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Sliding Mode Speed Control of Permanent Magnet Synchronous Motor

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Abstract: This paper deals with the sliding mode speed control(SMSC) of permanent magnet synchronous motor(PMSM). Sliding mode controller is an advanced technique to control the electrical Drive. By using this controlling technique, transient& steady state response can be improved compared with the conventional PI controller. In this paper, the rotor position of motor is tracked through outer speed loop and current through the inner current loop to control the PMSM. The entire SMC speed control of PMSM is designed in MATLAB (SIMULINK).

Keywords: SMSC, PMSM, MATLAB (SIMULINK), PI Controller.

1. INTRODUCTION

Sliding mode controlling technique is used to implement for then on linear systems. This SMC improves the system performance by continuous switching of variable parameters, and then it reaches the system to steady state condition.

The synchronous machine, with its conventional field excitation in the rotor is replaced with permanent magnet those machines we call those machines as permanent magnet synchronous machine.

The PMSM was designed in two ways on the basis of direction of field flux. If the flux direction is along with the rotor of machine then that flux is said to be radial field flux. If it is in parallel with the rotor of machine then it said to be axial field flux[1][2]. The radial field Permanent Magnet Machine usage is more in industry due to low power density & less acceleration compared with axial field machine. In the view of construction PMSM is mechanically robust and can be suited for high speed applications.In this paper, the permanent PMSM is designed with field oriented control of motor by keeping the torque of motor as constant along with flux weaking regions are controlled by the closed loop of Sliding Mode Speed Control

2. DYNAMICAL MODELING OF PMSM

We write the mathematical equations of any machine, it should have three stator voltage equations and three rotor voltage equations but when we go for mathematical modeling of a machine then we have to consider them in two axis representations which are direct axis and quadrature axis. The stator winding is aligned on direct axis, so the inductance offered by the stator winding is said to be direct axis inductance [3].

Similarly the rotating magnets are aligned a quadrature axis with phase shift of 90 degrees, the stator flux inter polar with the rotor, then the inductance of stator is referred to rotor as quadrature axis inductance.

$$L_q > L_d$$

Therefore, dynamic modeling of PMSM was done in d-q axis which are developed on rotor reference frame [3].The equations of stator flux linkage are

$$V_{qs}^r = R_q i_{qs}^r + P\lambda_{qs}^r + W_r\lambda_{qs}^r \qquad (1)$$

$$V_{ds}^r = R_d i_{ds}^r + P\lambda_{ds}^r - W_r\lambda_{ds}^r \qquad (2)$$

Where R_q and R_d are the quadrature and direct axis winding resistances, which are equal to as Rs.

The rotor reference frames on q and d axes of stator flux linkages are

$$\lambda_{qs}^r = L_s i_{qs}^r + L_m i_{qr}^r \qquad (3)$$

$$\lambda_{ds}^r = L_s i_{ds}^r + L_m i_{dr}^r \qquad (4)$$

but the self inductances of the stator q and d axes windings are equal to Ls only when the rotor magnets have an arc of electrical 180 degree. The inductance of the q axis winding is Lq at this time. As the rotor magnets and stator q and d axis windings are fixed in space that the winding inductance do not change in rotor reference frames is to be noted. The stator flux linkages in the q and d axes, the currents in the rotor and stator are required. The permanent magnet excitation can be modeled as a constant current source, i_{fr}. The rotor flux is along the d axis, so the d axis rotor current is i_{fr}[2] .The q axis current in the rotor is zero, because there is no flux along this axis in the rotor , then the flux linkages are written as

$$\lambda_{qs}^r = L_q i_{qs}^r \qquad (5)$$

$$\lambda_{ds}^r = L_d i_{ds}^r + L_m i_{fr} \qquad (6)$$

where L_m is the mutual inductance between the stator and rotor magnets. Substituting these flux linkages into stator voltage equations gives the stator equations as

$$V_{qs}^r = \left(R_q + PL_q\right)i_{qs}^r + W_r L_d i_{ds}^r + W_r\lambda_{qs}^r \qquad (7)$$

$$V_{ds}^r = -W_r L_q i_{qs}^r + (R_d + PL_d)i_{ds}^r \qquad (8)$$

When the motor was rotor reference frames, the d-q axis of stator windings are referred to rotor reference, then they

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run at rotor speed [1][2]. The electromagnet torque is given by

$$T_e = 1.5\left(\frac{P}{2}\right)(\lambda_{ds}^r i_{qs}^r - \lambda_{qs}^r i_{ds}^r) \quad (9)$$

Which, upon substitution of the flux linkages in terms of the inductances and currents are

$$T_e = 1.5\left(\frac{P}{2}\right)\left(\lambda_{af} i_{qs}^r + \left(L_d - L_q\right) - i_{qs}^r i_{ds}^r\right) \quad (10)$$

Where the rotor flux linkages that link the stator are

$$\lambda_{af} = L_m i_{fr} \quad (11)$$

3. SLIDING MODE CONTROL

Sliding mode control is a latest development technique applicable to the non –linear systems. To utilize the control law to drive, the system should need the pre-specified parameters in the state space to sustain the controlling system state trajectory on the surface.

There are two phases of phase trajectory of a sliding mode to the system. The first phase is preferred to elevate the sliding surface, with this phase the system is limited to the dynamic conditions of the sliding surface system. In this phase, the trajectory starts at anywhere of the system on the phase which reaches the sliding surface at finite time [6]. Because of the reaching the sliding surface, it is said to be reaching phase of the system. The second phase is developed to control the trajectory of drive of the system state to surface which can be intercepted throughout the surface of the system. To implement the second phase on the system a Lyapunov method is approached. In the second phase, the state trajectory moves towards the origin with the sliding surface. This sliding surface in the second phase never goes away from it, so it is said to be sliding phase of the system. The first phase of the system is sensitive because it responses to the external disturbances and variable parameters but whereas the second phase does not get affected with any disturbance outside of the system[9].Reaching Phase and sliding phase are the two phases of sliding mode. A trajectory of reaching phase in the system moves to sliding mode and sliding phase of trajectory stays on the sliding mode at any time [10]. In both the phases the system has to obey two conditions

1. When it reaches the sliding mode, reaching phase condition has to be satisfied by trajectory.
2. It has to continue the existing condition throughout the sliding phase without changing its position.

The ultimate objective of the system is to force the trajectory on to the sliding surface, 'S' and it should reach towards origin. This origin is the coordinate axes which have to be maintained as state equilibrium.

Consider a non linear system with single input as

$$X = A(x,t) + B(x,t)u + D \quad (12)$$

Then the states of the system are,

$X = [\dots\dots\dots\dots]$

Where, D =external disturbances
B =uncertainty in input
u =control input

A sliding surface is represented as

$$S = C^T X \quad (13)$$

Where, 'C' is designed by using pole placement method which is sliding surface parameter. A major drawback in non linear system is chattering, which is switching surface get inherent to inertia of velocity. If the trajectory of motion and the velocity of the system with which the switching surface is attained can be controlled then the dynamic characteristics of the trajectory can be improved. A Reaching Law approach is employed, for convergence of the state trajectory onto the sliding surface by control of the dynamic characteristics. The Reaching Law approach directly specifies the dynamics of the switching surface during the reaching phase. The reaching law approach can be represented as

$$\dot{S} = -\varepsilon sgn(S) - Kf(s) \quad (14)$$

Where the gains €>0, K >0 Signum function sgn(s) is defined as Where f(s) =fun(s)

$$sign(s) = \{(1 \quad if\ s > 0; \quad (-1 \quad ifs < 0)\} \quad (15)$$

To satisfy the reaching phase of sliding mode of the system through reaching condition which are obeyed by, Lyapunov stability of second theorem. Lyapunov, [11][12] has two methods for demonstrating stability. The second method is generic and easy to use Lyapunov function V(x) which has an analogy to the potential function of classical dynamics. The following are the point of equilibrium for a system at x=0. [15][14]Let us assume a function

$V(x): R^n \rightarrow R$ such that

- $V(x) \geq 0$ this gives positive definite, with equality if and only if.
- $\frac{d}{dt}V(x) \leq 0$this gives negative semi definite, with equality not constrained to only x= 0.

When the system under goes through the reaching phase depends on the uncertainty of the system and reaching law which is selected, the reaching law takes very smaller duration for reaching time which are affected by uncertainties of reaching phase. Then the sliding mode system is reached faster Here the exponential reaching law approach is -€sgn(s) – Ks

The velocity of the system changes gradually and it approaches the switching surface in the exponential reaching law control technique. The trajectory doesn't reach the switching surface in limited time. Thus sliding mode is no longer reached. When ' S' approaches to zero, the velocity '€' should not be zero for the system to converge in a finite limited time. To determine the parameters € and K, Slotine for a tracking problem was followed with below equation [8]

$$K = \frac{(BR+D+Y)}{(1-B)} \quad (16)$$

Where,$^{\eta}$= A positive real number

$$R = (\dot{X_{ef}}) - f - e \quad (17)$$

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Where,η= A positive real number
Where, e =desired value-actual value

If the trajectory started at a point, then the time taken by the trajectory to reach at S =0 is given as,

$$t_{reach} \leq \frac{1}{\varepsilon}\ln\left(\frac{(\varepsilon|s(0)|+\gamma)}{\gamma}\right) \qquad (18)$$

The magnitude of K specifies the discontinuity in the control law. Since the reaching law meets the sliding mode reaching condition, the sliding mode controller parameters are not limited by the system parameters.

4. DESIGN OF SLIDING MODE SPEED CONTROL WITH PMSM

A PI controller is sufficient for many industrial applications of PMSM because based on the proper selection of gain& time constants of the controller, the closed loop operation of speed controller [5][13] is optimistic and said to be linear system when

$$i_{ds}^{r} = 0$$

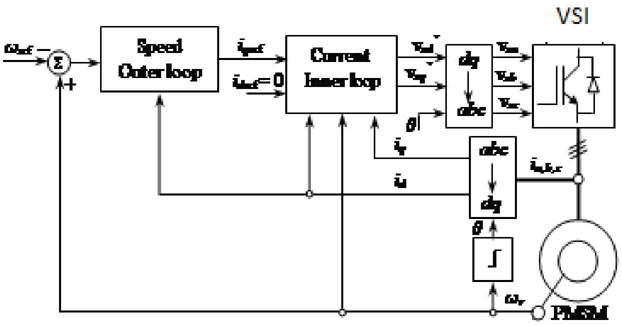
When we go for SMSC, we operate with two closed loops which are speed loop &current loop as shown in below fig. Speed loop controller are the outer loop controller of motor which minimizes by continuous variable constants, gamma(γ) and zeta(ζ) to get the desired speed under closed loop operation of PMSM where positive constants are varied for outer speed loop equation is

$$V = L(\propto sgn(s_1) + \beta s_1 + (d\acute{\imath})/dt + \in + (\acute{\imath} - e_1)R \qquad (19)$$

The output from the speed controller is fed as input to the current controller loop. Current loop controller are the inner loop controller of motor which minimizes by continuous variable constants, alpha(α) and beta (β) to get the current under closed loop operation of PMSM[6][7] where positive constants are varied for inner current loop equation is

$$T = \left[\gamma sgn(s_2) + \xi s_2 + \frac{d\acute{w}}{dt}\right] + T_L + (\acute{w} - e_2)B \qquad (20)$$

4.1Block Diagram of the Sliding Mode Controller with PMSM



5. SIMULATION RESULTS FOR SLIDING MODE SPEED CONTROL OF PMSM

The proposed SMC of PMSM drive is modeled in Mat lab- Simulink. PMSM is modeled with set of equations on d-q axes and SMC is designed with inner and outer controlled loops [13]. By using this software we can implement modeling, simulating and analyzing of dynamical systems under a graphical user interface [16]. The simulation of SMC using PMSM Controller results are shown below in fig 5.1.

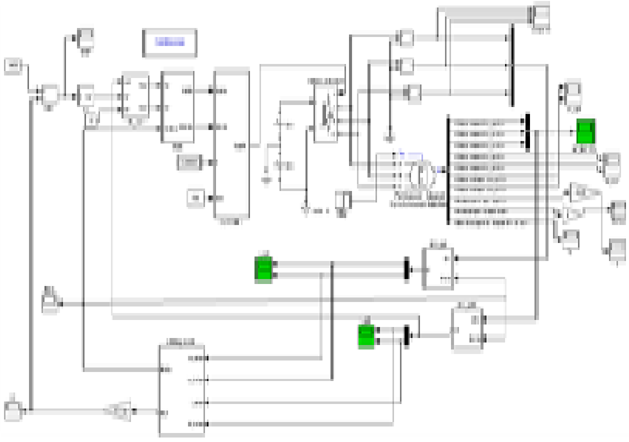


Fig5.1 SIMULINK MODEL OF PMSM WITH SMC CONTROLLER

The detailed data of the motor are rated power: 1.5 kW, rated speed: 1500 rpm, rated current: 4.0 A, number of poles: 4, stator resistance (R): 0.315 Ω/ph., direct axis inductance 8.5mH, quadrature axis inductance 8.5mH, back EMF constant (Kb): 0.615 Vsec/rad, inertia (J):0.8m Kg-m2.Flux Linkage established by magnets is 0.175, Torque Constant is 1.05N-m/A_peak and Voltage constant is 126.966 V_peak. By using MATLAB SIMULINK software, SMC of PMSM was designed.

The various performance results are rotor speed response, Electromagnetic Torque, rotor angle and three phase stator currents of the motor are shown in below figures. The responses of the PMSM drive system are discussed with the reference speeds of 1000 rpm.

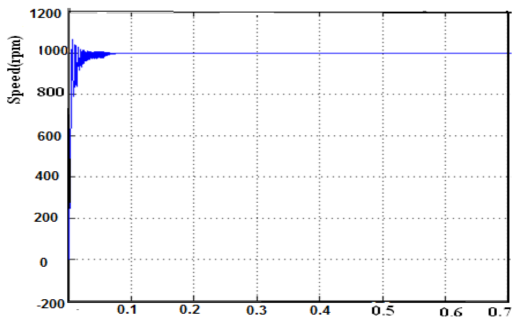


Fig 5.2 Rotor speed of PMSM motor using SMC Controller

From the figure it is clear that the starting speed of the PMSM drive using SMC controller is less. The speed fluctuates for a period less than 0.05seconds. PMSM motor attains stability i.e., the settling time of the speed curve is nearly 0.05seconds.

The Electromagnetic torque developed by PMSM using SMC controller is shown fig 5.3.

As speed is directly proportional to torque, the torque also has pulsating torque less than 0.1seconds. When the speed curve reaches the steady state, then the torque also reaches the steady state at the same instant of time. The torque

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developed by the PMSM motor attains stability nearly at 0.05seconds.

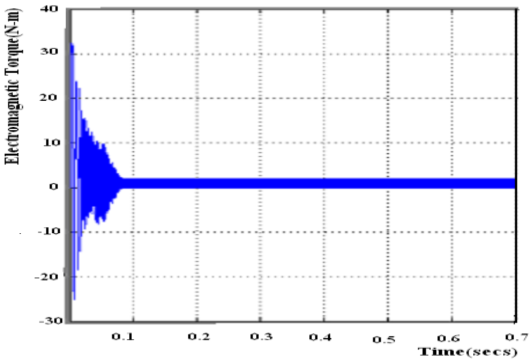

Figure 5.3 Electromagnetic Torque of PMSM motor using SMC Controller

The rotor angle of the PMSM motor drive varies linearly with time. As the time in seconds increases the rotor angle varies accordingly as shown in figure 5.4. The rotor angle curve of the PMSM drive system is shown below. The plot is drawn between rotor angle in (N-m)2 in y-axis and time period in seconds in x-axis. As the time varies, the angle also varies accordingly. For a time change in 0.1 second there will be 100degrees change in rotor angle of PMSM.

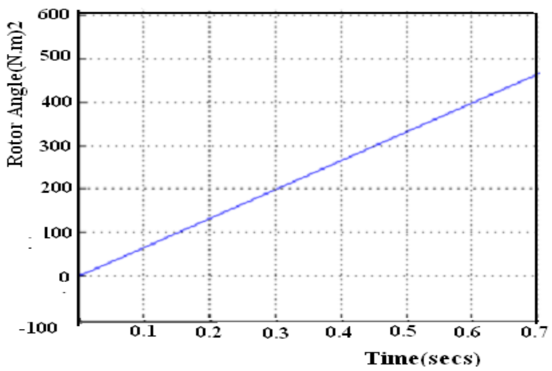

Fig. 5.4 Rotor Angle of PMSM motor using SMC controller

6. CONCLUSION

In this paper sliding mode control (SMC) proposed to speed control of PMSM Then PMSM is modeled after that speed controller is designed. As sliding mode control is based on the system Dynamic characteristics also it took a lack of influence of external disturbances from user as result it worked more useful and results confirms that used sliding mode control for speed control.

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