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Design of an Adaptive Gain variation Sliding Mode Control Algorithm for Extended Non-singular Terminal Sliding Mode Observer based Sensorless PMSM Drive

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Abstract

This paper proposes a sliding mode observer (SMO) with adaptive gain variation for the permanent synchronous motor magnet (PMSM) for estimating motor speed and position. The observer is designed to make the drive sensorless, speed estimation and rotor position using back-electromotive force (Back-EMF). The variation in motor speed is smooth with the proposed observer. Using a designed observer, the PMSM drive is controlled by field oriented control strategy. Simulation results are obtained using MATLAB / Simulink and experimentally verified, showing the effectiveness of the proposed application of the SMO algorithm to the PMSM drive.

Keywords: PMSM; Field oriented control; Adaptive gain variation; Sliding-mode observer; Back-emf

1. INTRODUCTION

The use of PMSM in servo drive applications in industry has increased due to its high efficiency zero loss in the rotor, absence of brush and slip ring / commutator, good control of the wide range of speeds and high power density of machine. The precise rotor position is required in any case of the machine obtained by a position / speed sensor mounted on the shaft in order to implement field-oriented control. This sensor is usually a decoder or encoder that is connected to the circuit from the machine. The cost of this sensor is high and needs to be removed as it affects the control algorithm selection. The mounting of the physical sensors on the shaft is also limited and should be less susceptible to noise and the industry's environment. These limitations and the advancement of the high- speed processor have enabled researchers to propose and implement a sensorless algorithm in order to reduce costs and hardware dependence that can be applied to any machine size in any environment.

PMSM is a nonlinear machine and parameter variation is a major constraint for any observer and estimator, yet many authors have different sensorless drive and motor speed and position estimation schemes [1-28] in place.

A sensorless PMSM with second - order luenberger observer is shown in [1,5] to estimate the speed and position of the rotor by means of a reduced-order rotor flux observer. The position and speed estimates of the back-EMF are shown in [2,7,10,11,24,26,27]. The back-EMF-based methods are normally used both for medium and high-speed use. In [20], the problem of chattering in SMO is discussed, which can lead to the undesirable frequency of finite frequency and amplitude oscillations. In [9,12,13], a discrete and digital sliding mode observer is reported. Sensorless PMSM drive simulation study is given for SMO and back-EMF observers in [16,18,20,23,25,26,27]. An extended Kalman Filter is available for sensorless control of the PMSM drive for both non-salient and salient pole motors [19].

A sliding mode observer with adaptive gain variation for the PMSM is proposed to estimate the motor speed and position. The motor vector control method is used to control this.

2. PMSM MODEL

The PMSM mathematical model is shown in [28, 29, 30, 31, 32, 33, 34, 35]. For the PMSM motor, a three - phase input is applied. With the transformation of Clark, three phase inputs are transferred to two phase systems.

Let v_a, v_b and v_c are the three-phase supplied voltage at the stator terminal of the machine and i_a, i_b and i_c are the three-phase current flowing though the machin

$$v_\alpha = \frac{2}{3}\left(v_a - \frac{1}{2}v_b - \frac{1}{2}v_c\right) \quad (1)$$

$$v_\beta = \frac{2}{3}\left(-\frac{\sqrt{3}}{2}v_b + \frac{\sqrt{3}}{2}v_c\right) \quad (2)$$

Similarly,

$$i_\alpha = \frac{2}{3}\left(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c\right) \quad (3)$$

$$i_\beta = \frac{2}{3}\left(-\frac{\sqrt{3}}{2}i_b + \frac{\sqrt{3}}{2}i_c\right) \quad (4)$$

After transforming the stator quantities into the alpha-beta transformation, machine can be analyzed as two-phase machine. The expression of v_α and v_β of the machine can be expresses as

$$v_\alpha = R_s i_\alpha + L_\alpha + \frac{di_\alpha}{d_t} + e_\alpha \quad (5)$$

$$v_\beta = R_s i_\beta + L_\beta + \frac{di_\beta}{d_t} + e_\beta \quad (6)$$

Where, $e_\alpha = -K_D \omega \sin\theta_e$ and $e_\beta = K_D \omega \cos\theta_e$ is the induced electromotive force in that specific phase that is orthogonal to each other and depends on the speed of the machine where K_D is voltage constant of induced emf in PMSM.

To reduce the alternating behavior of voltage and current and to achieve qualities in dc, these variables can be transformed from αβ to dq, referred to as the Park transformation, on which the two-axis rotates at the rotor speed, the so-called rotor reference frame.

$$v_d = v_\alpha \sin\theta_e + v_\beta \cos\theta_e \quad (7)$$

$$v_q = v_\alpha \cos\theta_e - v_\beta \sin\theta_e \quad (8)$$

and similarly

$$i_d = i_\alpha \sin\theta_e + i_\beta \cos\theta_e \quad (9)$$

$$i_q = i_\alpha \cos\theta_e - i_\beta \sin\theta_e \quad (10)$$

In dq axis the PMSM can be expressed as following

$$v_d = Ri_d + L_d \frac{di_d}{d_t} - \omega_e L_q i_q \quad (11)$$

$$v_q = Ri_q + L_q \frac{di_d}{d_t} + \omega_e L_d i_d + \omega_e \lambda_{PM} \quad (12)$$

$$\omega_e = \frac{d\theta_e}{d_t} \quad (13)$$

Expression for the electromagnetic torque can be written as,

$$T_e = (\frac{3}{2})(\frac{P}{2})(\lambda_{PM} i_q - (L_q - L_d) i_q i_d) \quad (14)$$

and equation for the motor dynamics is

$$T_e = T_L + B\omega_e + J\frac{d\omega e}{d_t} \quad (15)$$

also, P is total number of poles, T_e is electromagnetic torque, T_L is load torque, B is damping coefficient and J is moment of inertia.

Inverter frequency is related to the rotor speed as

$$\omega_i = (\frac{P}{2})\omega_e \quad (16)$$

3. PMSM DRIVE WITH FIELD ORIENTED CONTROL

The PMSM drive can be regarded as the integration of four main system components. PMSM, power converter unit, DSP / FPGA sensorless control algorithm and voltage, currency sensing devices. PMSM is powered by the power converter unit, giving the required voltage and frequency in accordance with the signal received from the control circuit. Power converter unit usually comes with battery or controlled / uncontrolled ac–dc converter. In sensorless drive, speed or position sensor is removed, but the speed and position, current and voltage applied to the stator must be estimated at each sample time Two current sensors are used and the third current can be calculated without a neutral connection by mathematical expression. For sensing voltage, control algorithm voltage is sometimes considered to be a feedback voltage, thus avoiding noise in the signal feedback to reduce the transducer costs.

In the rotor reference frame, field-oriented control is used for rapid dynamic control. The stator flux produced by the winding of the stator must be produced at the orthogonal flux. In PMSM, the flux of the rotor is produced by permanent magnets, so that the current of the d-axis is not needed more and now pmsm is single-excited machine. In this study, surface mounted PMSM in which the d-axis and q-axis inductance are the same are considered. Therefore, PMSM mounted on the surface is found without a torque of reluctance because there is no salience. To achieve maximum torque per ampere below the rated speed and at the given dc voltage, only q-axis current is the torque producing component in the field oriented control. Now in the sensorless algorithm, this position update should be from the algorithm itself, as no physical sensors can detect the position. The processor must calculate the calculation at such an interval that the field orientation is not affected. The conceptual diagram of the PMSM sensorless drive is shown in Fig.1

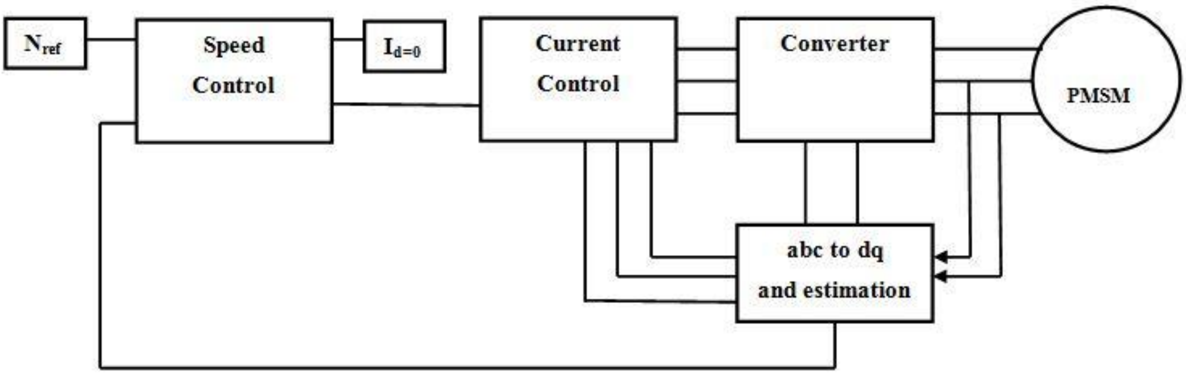

Fig.1: Sensorless PMSM Drive

In order to control speed and achieve field-oriented control, reference speed is compared to actual / estimated speed and an error is generated by the PI [36] series regulator. This can be identified as the current command of the torque or the q-axis. A limiter is used to limit the current of the stator at the output of the speed controller. The required q-axis current and d-axis current (zero) are now compared to the actual generation errors of the current. These errors are handled by PI series controllers that provide the required q-axis and d-axis voltage vectors. This voltage can be transformed in abc using given position which is the required output voltage. Using space vector pulse width modulation (SVPWM) technique, through the converter, reference voltage is produced from dc to ac which is fed to the terminals of the machine.

4. SPEED AND POSITION ESTIMATION

The estimation of the speed and position using the proposed adaptive gain sliding mode observer is discussed [37]. Voltage and current of supply are converted into αβ frame. Two - phase voltage and current transformed are given to the observer as input. The estimated reverse emf from the observer is used to calculate position and velocity. The estimation input for each algorithm is stator voltages and stator currents in a stationary reference frame, which can be achieved by the transformation of Clarke. In this reference framework, the basic equations can be written as

$$v_\alpha = R_s i_\alpha + L_\alpha \frac{di_\alpha}{dt} + e_\alpha \qquad (17)$$

$$v_\beta = R_s i_\beta + L_\beta \frac{di_\beta}{dt} + e_\beta \qquad (18)$$

Where $e_\alpha = -K_E \omega \sin\theta_e$ and $e\beta = K_E \omega \cos\theta_e$

Back-EMF in the stationary reference frame can be estimated from the basic input of voltage and current. The rotor position can be calculated from the back-EMF according to the basic mathematical equation.

$$\theta_e = \arctan(-\frac{e_\alpha}{e_\beta}) \qquad (19)$$

In sliding-mode observer, inputs are stator voltage and current in the stationary reference frame

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L_\alpha} i_\alpha + \frac{1}{L_\alpha} v_\alpha - \frac{1}{L_\alpha} e_\alpha \qquad (20)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L_\beta} i_\beta + \frac{1}{L_\beta} v_\beta - \frac{1}{L_\beta} e_\beta \qquad (21)$$

To estimate current in rotor reference frame, SMO can be designed as [38]

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L_\alpha} i_\alpha + \frac{1}{L_\alpha} v_\alpha - \frac{1}{L_\alpha} k_\alpha \qquad (22)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L_\beta} i_\beta + \frac{1}{L_\beta} v_\beta - \frac{1}{L_\beta} k_\beta \qquad (23)$$

Where $k_\alpha = K_B(s_\alpha)$, $k_\beta = K_B(s_\beta)$,

$$s_\alpha = \left|\dot{\bar{i}}_\alpha\right|^{\frac{1}{p}} \mathrm{sgn}(\dot{\bar{i}}_\alpha) + c\bar{i}_\alpha \quad s_\beta = \left|\dot{\bar{i}}_\beta\right|^{\frac{1}{p}} \mathrm{sgn}(\dot{\bar{i}}_\beta) + c\bar{i}_\alpha$$

Here, K_B the observer gain is to be selected to converge in the sliding mode. The output is transferred to a controller that receives a control signal that is back emf for that particular coordinate. The problem with the sliding mode observer is the problem of convergence with low speed and high speed. Observer gain K_B should change accordingly to overcome the above mentioned. If the current estimation error is too high, the gain required by the observer is greater and if the error is too small, the gain required must be reduced. Current error estimation signals $(i_\alpha - i_\alpha)$ and $(i_\beta - i_\beta)$ are used to produce the gain correction factor. The sliding mode observer with modification is designed as

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L_\alpha} i_\alpha + \frac{1}{L_\alpha} v_\alpha - \frac{1}{L_\alpha} k_{\alpha\_ag} \quad (24)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L_\beta} i_\beta + \frac{1}{L_\beta} v_\beta - \frac{1}{L_\beta} k_{\beta\_ag} \quad (25)$$

$$k_{\alpha\_ag} = K_{BG}(s_\alpha) \quad (26)$$

$$k_{\beta\_ag} = K_{BG}(s_\beta) \quad (27)$$

$$K_{BG} = K_B.g_c \quad (28)$$

$$g_c = l.((i_\alpha - i_\alpha)^2 + (i_\beta - i_\beta)^2) \quad (29)$$

The gain correction factor g_c for the gain K_{BG} is generated [37] to give the sliding mode observer the estimated emf at a wide velocity. This method is used as a feed-forward technique because the gain varies according to the error in the current error to remain within a limited range and to converge a sliding mode observer into a wide range of speed.

Since back-EMF is proportional to the speed of the rotor, the discontinuous control function used to obtain estimated back-EMF should be adjusted at the different speeds. The switching gain of satmod (S) [37] is designed to be proportional to the given speed in order to improve the performance of SMOs in different speed regions.

$$k_\alpha, k_\beta = mk \text{, where } m = \frac{\omega_{ref}}{\omega_{base}} \quad (30)$$

Where ω_{base} and ω_{ref} are the base and reference rotor speeds, k is the referenced saturation function switching gain. The conventional saturation function is modified by placing a sinusoidal function [37] in the neighborhood of the sliding surface to solve the problem of chattering.

$$k_\alpha, k_\beta.\text{sign}_{mod}(s) = \begin{Bmatrix} mk, s > \Delta \\ mk.\sin(\frac{\pi s}{2\Delta}), -\Delta < s < \Delta \\ -mk, s < \Delta \end{Bmatrix} \quad (31)$$

where [-Δ, Δ] is the switching interval. Improved switching function curve is shown in Fig.2.

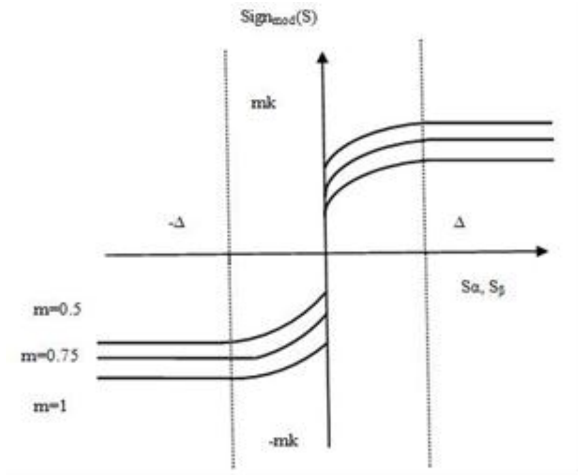

Fig.2.: Modified switching function curve

5. SIMULATION RESULTS

Sensorless PMSM drive with field-oriented control is simulated using MATLAB - Simulink environment. Motor speed using adaptive gain variation sliding mode observer is shown in figure.3. Initially the motor speed is at 1500rpm after attaining steady state, and at intervals of 0.25s, 0.51s and 0.85s the speed is changed to 500rpm, 2500rpm and-1000rpm respectively. Adaptation to speed variation is evident from figure.3

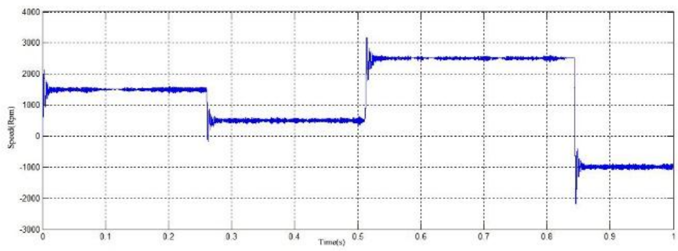

Fig.3: Motor Speed using adaptive gain variation sliding mode observer

Estimated and actual rotor position using adaptive gain variation sliding mode observer is shown in figure.4. Estimated of rotor position is smooth.

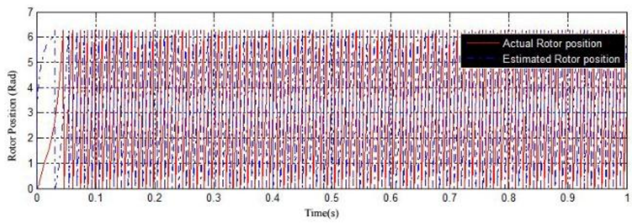

Fig.4: Estimated and actual rotor position

Torque variations are given as shown in figure.5. With speed changed from 1500 rpm to 500 rpm, torque changes from 1.5

Nm to 1Nm. Then speed is changed from 500 rpm to 2500 rpm, torque changes from 1Nm to 0.5Nm. Finally, speed is changed from 2500 rpm to -1000 rpm, and torque varies from 05 nm to 0.25 Nm. Torque ripple reduction can be observed with variation in speed and minimal ripple is observed at negative speed -1000 rpm.

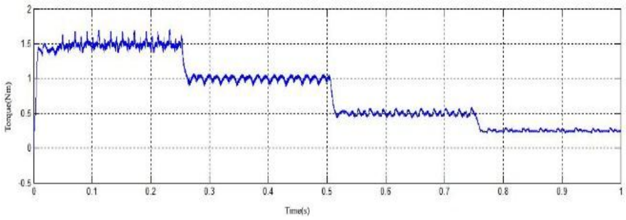

Fig.5: Torque Output

Figure.6 shows variation in current when the torque changes. As speed changes torque changes. Output power of the motor varies, as torque varies with the torque variation reflected by change in motor current.

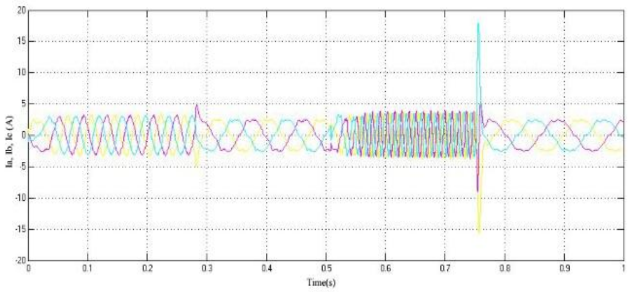

Fig.6: Three phase current waveform

6. EXPERIMENTAL RESULTS

Figure.7 shows the experimental setup. Table 1 lists theparameters of tested surface mount permanent magnet synchronous motor (SMPMSM). Intelligent power module supplies the pmsm. Developed adaptive gain sliding mode observer is coded in field programmable gate array (FPGA), which is also digital controller. Using data acquisition system (DAQ) output from FPGA is measured and displayed in digital storage oscilloscope.

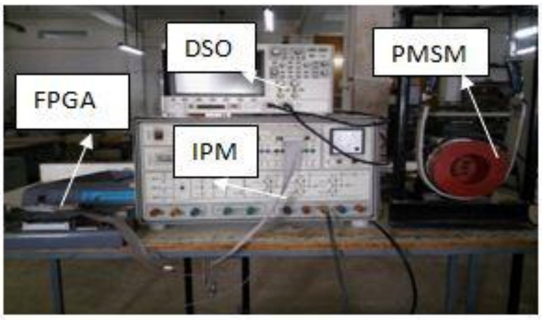

Fig.7: Experimental setup

Figure.8 shows actual speed of the motor obtained experimentally.

Initially the motor speed is at 1500rpm. Then speed is changed to 500rpm, 2500rpm and-1000rpm respectively.

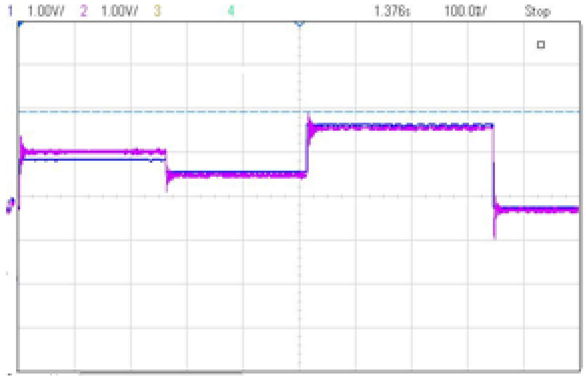

Fig.8: Motor speed obtained using adaptive gain variation sliding mode observer experimentally

Figure.9 shows the variation in torque as speed is varied. Torque changes from 1.5 Nm to 1 Nm when speed changes from 1500 rpm to 500 rpm and 1 Nm to 0.5 Nm when speed changes from 500 rpm to 2500 rpm respectively. Torque ripple can be observed when speed is varied from 2500 rpm to -1000 rpm, that when speed changes from forward rotation to reverse rotation.

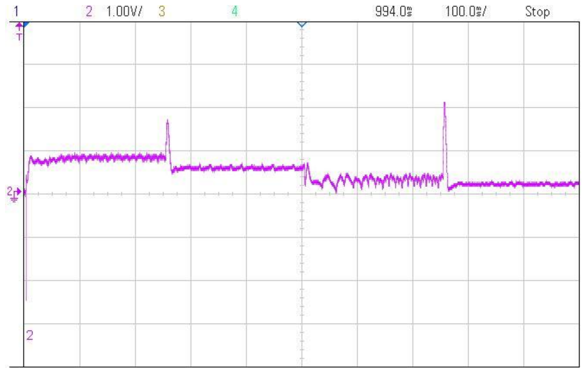

Fig.9: Torque variation

Figure.10 shows variation in motor current when torque varies. Current waveform appears clear at lower speed, 500 rpm when compared to 1500 rpm and 2500 rpm. Phase currents, phase R and phase B were measured due to non-availability of data acquisition system (DAQ) which measures all three currents.

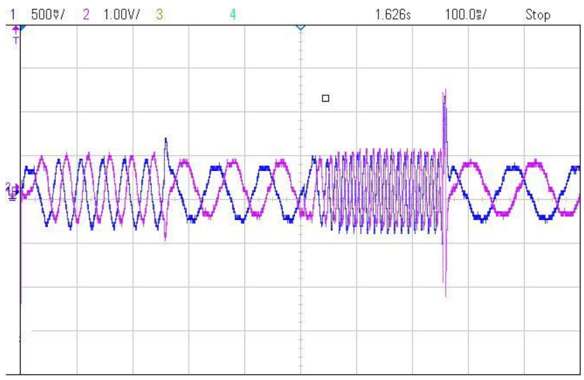

Fig.10: Variation in motor current

TABLE 1

Parameters of Tested SMPMSM

Number of pole pairs	2
Rated speed	4600 rpm
Armature resistance R_a	3.07Ω
d-axis inductance L_d	6.57e-3mH
q-axis inductance L_q	6.57e-3mH
Permanent magnet flux	0.2 Wb
Rated torque	2.2 Nm

7. CONCLUSION

A sliding mode observer (SMO) with adaptive gain variation for the permanent magnet synchronous motor (PMSM) to estimate speed and position of the motor is designed. Motor speed variation is smooth with the proposed observer. Simulation results are verified experimentally, showing the effectiveness of proposed SMO algorithm application to PMSM drive.

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