Sensorless Control of PMSM Using Sliding Mode Technique

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Abstract:
This paper proposes a sensorless control method for a surface-mounted Permanent-Magnet Synchronous Machine (PMSM) based on the stator parameters. The toque of the motor is indirectly controlled based on the stator voltage measurements and current measurements and also on knowledge of stator inductance and stator resistance. The rotor speed is also indirectly calculated and used for sensorless speed control. The use of sliding control (smc) technique method provides a straight forward solution for the control input. It is a dynamic control scheme which minimises error by comparing input and output values. It is a robust control scheme based on the concept of changing the structure of the controller in response to changing the state of the system in order to obtain desired output. Experimental results confirm good dynamical performance, even at low speeds.

Key words: PMSM, SMC

1. Introduction

For the Field oriented control of Permanent-Magnet Synchronous Machine (PMSM), the mechanical rotor position and also the information of the current components is required. The current measurement is done directly in the inverter, but the position information has to be detected at the machine, inheriting a strong disadvantage if suppose a high distance to the power electronics is required. The position measurement, in contrast to the current measurement, is very expensive and fault sensitive. Some applications do not offer the possibility to attach a sensor due to space limitations or harsh environmental conditions. The need for a mechanical sensor is avoided by the sensorless control. Sensorless control convinces with high mechanical robustness as no sensitive electronic components are present in the machine. By using sensorless methods, the extraction of the position information is done indirectly at the power electronics, similar to the current information, which makes it insensitive to the machine environment. sensorless schemes can also be applied to design redundancy for fault detection and fault isolation. There are 4 methods for position sensorless control. They are (1) Estimation using stator voltages and currents, (2) Estimation using the spatial saturation third-harmonic voltage component, (3) Estimators based on inductance variation due to geometrical and saturation Eﬂects, (4) Estimators using observers (5) Estimators using artificial intelligence. This paper is based on the first method.

2. Mathematical Model of PMSM Control

Symmetrical three-phase, smooth-air-gap machine with sinusoidally distributed windings is considered. Then the voltage equations of stator in the instantaneous form can be expressed as

$$U_{SA} = R_S i_{SA} + \frac{d}{dt}\Psi_{SA} \qquad (1)$$

$$U_{SB} = R_S i_{SB} + \frac{d}{dt}\Psi_{SB} \qquad (2)$$

$$U_{SC} = R_S i_{SC} + \frac{d}{dt}\Psi_{SC} \qquad (3)$$

Where u_{SA}, u_{SB}, and u_{SC}, are the instantaneous values of stator voltages, i_{SA}, i_{SB}, and i_{SC}, are the instantaneous values of stator

currents, and Ψ_{SA}, Ψ_{SB}, and Ψ_{SC} are instantaneous values of stator flux linkages in phase SA, SB, and SC.

The instantaneous equations using two axis theories (Clark transformation) can be written as follows

$$U_{S\alpha} = R_S i_{S\alpha} + \frac{d}{dt} \Psi_{S\alpha} \qquad (4)$$

$$U_{S\beta} = R_S i_{S\beta} + \frac{d}{dt} \Psi_{S\beta} \qquad (5)$$

$$\Psi_{S\alpha} = R_S i_{S\alpha} + \Psi_{S\alpha} \cos\Theta_r \qquad (6)$$

$$\Psi_{S\beta} = R_S i_{S\beta} + \Psi_{S\beta} \sin\Theta_r \qquad (7)$$

$$\frac{dw}{dt} = \frac{P}{J} \left[\frac{3}{2} P(\Psi_{S\alpha} i_{S\beta} - \Psi_{S\beta} i_{S\alpha}) - T_L \right] \qquad (8)$$

$\square\square\square$ - Stator orthogonal coordinate system, $u_{S\square\square}$ - Stator voltages, $i_{S\square\square}$ - Stator currents, $\square_{S\square\square}$ - Stator magnetic fluxes, $\square_M$ - Rotor magnetic flux,

R_S - Stator phase resistance, L_S - Stator phase inductance, P - No of poles, J – Inertia, T_L - Load torque, Θ_r - rotor position in $\square\square\square$ coordinate

System, ω/ω$_f$ - Electrical rotor speed / fields speed

The equation (4) to (8) represents the model of a PMSM in the stationary frame $\square$, $\square$ fixed to the stator. The main idea of the vector control is to decompose the vectors into a magnetic field generating part and a torque generating part. In order to do so, it is necessary to set up a rotary co-ordinate system attached to the rotor magnetic field. This coordinate system is generally called 'd-q-co-ordinate system' (Park transformation). Thus these equations can be written as

$$U_{sd} = R_S i_{sd} + \frac{d}{dt} \Psi_{sd} - w_f \Psi_{sq} \qquad (9)$$

$$U_{sq} = R_S i_{sq} + \frac{d}{dt} \Psi_{sq} - w_f \Psi_{sd} \qquad (10)$$

$$\Psi_{sd} = L_S i_{sd} + \Psi_M \qquad (11)$$

$$\Psi_{sq} = L_S i_{sq} \qquad (12)$$

$$\frac{dw}{dt} = \frac{P}{J} \left[\frac{3}{2} P(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) - T_L \right] \qquad (13)$$

The electromagnetic torque can be given as $\qquad t_e = \frac{3}{2} P(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) \qquad (14)$

3. Position Estimation Using Stator Voltage and Current

It is possible to estimate the rotor angle and the speed in both the transient and steady state of the PMSM by using the estimated stator flux-linkage components. In the steady state the speed of the stator flux-linkage space vector (ω$_{ms}$) is equal to the rotor speed (ω$_r$), since in this case the angle (δ) between the stator flux-linkage space vector and the direct-axis of the rotor is constant. However, in the transient state like when there is a change in the torque reference, the stator flux-linkage space vector moves relative to the rotor to produce the desired new torque. θ_r Is the rotor angle (the angle between the real axis of the stationary reference frame and the real axis of the rotor reference frame), and ρs is the angle of the stator flux-linkage space vector with respect to the real axis of the stationary reference frame. It can be seen that δ is the angle between the stator flux linkage space vectors.

$$\Theta_r = \rho s - \delta \qquad (15)$$

Thus the speed can be expressed as

$$\omega r = \frac{d\theta_r}{dt} = \frac{d\rho_s}{dt} = \omega_{ms} - \omega_d \qquad (16)$$

$$\omega_{ms} = \frac{d\rho_s}{dt} = \frac{d[\tan^{-1}(\Psi_{sq}/\Psi_{sd})]}{dt} \qquad (17)$$

$$\rho_s = \tan^{-1}(\Psi_{sq}/\Psi_{sd}) \qquad (18)$$

4. Sliding Mode Control

Sliding-mode control (SMC) is one of the robust and nonlinear control methods. Systematic design procedure of the method provides a straightforward solution for the control input. The method has several advantages such as robustness against matched external disturbances and unpredictable parameter variations. Traditionally, the conventional sliding-mode control method has been designed for the systems with relative degree of one. Since the control input appears in the first derivative of sliding function, its relative degree with respect to control is one. This type of sliding-mode control method is called as first-order SMC.

A first-order sliding-mode controller consists of two distinct control laws: switching control and equivalent control. The most important task is to design the switching control law which enforces the system to the sliding surface, s(t), defined by the user, and to

maintain the system state trajectory on this surface as shown in Fig 1 in which e and ė denote the tracking error and first-time derivative of the tracking error, respectively. '*t*' in s(t) is the independent variable time. The dynamic performance of the system is directly dependent choosing an appropriate switching control law.
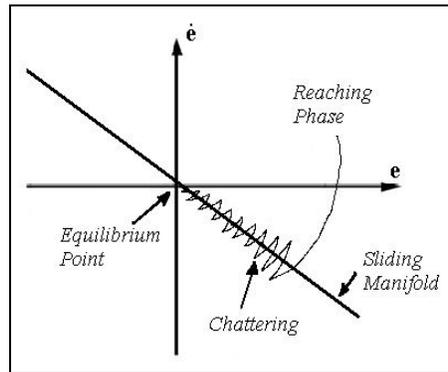
Figure 1: Graphical representation of sliding-mode control

Ideal sliding-mode can be found by equivalent control approach. First time derivative of along the system trajectory is set equal to zero and the resulting algebraic system is solved for the control law. If the equivalent control exists, it is substituted into s(t) and the resulting equations are the ideal sliding-mode.

The first step in the sliding-mode control solution is to determine a sliding manifold which is also called sliding surface or sliding function, s(t) being a function of the tracking error, e(t), e(t) ϵ R that is the difference between set point and output measurement, as

$$s(t) = \left(\lambda + \frac{d}{dt}\right)^{n-1} e(t) \qquad (19)$$

Where *n* denotes the order of uncontrolled system, λ is a positive constant, where $\lambda \in R^+$ where R and R^+ denotes set of real and positive real numbers, respectively. λ is the tuning parameter which determines the slope of sliding manifold. When the system is in the sliding-mode, both s(t) and $\dot{S}(t)$ are equal to zero, where s(t) and $\dot{S}(t)$ are equal to 0. The control law u (t) is determined so that the tracking error and its derivative should converge to zero from any initial state to the equilibrium point in a finite time. U (t) consists of two additive signals switching (discontinuous) signal, $u_{sw}(t)$, and equivalent (continuous) signal, $u_{sw}(t)$, determined separately.

$$u(t) = u_{eq}(t) + u_{sw}(t) \qquad (20)$$

If the initial trajectory is not on the sliding surface, the switching control, $u_{sw}(t)$ enforces the error toward the origin of the sliding surface and this is called the reaching phase. The equivalent control may not be able to move the system state toward sliding surface. Therefore, the switching control is designed on the basis of relay-like function because it allows changes between the structures infinitely fast. The equivalent control is found by equating derivative of sliding function to zero. On the other hand, the switching control can be selected directly as

$$u_{sw}(t) = - K sign\ (s(t)) \qquad (20)$$

Where *k* is a positive constant that should be large enough to suppress all matching uncertainties and unpredictable system dynamics and sign (t) is a signum function.

5. Block Diagram of PMSM Control
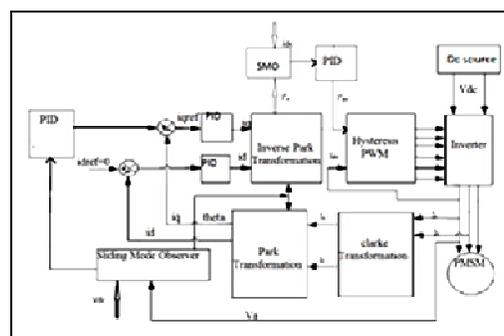
Figure 2: Block Diagram

Sliding mode observer (SMO) gets the reference voltage and actual stator voltage, the error is processed through a PID controller and generates the reference current. The i_{qref} current is responsible for the torque control. Hence torque is controlled using q-axis current. $I_{d}ref$ current is always kept zero in order to generate non zero torque. On other hand, one of the reference phase current is compared

with the input direct current and errors are processed through a PID controller. The output of the PID controller is used for generating the PWM pulses. For varying motor toque the speed and phase currents varies and correspondingly the rotor position varies. Based on this varying phase currents hysteresis pulses are generated for the inverter.

S. NO	PARAMETERS	VALUES
1	Electromagnetic torque	5 Nm
2	Speed	1460 (rpm)
3	Rated current	5(A)
4	Stator Resistance	10/ohm
5	Stator Inductance	0.835 mH

Table 1: Motor Ratings

6. Simulation Results

The sensorless PMSM control is simulated for the surface mounted PMSM motors of parameters presented in the table 1.with the stator parametes, the results obtained for the motor torque of 2.4 NM are presented below.
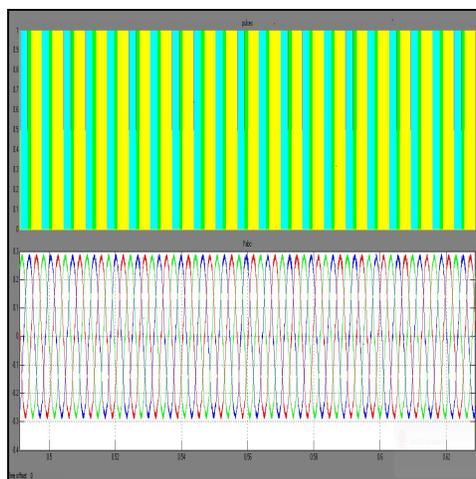
Figure 3: Hysteresis Pulses

Figure 3 shows the hysteresis pulses generated for the corresponding phase currents, accordingly the switches are turned on and so the rotors rotates to the new position.
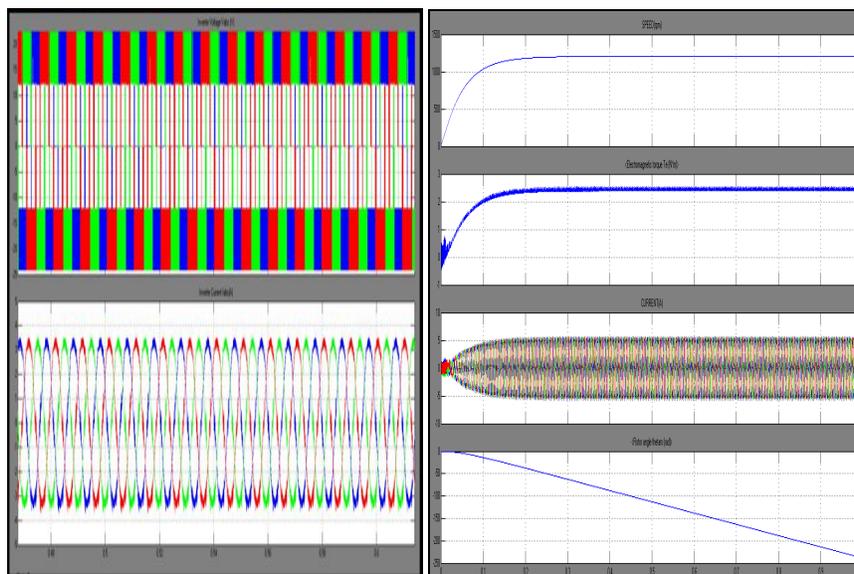
Figure 4: Input voltage and current
Figure 5: Speed, Toque, current and angle of rotor

Fig 5 shows that for the torque of 2.5 Nm the corresponding speed(1250 rpm), Electromagnetic Torque(2.5 Nm) was obtained. For this phase currents, the rotor turns to the angle of 240(rad). Hence the PMSM motor is controlled without signals from the position sensors.

7. Conclusion

This project proposes a sensorless control for Permanent Magnet Synchronous Motor (PMSM) adopting sliding mode technique. Using sliding mode technique the error between the input and output is reduced and accurate speed control is obtained then the conventional method also by using PID controller, the distortions in the torque is reduced then the conventional method and Speed control over wide range is obtained.

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