have slight variations with some external disturbances.

4. SLIDING MODE OBSERVER (SMO)

The sliding mode control is the essence of high-frequency switching feedback control. The switching value of its control law switches over according to the system state. Design of sliding mode observer is composed of two parts, namely sliding surface and control law. So that the dynamic system have been bound at the sliding mode surface. This kind of state also is known as sliding mode state, which is only relative with the choice of sliding surface. The dynamic system of the sliding state is without outside influence. In other words, when the system goes into the sliding state, the sliding mode variable also is able to converge to zero. The error between control objective, reference input and its derivative is used to form the sliding surface. If the sliding surface is the linear combination of the error and its corresponding differentiation, it becomes a linear sliding surface. In a similar way, if the sliding surface is the nonlinear combination of the error and its corresponding differentiation, it becomes a nonlinear sliding surface.

4.1 Conventional Sliding Mode Observer

The sliding-mode control is used to restrict the state variables on the sliding surface by changing the system structure dynamically. It is widely used for nonlinear system control since it is robust against system parameter variations. For the sensorless control of the PMSM, the sliding-mode controller is adopted for use in the observer design and so is named the SMO. Figure. 2 shows the conventional sliding-mode observer[17], [18], [19] where the signum function is used as the switching function and the low-pass filter (LPF) is used to eliminate the chattering effects from the switching. The conventional SMO uses the Lyapunov function; it is the control method used to estimate the position and speed of the rotor at the same time.

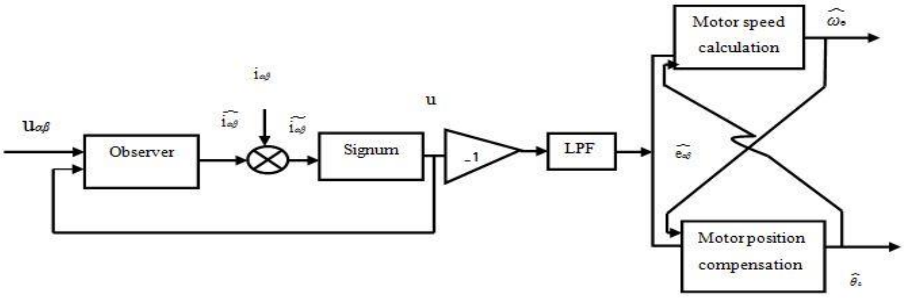

Figure 2. Conventional sliding mode observer

The dynamic equations of a PMSM without saliency in the stationary reference frame (α-β) can be expressed as follows

$$L_s\left(\frac{di_\alpha}{dt}\right) = -R_s i_\alpha - e_\alpha + u_\alpha \tag{8}$$

$$L_s\left(\frac{di_\beta}{dt}\right) = -R_s i_\beta - e_\beta + u_\beta \tag{9}$$

$$e_\alpha = -\psi_f \omega_r \sin\theta \tag{10}$$

$$e_\beta = \psi_f \omega_r \cos\theta \tag{11}$$

where iα, iβ, uα, uβ, and eα, eβ are the phase currents, phase voltages, and back EMF in the stationary reference frame, respectively, Rs is the stator phase resistance, Ls is the stator phase inductance, ψf is the flux linkage of the permanent magnet, ωr is the electrical angular velocity, and θ is the electrical rotor position.

The sliding surface is, $s(x) = \hat{i}_s - i_s$ (12)

where $i_s = [i_\alpha \quad i_\beta]$ is the estimated value of current and $i_s = [i_\alpha \quad i_\beta]$ is its measured value. With reference to the mathematical model of PMSM in the stationary reference frame, the equations governing sliding mode observer is expressed as follows,

$$L_s\left(\frac{d\hat{i}_\alpha}{dt}\right) = -R_s i_\alpha + u_\alpha - K\operatorname{sgn}(\hat{i}_\alpha - i_\alpha) \tag{13}$$

$$L_s\left(\frac{d\hat{i}_\beta}{dt}\right) = -R_s i_\beta + u_\beta - K\operatorname{sgn}(\hat{i}_\beta - i_\beta) \tag{14}$$

With K being observer gain, $K > (|e_\alpha||e_\beta|)$ (15)

and back emf is estimated as

$$e_\alpha = K\,\mathrm{sgn}\,\bar{i}_\alpha \tag{16}$$

$$e_\beta = K\,\mathrm{sgn}\,\bar{i}_\beta \tag{17}$$

The switch function sgn is a discontinuous value, So Equation 16 and 17 cannot be used to estimate the rotor position and speed directly. It is necessary to use a low-pass filter to extract the continuous estimated value of back electromotive force instead. Nevertheless, the low-pass filter will cause errors of amplitude and phase, and the error compensation is needed. So the system becomes complex. The back electromotive forces with low-pass filter are estimated by

$$\dot{e}_\alpha = (-e_\alpha + \sqrt{1+(\omega_e\tau_0)^2}\,k\,\mathrm{sgn}(\bar{i}_\alpha)) / \tau_0 \tag{18}$$

$$\dot{e}_\beta = (-e_\beta + \sqrt{1+(\omega_e\tau_0)^2}\,k\,\mathrm{sgn}(\bar{i}_\beta)) / \tau_0 \tag{19}$$

where $\dot{e}_\alpha$ and $\dot{e}_\beta$ are the differential of estimated back electromotive force at the $\alpha\beta$ axis, ω_e is the estimated electric angular speed of rotor, τ_0 is the time constant of low-pass filter. Making phase compensation, the estimated value of electric angle can be obtained as follows:

$$\theta_e = \arctan(-e_\alpha / e_\beta) + \arctan(\omega_e / \omega_{cutoff}) \tag{20}$$

where ω_{cutoff} = (1/ τ_0) is the cut-off frequency of low-pass filter and speed is estimated as

$$\omega_e = \left(\frac{\sqrt{e_\alpha^2 + e_\beta^2}}{\psi}\right)\mathrm{sgn}(e_\alpha\cos\theta_e - e_\beta\sin\theta_e) \tag{21}$$

With estimated rotor position and speed, closed loop sensorless control of PMSM is realized. However, there are the shortcomings of chattering and time delay for the rotor position compensation in the conventional SMO.

4.2 Sliding Mode Observer With Sigmoid Function

In equation (13) & (14) signum function is replaced with sigmoid function [20] , by which the switching between system states will be smooth so that the effect of chattering will be very less and hence the requirement of a low pass filter at the output and its phase angle compensation requirement can be avoided. . Figure. 3 shows the Structure of SMO with sigmoid function. Speed and position of the rotor can be estimated with the help of this observer. The output of this sliding mode observer will be back emfs of the machine in the stationary reference frame. This can be employed to estimate the speed and position as follows,

$$\omega_e = \frac{(\sqrt{e_\alpha^2 + e_\beta^2})}{\psi} \tag{22}$$

and speed is integrated to obtain position

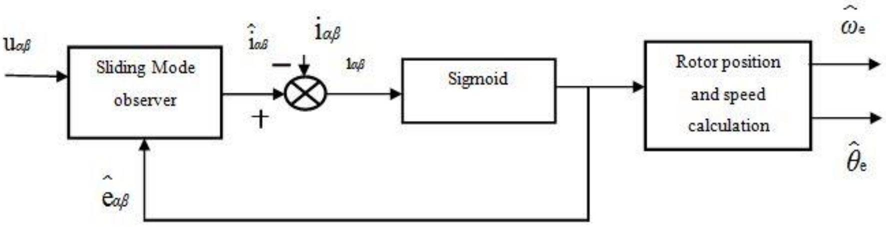

Figure 3. Structure of SMO with sigmoid function

4.3 Terminal sliding mode observer

From equation (13) and (14) it could be observed that the errors are designed as linear hyperplanes, even with signum function replaced by sigmoid function, result in asymptotic convergence of error during sliding mode. In order to ensure finite time convergence, nonlinear sliding mode called terminal sliding mode [21] has been proposed, which are designed using a power function of a system state which guarantee the system state reaching zero in finite time. Terminal sliding surface for the system shown in (8) and (9) is given as

$$s = \dot{\bar{i}}_s + \gamma \bar{i}_s^{\frac{q}{p}} \tag{23}$$

where $s = [s_\alpha, s_\beta]$ (24)

$$\bar{i}_s = [\bar{i}_\alpha, \bar{i}_\beta] \tag{25}$$

with $\gamma > 0$, and p, q are positive odd integers being p>q
the stator current error converge to zero in finite time and control law is given as

$$u = u_{eq} + u_n \tag{26}$$

$$u_{eq} = R_s \dot{\bar{i}}_s \tag{27}$$

$$u_n = -\int_0^{t1} [(L_s q / p)\gamma^{-1} \bar{i}_s^{\frac{q}{p}-1} + (k_1' + \eta_1)\mathrm{sgn}(s) + \mu_1 s] d\tau_1 \tag{28}$$

where K1’, η1,μ1 are design constants with η1>0 and μ1>0. Figure.4 shows the structure of terminal sliding mode observer. Equation (23) forms the terminal sliding surface which makes the stator current error converge to zero in finite time and equation (27) maintain the stator current error in sliding mode

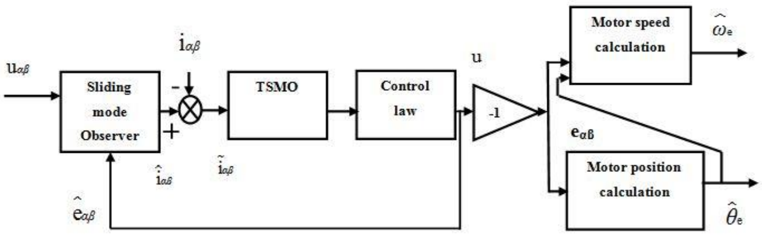

Figure.4. Structure of terminal sliding mode observer

4.4 Non-Singular Terminal Sliding Mode Observer

Terminal sliding surfaces suffer from singularity because, designed control law has non-linear terms which results in the unboundedness of the control input when the state variable diminishes to zero and has restrictions on the range of the exponent of a power function. The exponent should be a rational number with positive odd numerator and denominator . Here, the state variables refer to stator current error in stationary reference frame. To make the control input bounded when state variable diminish to zero, non-singular terminal sliding surface [22]-[23] for the system shown in (1) and (2) is given as

$$s = \bar{i}_s + \beta \dot{\bar{i}}_s^{\frac{p}{q}} \tag{29}$$

Where, $s = [s_\alpha, s_\beta]$ (30)

$$\bar{i}_s = \left[\bar{i}_\alpha, \bar{i}_\beta\right] \tag{31}$$

$$\dot{\bar{i}}_s^{\frac{p}{q}} = \left[\dot{\bar{i}}_\alpha^{\frac{p}{q}}, \dot{\bar{i}}_\beta^{\frac{p}{q}}\right] \tag{32}$$

$\bar{i}_s$, $\dot{\bar{i}}_s$ represent stator current error, first derivative of stator current error

with $\beta > 0$, and p, q are positive odd integers being 1<p/q<2

the stator current error converge to zero in finite time and control law is given as

$$u = u_{eq} + u_n \tag{33}$$

$$u_{eq} = R_s \bar{i}_s \tag{34}$$

$$u_n = -\int_0^{t2} [(L_s q / p)\beta^{-1} \dot{\bar{i}}_s^{2-\frac{p}{q}} + (k_2' + \eta_2)\mathrm{sgn}(s) + \mu_2 s] d\tau_2 \tag{35}$$

where K2’, η2,μ2 are design constants with η2>0 and μ2>0. Figure 5 shows the structure of terminal sliding mode observer. Equation (30) forms the terminal sliding surface which makes the stator current error converge to zero in finite time and equation (34) maintain the stator current error in sliding mode.

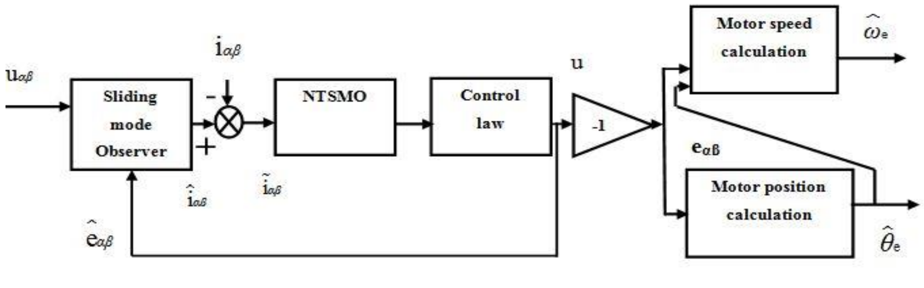

Figure. 5 Structure of non-singular terminal sliding mode observer

Figure .6 shows the block diagram of the sliding mode observer based sensorless speed control system. PMSM is modeled in three-phase stationary coordinates, and is transformed into the (d,q) two-phase synchronous coordinates system for vector control. In the control of speed and current references, the PI control is used to effectively reduce the accumulative errors. The current is supplied to the stator of the motor through the SVPWM control in the form of sinusoid. Using the estimated position and speed of the rotor, the closed loop sensorless control of the motor is implemented.

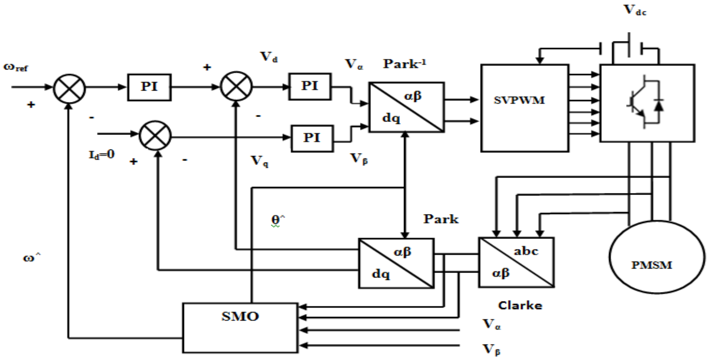

Figure. 6 Block diagram of the sliding mode observer based sensorless speed control system

Table 1 compares sliding mode types and the characteristics. Every type has it’s merit and the demerit led to development of other type of observer. Conventional observer’s error convergence time is infinite, whereas terminal sliding mode observer has finite time. Singularity exists in terminal sliding mode observer which is overcome in non-singular terminal sliding mode observer. Restriction on exponent of power function, in sliding surface design for terminal and non-singular terminal sliding mode observer remains however.

Table 1 Sliding mode types and the characteristics

S.No	Sliding mode type	Convergence time	Singularity	Restriction on exponent of power function
1	Conventional with signum and sigmoid function as switching function	Infinite	-	-
2	Terminal	Finite	Exist	Positive odd integer
3	Non-Singular	Finite	Does not exist	Positive odd integer

5. CONCLUSION

Permanent magnet synchronous motor (PMSM) drives are replacing classic dc and induction machine drives in a variety of industrial applications. PMSM drive research has been concentrated on the elimination of the mechanical sensors at the motor shaft without deteriorating the dynamic performances of the drive. Many advantages of sensorless ac drives such as reduced hardware complexity, low cost, reduced size, cable elimination, increased noise immunity, increased reliability and decreased maintenance. In this paper, a review of different speed and rotor position estimation schemes of PMSM drives based on sliding mode has been discussed. Each method has its advantages and disadvantages. Although numerous schemes have been proposed for speed and rotor position estimation, many factors remain important to evaluate their effectiveness. Among them are steady state error, dynamic behavior, noise sensitivity, low speed operation, parameter sensitivity, complexity, and computation time. In particular, zero-speed operation with robustness against parameter variations yet remains an area of research for speed sensorless control.

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