Sliding-Mode Control of the Permanent Magnet Synchronous Motor (PMSM) with Disturbance Compensation Techniques

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ABSTRACT

The main objective of this thesis is to track a reference speed being applied to permanent magnet synchronous motor (PMSM). As it known, these types of motors depend on a 3-phase time-dependent voltage source (3-Phase AC supply voltages) that generates a magnetic flux in the air-gap of the machine. This generated magnetic flux interacts with the permanent magnetic flux on the rotor, to generate the required torque. The mathematical model of this motor is a non-linear time-varying system. To apply different control techniques, we transform this model to an equivalent linear time-invariant system. These transformations not only yield a linear time-varying model, but also, reduce the number of states in the model. Classical control techniques, such as PI control, can provide a speed tracking of this type of motors with some limitations. In general, the performance of the motor is limited in term of the range of speed and the range of applied load torque. Also, the performance is affected by parameter variations or the high frequency, un-modeled states. In this project, a sliding-mode controller is used due to its insensitivity to the variations of the parameters.

KEYWORDS:
Disturbance observer, permanent-magnet synchronous motor (PMSM), Sliding-mode control (SMC), PI control .

I. INTRODUCTION

The Permanent Magnet Synchronous Machines (PMSM) are high-performance electromechanical motion devices essentially superseding traditional dc servomotors, and fractional horsepower induction machine because of their high performance capability [10]. This type of device can widely be seen in our daily life; for instance, different household machines, vending machines, factories, and computers. For such a diverse range of applications, the performance requirements necessitate different speed and/or angular position specifications to meet designated operational goals. The necessity for high performance electromechanical systems increases as the demand for precision controls increases. Permanent magnet synchronous motors (PMSMs) constitute a significant electro-mechanical design option in many applications due to their high performance, high efficiency, high power density, and fast dynamics [2],[16] and [9]. In high performance drivers, servos, and power generation systems (up to 200 KW), three-phase permanent magnet synchronous machines (motors and generators) are the preferable choice. In high-power (from hundreds of KW to hundred of MW range)generation systems, conventional three phase synchronous generators are used[10]. Given the complexity and the nonlinearity of PMSMs, substantial research has been reported detailing control and performance challenges. The classical proportional integral (PI) controller, due to its simplicity of implementation, is still the dominant choice in most applications; however, due to load disturbances, un-modeled states, parameter variations and friction forces, PI controllers are unable provide effective solutions to many practical problems [15]. To avoid these aforementioned problems, a nonlinear controller is used in this thesis. Sliding-mode control (SMC) has the striking feature that it is insensitive to modeling uncertainty [5]. Also, with the addition of an observer to estimate the applied load torque, it has the ability to compensate for load torque disturbances.

II. LITERATURE SURVEY

During the last decade, permanent magnet synchronous motors have been used widely in the industry to replace DC motors and induction machines. The main characteristics of these motors are the low inertia, the high efficiency, power density and reliability. Due these advantages, permanent magnet synchronous motors are ideal for the applications where a quick accurate torque control is required.The Permanent Magnet Synchronous Motor is a rotating electric machine where the stator is a classic three phase coils like that of an induction motor and the permanent magnets are located on the rotor surface. A PMSM provides rotation at a fixed speed in synchronization with the frequency of the power source, regardless of the fluctuation of the load or line voltage. The motor runs at a fixed speed synchronous with mains frequency, at any torque up to the motor's operating limit. PMSM are used in high-accuracy direct-drive applications mainly due to their advantages. Compared to conventional DC motors, they have no brushes or mechanical commutators, which eliminates the problems due to mechanical wear of the moving parts. In addition, the better heat dissipation characteristic and ability to operate at high speed render them superior to the PMSM drives.

2.1. Permanent Magnet Synchronous Motor Drive

The motor drive consists of four main components, the PM motor, inverter, control unit and the position sensor. The components are connected as shown in Fig.

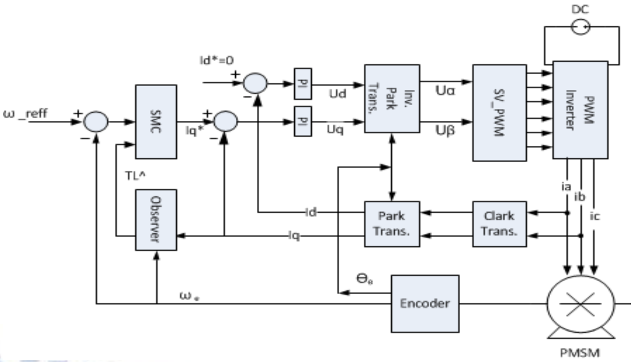


Fig.1 Drive System Schematic

Descriptions of the different components are as follows

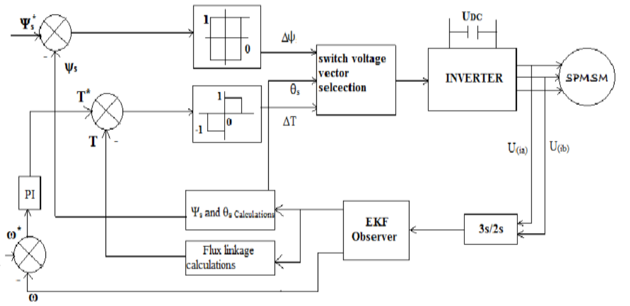
A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications.

III. PI CONTROL AND SMC CONTROL

With the ever increasing need for the use of drives in the modern applications, it is necessary that the drive being used should be compatible. The PMSM drives are mostly used in all robotic and position control devices. The different techniques employed for the control of this drive system has a direct relation with its performance. So for a system run effectively the drive should have smooth performance characteristics. Hence the present work relates it to this by the use of speed sensorless SVMDTC based on EKF with SMD controllers.

3.1 Speed Sensor less Direct Torque Control (DTC):

Schematic diagram of speed sensorless DTC control for SPMSM based on EKF is shown as Fig.1. Switch voltage vector selection is shown as TABLE I.



Speed Sensorless DTC for SPMSM based on EKF

Fig.1Speed sensor less DTC for SPMSM for based on EKF

Table 1. Switch Voltage Vector Selection

Δψ	ΔT	1	2	3	4	5	6
1	1	U_{s2}	U_{s3}	U_{s4}	U_{s5}	U_{s6}	U_{s1}
	0	U_{s7}	U_{s8}	U_{s7}	U_{s8}	U_{s7}	U_{s8}
	-1	U_{s6}	U_{s1}	U_{s2}	U_{s3}	U_{s4}	U_{s5}
-1	1	U_{s3}	U_{s4}	U_{s5}	U_{s6}	U_{s1}	U_{s2}
	0	U_{s8}	U_{s7}	U_{s8}	U_{s7}	U_{s8}	U_{s7}
	-1	U_{s5}	U_{s6}	U_{s1}	U_{s2}	U_{s3}	U_{s4}

3.2 Detailed Modeling of PMSM

Detailed modeling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame as shown in Fig. 2 At any time t, the rotating rotor d-axis makes and angle ¸r with the fixed stator phase axis and rotating stator mmf makes an angle ± with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

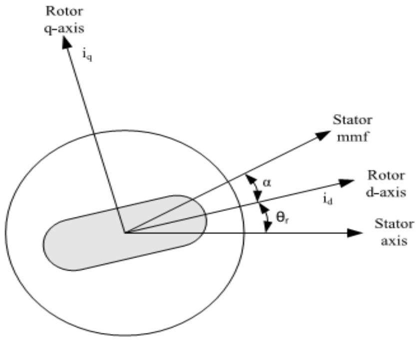


Fig. 2motor axis

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible
4) There are no field current dynamics

Voltage equations are given by:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho\lambda_q$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho\lambda_d$$

Flux Linkages are given by

$$\lambda_q = L_q i_q$$

$$\lambda_d = L_d i_d + \lambda_f$$

Substituting equations 3.3 and 3.4 into 3.1 and 3.2

$$V_q = R_s i_q + \omega_r\left(L_d i_d + \lambda_f\right) + \rho L_q i_q$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho\left(L_d i_d + \lambda_f\right)$$

Arranging equations 3.5 and 3.6 in matrix form

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho\lambda_f \end{pmatrix}$$

The developed torque motor is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right)$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt}$$

Solving for the rotor mechanical speed from equation 3.9

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt$$

And

$$\omega_m = \omega_r\left(\frac{2}{P}\right)$$

In the above equations ωr is the rotor electrical speed ωm is the rotor mechanical speed

3.3 Parks transformation and d q modeling

The dynamic d q modeling is used for the study of motor during transient and steady state. It is done by converting the three phase voltage s and currents to dqo variables by using parks transformation.

Converting the phase voltages Vabc to Vdqo variables in rotor reference frame the following equations are obtained

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad 3.12$$

Convert Vdqo to Vabc

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin\theta_r - 120 & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \quad 3.13$$

3.4 Equivalent circuit of permanent magnet motor

Equivalent circuits of the motors are used for study and simulation of motors, from the d-q modeling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source as described in the following equation. $\lambda_f = L_{dm} i_f$

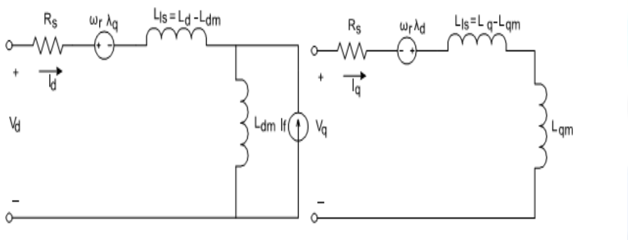


Fig.3.Permanent magnet motor electric circuit without damper windings

IV. SIMULATION RESULTS

In this section, to demonstrate the effectiveness of the proposed SMC+ESMDO approach, simulations, and experiments of the PI method and the SMC+ESMDO method in one PMSM system were made. Simulations are established in MATLAB/Simulink,

4.1 PI Control:

The PI simulation parameters of the both current loops are the same: the proportional gain Kpc = 10, the integral gain Kic = 2.61. The PI simulation parameter of the speed loop is that proportional gain Kps = 0.5, and integral gain Kis = 20. The parameters of the SMC+ESMDO speed loop are: k = 20, δ = 10, ε = 0.1, and x1 = e. The simulation results of the PI controller and the SMC+ESMDO controller . From the simulation results, it can be observed that the SMC+ESMDO method has a smaller overshoot and a shorter settling time compared with the PI method when the reference speed is 1000 r/min. Moreover, when load torque TL = 4 N·m is added suddenly at t = 0.1 s and removed at t = 0.2 s, the SMC+ESMDOmethod gives less speed and electrical magnetic torque fluctuations. Estimated load disturbance of the ESMDO and load disturbance command are shown in It can be observed that the ESMDO can estimate the disturbance exactly and quickly with low chattering.

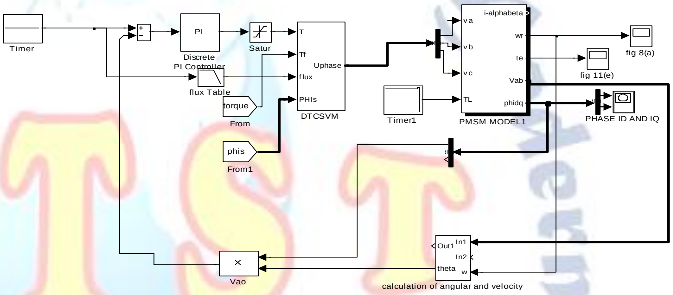


Fig 4: Simulation diagram for PMSM drive for PI Control

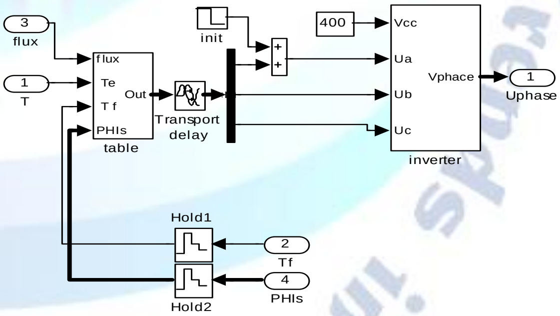


Fig 5: Simulation diagram for DTCSVM

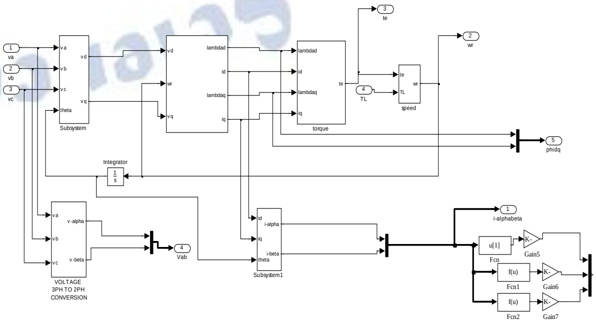


Fig 6: Simulation diagram for PMSM model

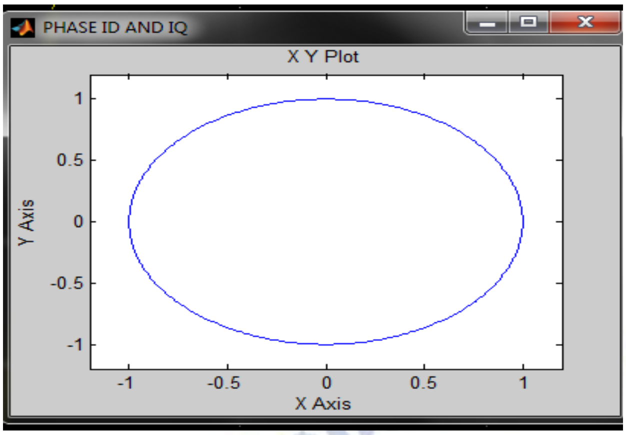


Fig 7: Simulation results for flux linkages for PI Control

The above graph shows the relation between flux linkages between the direct and quadrature axis

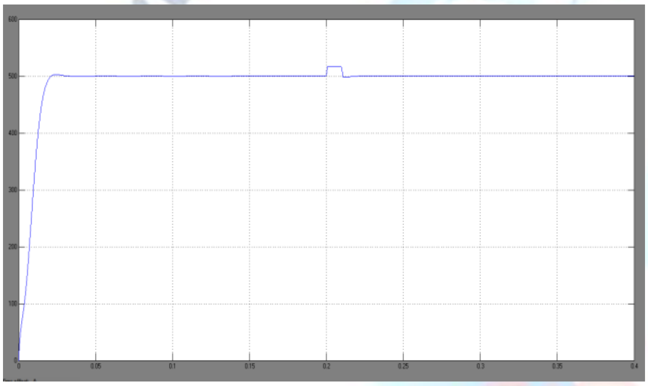


Fig 8: Simulation results for speed of PMSM drive for PI Control

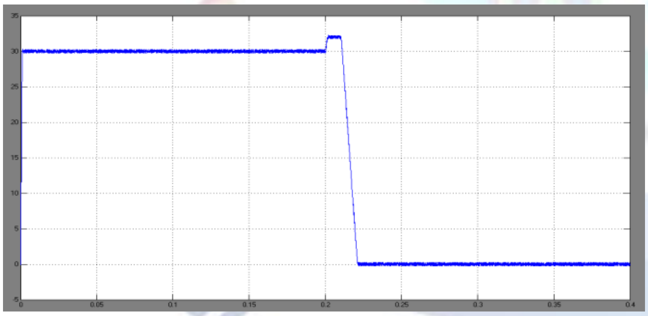


Fig 9: Simulation results for torque of PMSM Drive for PI control

4.2 SMC Control:

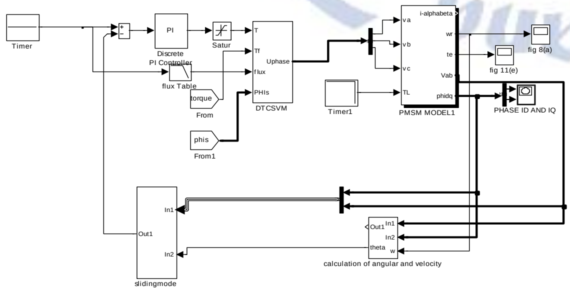


Fig 10: Simulation diagram for PMSM drive for SMC Control

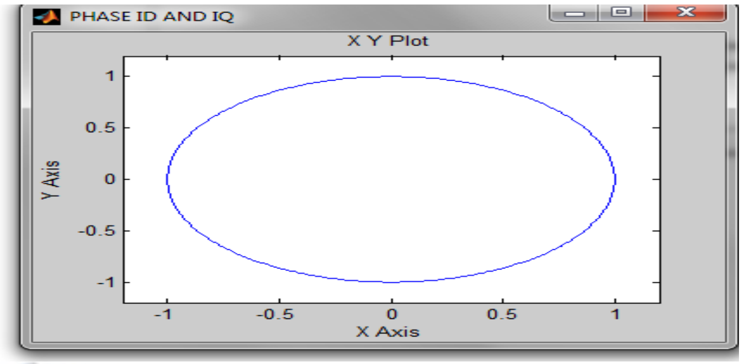


Fig 11: Simulation results for flux linkages for SMC Control

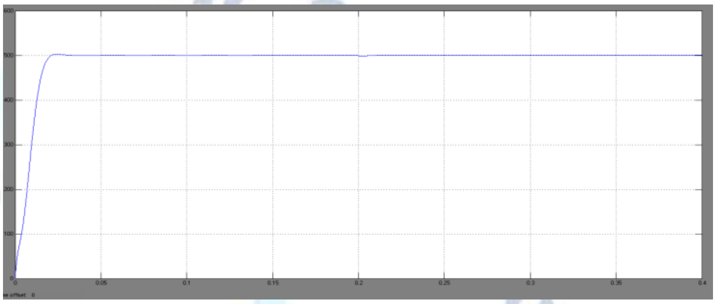


Fig 12: Simulation results for speed of PMSM drive for SMC Control

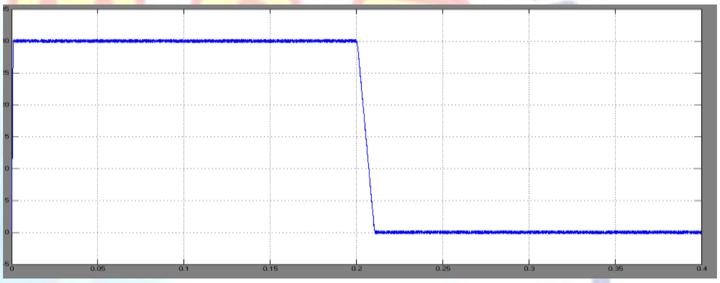


Fig 13: Simulation results for torque of PMSM Drive for SMC control

First, an SMC speed controller should be constructed according to the proposed reaching law, and then drives the PMSM. Second, the ESMDO can also be constructed using the, then we need to test the effectiveness of the ESMDO when the load is added or removed suddenly. If the disturbance estimate is different from the actual load, one must check whether the parameters of the ESMDO are right. Finally, if the ESMDO can estimate disturbances exactly, estimated disturbances can be considered as the feed forward part to compensate disturbances

V. CONCLUSION

In this paper, one nonlinear SMC algorithm is proposed and has been A novel SMRL method is introduced to control the chattering. In order to estimate system PI disturbances, one extended sliding-mode disturbance observer is presented. A composite control method that combines PI and SMC is developed to further improve the disturbance rejection ability of SMC system. Simulation results have validated the proposed method.

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