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Speed Control of PMSM by Sliding Mode Control and PI Control

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ABSTRACT

In order to optimize the speed-control performance of the permanent-magnet synchronous motor (PMSM) system with different disturbances and uncertainties, a nonlinear speed-control algorithm for the PMSM servo systems using sliding-mode control and disturbance compensation techniques is developed in this paper. First, a sliding-mode control and PI control method based on one novel which allows chattering reduction on control input while maintaining high tracking performance of the controller. Then, an PI control extended sliding-mode disturbance observer is proposed to estimate lumped uncertainties directly, to compensate strong disturbances and achieve high servo precisions. Simulation results PI control better than the SMC control both show the validity of the proposed control approach.

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

I. Introduction

In the permanent-magnet synchronous motor (PMSM) control system, the classical proportional integral (PI) control technique is still popular due to its simple implementation [1][2]. However, in a practical PMSM system, there are large quantities of the disturbances and uncertainties, which may come internally or externally, e.g., unmolded dynamics, parameter variation, friction force, and load disturbances. It will be very difficult to limit these disturbances rapidly if adopting linear control methods like PI control algorithm[3]-[4]. Therefore, many nonlinear control methods have been adopted to improve the control performances in systems with different disturbances and uncertainties, e.g., robust control sliding-mode control (SMC) adaptive control back stepping control predictive control intelligent control and so on[5]-[6]. In these nonlinear control methods, SMC method is well known for its invariant proper-ties to certain internal parameter variations and external disturbances, which can guarantee perfect tracking performance de-spite parameters or model uncertainties. It has been successfully applied in many fields[7]-[8]. In the sliding-mode approach was applied to a six-phase induction machine. In a hybrid terminal sliding-mode observer was proposed based on the nonsingular terminal sliding mode and the high-order sliding mode for the rotor position and speed estimation in one PMSM control system. In the performance of a sliding-mode controller was studied using a hybrid controller applied to induction motors via sampled closed representations. The results were very conclusive regarding the effectiveness of the sliding-mode approach. A sliding-mode controller applied to induction machine can also be found in [9]-[10]. However, the robustness of SMC can only be guaranteed by the selection of large control gains, while the large gains will lead to the well-known chattering phenomenon, which can excite high-frequency dynamics. Thus, some approaches have been proposed to overcome the chattering, such as continuation control, high-order sliding-mode method, complementary sliding-mode method [11], and reaching law method. The reaching law approach deals directly with the reaching process, since chattering is caused by the non-ideal reaching at the end of the reaching phase. In [12]-[13], authors presented some reaching laws, which can restrain chattering by decreasing gain or making the discontinuous gain a function of sliding-mode surface. In [14]-[15], a novel exponential reaching law was presented to design the speed- and current-integrated controller. To suppress chattering problem, system variable was used in this reaching law[16]-[17]-[18]. However, in the aforementioned reaching laws, the discontinuous gain rapidly decreases because of variation of the functions of the sliding surface, thus reducing the robustness of the controller near the sliding surface and also increasing the reaching time[19]-[20]-[21].

In order to solve the aforementioned problems, a novel reaching law, which is based on the choice of an exponential term that adapts to the variations of the sliding-mode surface and system states, is proposed in this paper. This reaching law is able to deal with the chattering/reaching time dilemma. Based on this reaching law, a sliding-mode speed controller of PMSM is developed. Then, to further improve the disturbance rejection performance of SMC method, extended sliding-mode disturbance observer (ESMDO) is proposed, and the estimated system disturbance is considered as the feed forward compensation part to compensate sliding-mode speed controller. Thus, a composite control method combining an SMC part and a feed forward compensation part based on ESMDO, called SMC+ESMDO method, is developed. Finally, the effectiveness of the proposed control approach was verified by simulation and experimental results.

II. Literature Review

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.

A. *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.1.

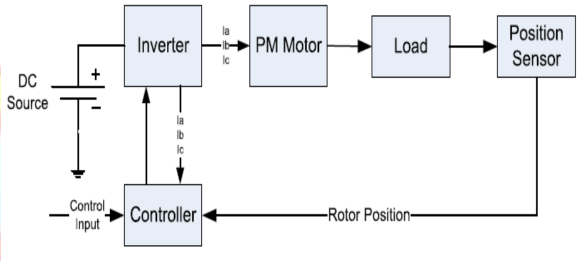

Fig.1 Drive System Schematic

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.

A. Speed Sensor less Direct Torque Control (DTC)

Schematic diagram of speed sensorless DTC control for SPMSM based on EKF is shown as Fig.2. Switch voltage vector selection is shown as TABLE I.

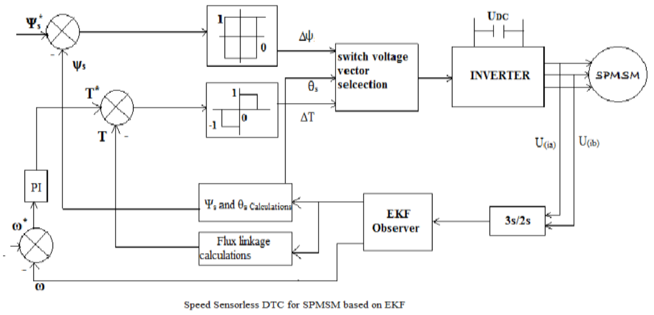

Fig.2 Speed sensor less DTC for SPMSM for based on EKF

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}

B. 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.

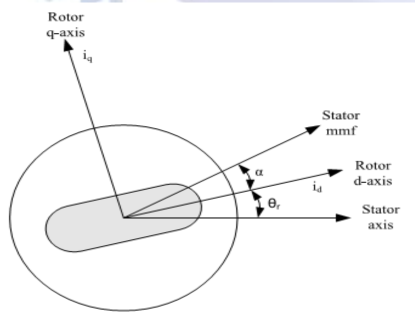

Fig. 3 Motor axis

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:

$$V_q = R_s i_q + \omega_r \lambda_d + p\lambda_q \qquad 3.1$$

$$V_d = R_s i_d - \omega_r \lambda_q + p\lambda_d \qquad 3.2$$

Flux Linkages are given by

$$\lambda_q = L_q i_q \qquad 3.3$$

$$\lambda_d = L_d i_d + \lambda_f \qquad 3.4$$

Substituting equations 3.3 and 3.4 into 3.1 and 3.2

$$V_q = R_s i_q + \omega_r \left(L_d i_d + \lambda_f\right) + pL_q i_q \qquad 3.5$$

$$V_d = R_s i_d - \omega_r L_q i_q + p\left(L_d i_d + \lambda_f\right) \qquad 3.6$$

Arranging equations 3.5 and 3.6 in matrix form

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + pL_q & \omega_r L_d \\ -\omega_r L_q & R_s + pL_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ p\lambda_f \end{pmatrix} \qquad 3.7$$

The developed torque motor is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \qquad 3.8$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \qquad 3.9$$

Solving for the rotor mechanical speed from equation 3.9

$$\omega_m = \int \left(\frac{T_e - T_L - B\omega_m}{J}\right) dt \qquad 3.10$$

And

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \qquad 3.11$$

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

C. 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

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

Convert Vdqo to Vabc

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

D. 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. $\lambda_f = L_{dm} i_f$

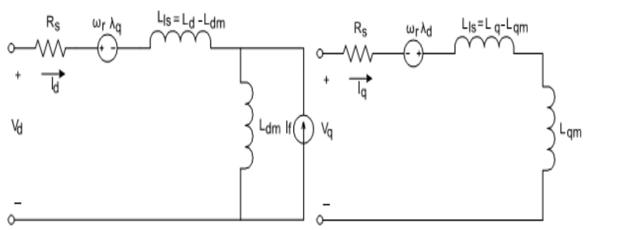

Fig.4.Permanent magnet motor electric circuit without damper windings

IV. SIMULINK 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,

A. 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.

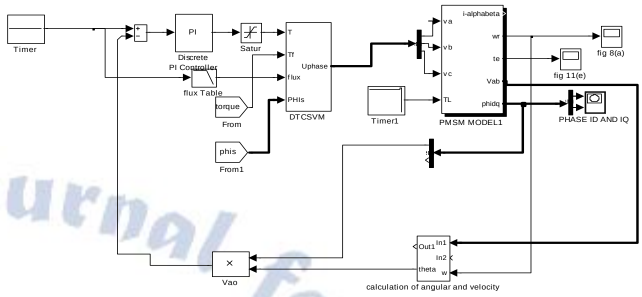

Fig 5: Simulation diagram for PMSM drive for PI Control

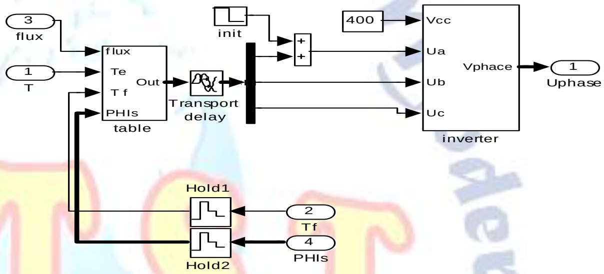

Fig 6: Simulation diagram for DTCSVM

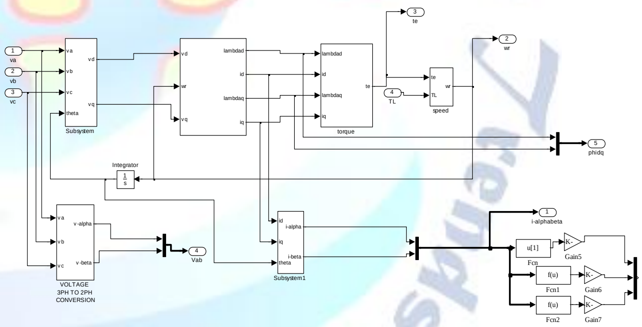

Fig 7: Simulation diagram for PMSM model

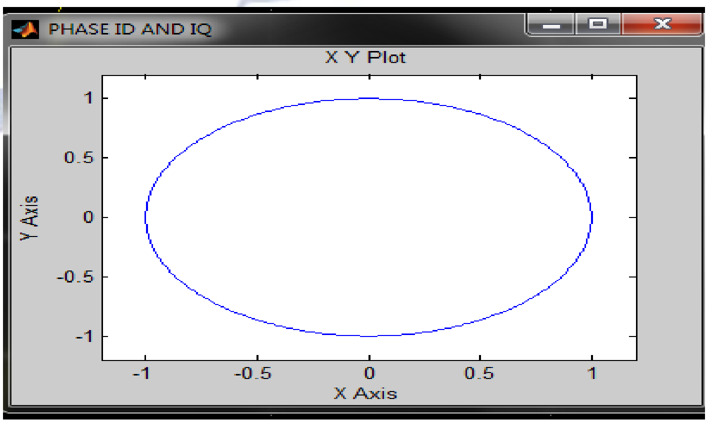

Fig 8: Simulation results for flux linkages for PI Control

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

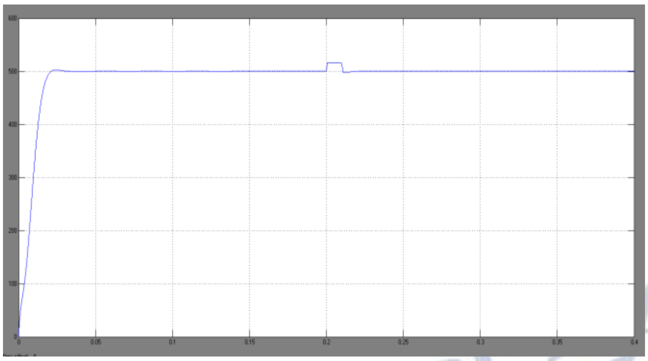

Fig 9: Simulation results for speed of PMSM drive for PI Control

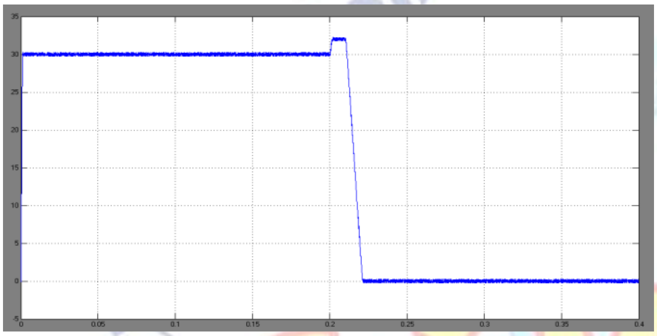

Fig 10: Simulation results for torque of PMSM Drive for PI control

B. SMC Control:

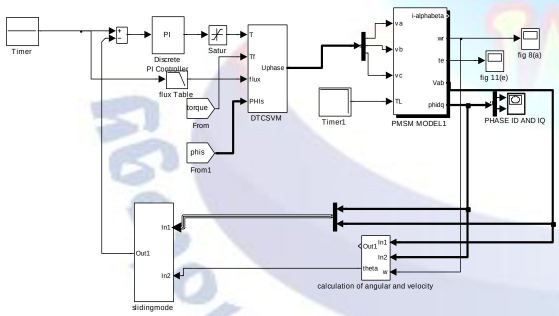

Fig 11: Simulation diagram for PMSM drive for SMC Control

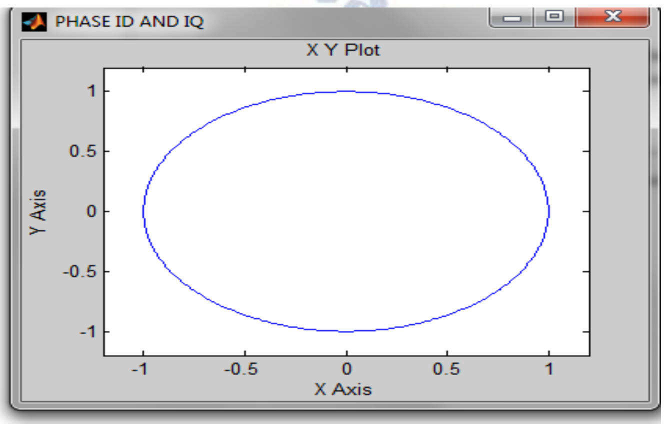

Fig 12: Simulation results for flux linkages for SMC Control

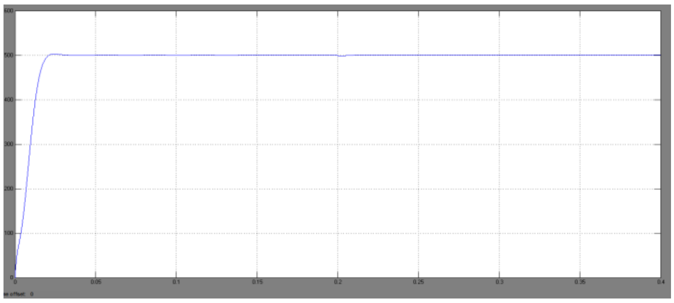

Fig 13: Simulation results for speed of PMSM drive for SMC Control

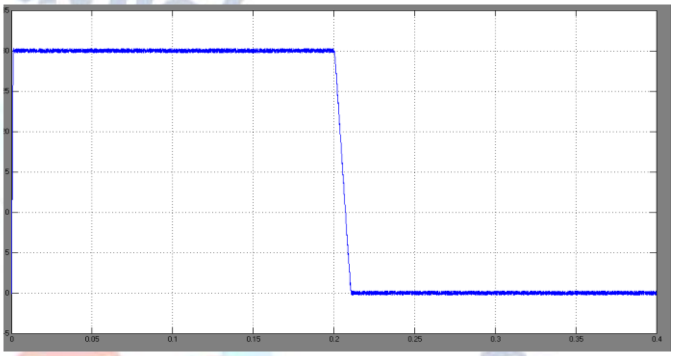

Fig 14: Simulation results for torque of PMSM Drive for SMC control

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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