Sliding Mode Speed Controller for Vector Controlled Induction Motor

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Abstract - ***In this work, an induction motor drive with a sliding mode controller is presented. In the design by using the measured stator terminal voltages and currents, the rotor speed is estimated. The estimated speed is used as feedback in an indirect vector control system achieving the speed control without the use of any sensor. The sliding mode controller is simulated under various conditions and a comparison of the results with the PI controller has been presented here. Lyapunov method is used for keeping the nonlinear system under control for sliding mode controller. This is a method in which a higher order system is transformed into first-order system in sliding mode approach. In this way, simple control algorithm is applied for induction motor, which is very straight forward and robust.***

Key Words: *IFOC, Induction motor, stationary reference frame, Sliding mode control.*

1. INTRODUCTION

Because of its good self-starting capability, simple and ruggedness, low cost and reliability etc. the induction motor is the most frequently used motor type in the industry. Along with variable frequency AC inverters, induction motors are used in many adjustable speed applications which do not need faster dynamic response [1]. Performance of induction motors can be achieved as good as that of DC or brushless DC motors by using vector control technique. To vary the speed of an induction motor over a wide range, this method is used called vector control. In the vector control technique, a complex current is synthesized from two quadrature components, one of which controls the torque production in the motor, and another which is responsible for the flux level in the motor. There are various advantages of vector control such as speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed [2].

2. MODELING OF INDUCTION MOTOR IN STATOR REFERENCE FRAME

Generally, an IM can be described uniquely in arbitrary rotating frame, stationary reference frame or synchronously rotating frame. By using generalized way the required transformation in voltages, currents, or flux linkages is derived. Flux linkages as variables can be used to represent the Equations of the induction motor in stationary reference frame of reference. By this number of variables in the dynamic equations is reduced. The flux linkages are continuous even when the voltages and currents are discontinuous. The stator and rotor flux linkages in the stator reference frame are defined as [10],

$$\left.\begin{aligned}\Psi_{qs} &= L_s i_{qs} + L_m i_{qr}\\ \Psi_{ds} &= L_s i_{ds} + L_m i_{dr}\\ \Psi_{qr} &= L_r i_{qr} + L_m i_{qs}\\ \Psi_{dr} &= L_s i_{dr} + L_m i_{ds}\\ \Psi_{qm} &= L_m (i_{qs} + i_{qr})\\ \Psi_{dm} &= L_m (i_{ds} + i_{dr})\end{aligned}\right\} \qquad \textbf{\textit{(1)}}$$

Stator and rotor voltage and current equations are as follows

$$\left.\begin{aligned}v_{ds} &= R_s i_{ds} + \rho\Psi_{ds}\\ v_{qs} &= R_s i_{qs} + \rho\Psi_{qs}\\ v_{dr} &= R_r i_{dr} + \omega_r\Psi_{qr} + \rho\Psi_{dr}\\ v_{qr} &= R_r i_{qr} - \omega_r\Psi_{dr} + \rho\Psi_{qr}\end{aligned}\right\} \qquad \textbf{(2)}$$

Since the rotor windings are short circuited, the rotor voltages are zero. Therefore

$$R_r i_{dr} + \omega_r\Psi_{qr} + \rho\Psi_{dr} = 0 \qquad \textbf{(3)}$$

$$R_r i_{qr} - \omega_r\Psi_{dr} + \rho\Psi_{qr} = 0 \qquad \textbf{(4)}$$

by solving above equation we get, the following equations [10],

$$\Psi_{ds} = \int (v_{ds} - R_s i_{ds})\mathrm{dt} \qquad (5)$$

$$\Psi_{qs} = \int (v_{qs} - R_s i_{qs})\mathrm{dt} \qquad (6)$$

$$\Psi_{dr} = \frac{-L_r\omega_r\Psi_{qr} + L_m i_{ds} R_r}{R_r + SL_r} \qquad \textbf{(7)}$$

$$\Psi_{qr} = \frac{L_r\omega_r\Psi_{dr} + L_m i_{qs} K_r}{R_r + SL_r} \qquad \textbf{(8)}$$

$$i_{ds} = \frac{v_{ds}}{R_s + SL_s} - \left[\frac{\Psi_{dr} s L_m}{L_r (R_s + SL_s)}\right] \qquad \textbf{(9)}$$

$$i_{ds} = \frac{v_{qs}}{R_s+SL_s} - \left[\frac{\Psi_{qr} SL_m}{L_r(R_s+SL_s)}\right] \qquad (10)$$

The electromagnetic torque of the induction motor in stator reference frame is given by,

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}(i_{qs}\Psi_{dr} - i_{ds}\Psi_{qr}) \qquad (11)$$

3. VECTOR CONTROL OR FIELD ORIENTED CONTROL (FOC)

Dynamic performance is improved of an IM is enabled due to the development of Vector Control analysis. Using vector control strategy, the torque and flux components can be controlled independently like dc motor [2]. To analyses of vector control, we have developed a dynamic model of the induction motor. For that we need to convert the 3-ϕ quantities into 2-axes system called the d-axis and the q-axis. This type of conversion is called axes transformation. The d-q axes can be chosen to be stationary or rotating. Then, the rotating frame can either be the rotor oriented or magnetizing flux oriented. However, synchronous reference frame where the d-axis is aligned with the rotor flux is found to be the most convenient technique for analysis point of view [8].

3.1 Principle of Vector Control

The basic principles of vector control implementation can be explained with the help of fig. 1, where synchronously rotating reference frame machine model is represented. The inverter is not included in the figure, assuming that its current gain is unity. Command currents i^*_a, i^*_b, and i^*_c from the controller used to generate currents i_a, i_b and i_c as dictated. The i_{ds} and i_{qs} components are obtained by the machine terminal phase currents i_a, i_b and i_c are by using $3\phi/2\phi$ transformation [8].
They are then converted to synchronously rotating reference frame by the unit vector components $\cos\theta_e$ and $\sin\theta_e$ before applying to the d-q machine model. The controller makes two stages of inverse transformation so that the control currents i^*_{ds} and i^*_{qs} corresponds to the machine currents i_{ds} and i_{qs} respectively. Also the Correct alignment of current i_{ds} with the flux vector Ψ_r and i_{qs} perpendicular to it is ensured by unit vectors.
The vector control method is broadly classified into two types-

- Direct vector control
- Indirect vector control(IFOC)

In indirect vector control strategy rotor flux vector is estimated using the field oriented control equations (current model) requiring a rotor speed measurement. Due to its implementation simplicity, indirect vector control is more popular than direct vector control and has become the industrial standard [7].

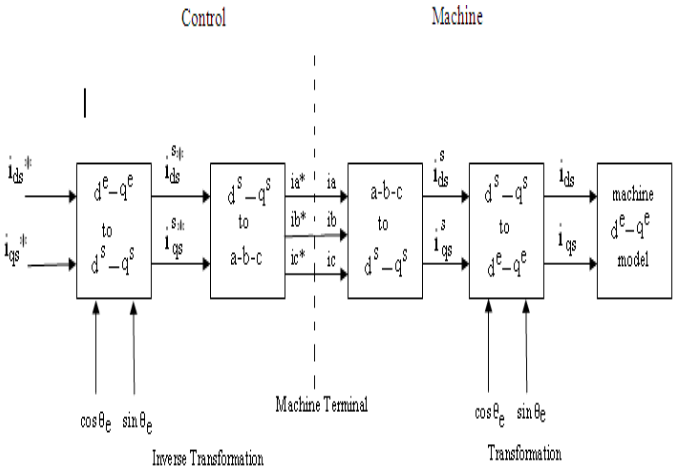

Fig-1: Vector control implementation principle with machine d-q model [5].

4. INDIRECT FIELD ORIENTED CONTROL (IFOC)

In the indirect field oriented control method, by using summation of the rotor speed and slip frequency, the rotor flux angle is calculated, hence the unit vectors $\cos\theta_e$ and $\sin\theta_e$ are obtained indirectly [2]. The direct vector control method and the indirect vector control is essentially same except that the rotor angle is generated indirectly using the measured speed ω_e and the slip frequency ω_{sl}.

Indirect vector control is explained in the phasor diagram shown in figure 2. On the de axis the stator flux component of current i_{ds} should be aligned and on the qe axis the torque component of current i_{qs} should be aligned.

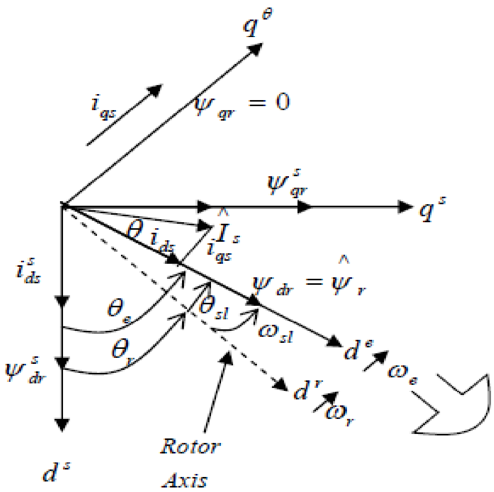

Fig-2: Phasor diagram of IFOC method of Induction Motor [5].

To achieve vector control the flux component (d-axis component) of stator current i_{ds} is aligned in the direction of rotor flux, Ψ_r, and the torque component of stator current i_{qs} is aligned in direction perpendicular to it. At this condition [5]:

$$\Psi_{qr} \text{ and } \frac{d\Psi_{qr}}{dt} \tag{12}$$

$$\Psi_{dr} = \Psi_r = rotor\ flux \tag{13}$$

It is necessary to take (12,13) into considerations for implementation of the indirect vector control strategy.

5. SLIDING MODE CONTROLLER

The sliding mode control technique is developed from Variable Structure Control(VSC) [12]. In variable structure control technique, a surface is defined and the system that we need to control is forced to that surface till the system slides to the desired equilibrium point. To keep the nonlinear system under control for sliding mode controller, lyapunov stability method is applied [5]. Structure of sliding mode controller for induction is shown in figure 3. Designing steps for sliding mode controller of induction motor is given below.

The mechanical equation of an induction motor is given by [7],

$$J\dot{w}_m + Bw_m + T_L = T_e \tag{14}$$

Electromagnetic torque for vector controlled can be simplified as;

$$T_e = \frac{3}{4} p \frac{L_m}{L_r} \psi_{dr}\, i_{qs} \tag{15}$$

Then the mechanical equation becomes,

$$\dot{\omega}_m + a\omega_m + f = bi_{qs} \tag{16}$$

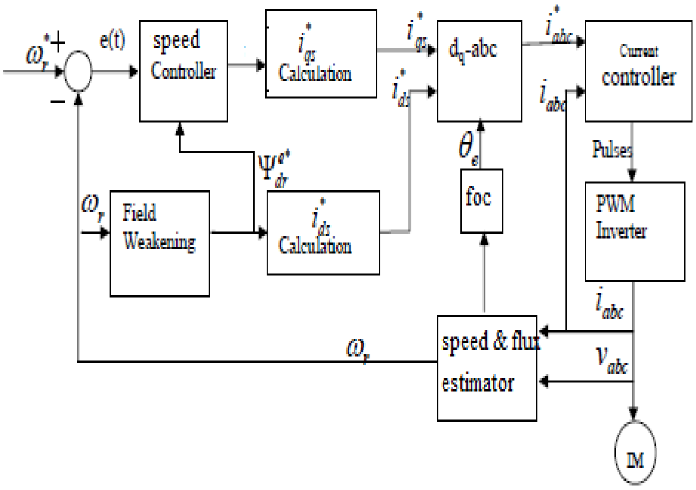

Fig-3: Block diagram of sliding mode control for induction motor [13].

Where the parameters are defined as

$$a = \frac{B}{J},\ b = \frac{K_T}{J},\ f = \frac{T_L}{J} \tag{17}$$

Previous mechanical Equation with uncertainties as follows

$$\dot{\omega}_m = -(a + \Delta a)\omega_m - (f + \Delta f) + (b + \Delta b)\, i^*_{qs} \tag{18}$$

Let us define the tracking speed error as follows

$$e(t) = \omega_m(t) - \omega^*_m(t) \tag{19}$$

Taking the derivative of the previous equation with respect to time yields [7]:

$$\dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}^*_m(t) = -ae(t) + u(t) + d(t) \tag{20}$$

Where following terms have been collected in the signal u (t),

$$u(t) = bi^*_{qs} - a\omega^*_m(t) - f(t) - \dot{\omega}^*_m(t) \tag{21}$$

And, the uncertainty terms have been collected in the signal d(t),

$$d(t) = -\Delta a\omega_m(t) - \Delta f(t) + \Delta\, bi^*_{qs} \tag{22}$$

Here the sliding variable S(t) for speed controller is defined with integral component as

$$s(t) = e(t) - \int_0^t (k - a)e(\tau)\,d\tau \tag{23}$$

Where, k is a constant gain.
Then the sliding surface is defined as:

$$s(t) = e(t) - \int_0^t (k - a)e(\tau)\,d\tau = 0 \tag{24}$$

The sliding mode controller for speed is designed as [6,7],

$$u(t) = ke - \beta sgn(s) \tag{25}$$

where β is switching gain, it must be chosen so that β ≥ d(t) for all time.

Consider the Lyapunov function

$$v(t) = {}^1\!/_2\,(s(t)^2) \tag{26}$$

As per Lyapunov's direct method, if $v(t)$is positive definite, $\dot{v}(t)$ is negative definite and $v(t)$tends to infinity as $s(t)$ tends to infinity then equilibrium at the origin $s(t) = 0$ is globally asymptotically stable. Lyapunov method is used for keeping the nonlinear system under control for sliding mode controller [13]. When the sliding mode occurs on the sliding surface, then, $s(t) = \dot{s}(t) = 0$ and the tracking error e(t) converges to zero exponentially.

Finally, the torque current i^*_{qs} command, can be obtained directly substituting u (t) in the previous equation [7].

$$i^*_{qs} = \frac{1}{b}\left[ke - \beta sgn(t) + a\omega^*_m(t) + \dot{\omega}^*_m(t) + f\right] \tag{27}$$

Thus, sliding mode control solves the speed tracking problem for the induction motor.

6. SIMULATION RESULTS

The simulation of indirect vector controlled induction motor is done using squirrel cage induction motor. The simulation is done with PI controller and sliding mode controller. For simulation MATLAB /SIMULINK is used to simulate induction motor model and controllers. The reference speed of 100 rad/sec is considered for the drive system. Fig- 4 shows speed responses of PI and SMC controllers for No Load.

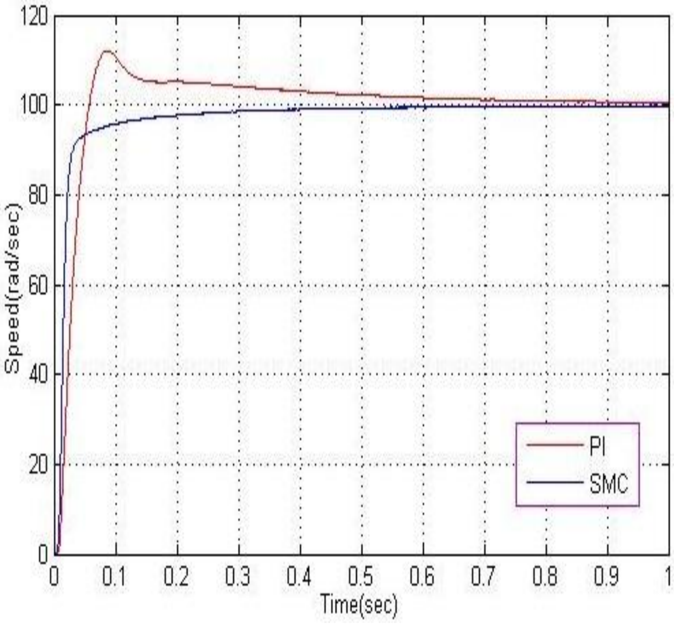

Fig -4: Speed responses of PI and SMC controllers for No Load.

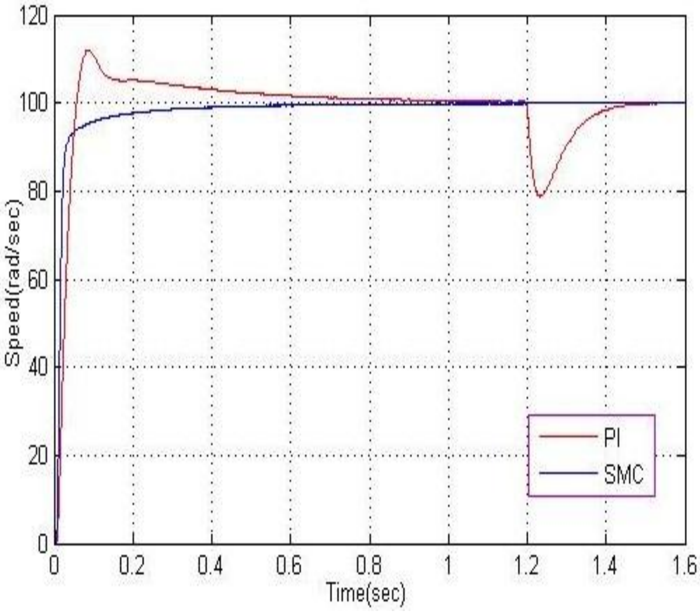

Fig -5: Speed responses of PI and SMC controllers for 15 N-m Load.

Fig- 5 shows speed responses of PI and SMC controllers for 15 Load applied after 1.2 sec. At start no load is applied on the motor and after some time torque load is applied. Figure shows that speed response of the PI controller is affected by the torque load.

Fig- 6 shows speed responses of PI and SMC controllers for step changes in reference speed. From figure it clear that the sliding mode controller gives better dynamic response compared with PI controller for steps changes in reference speed.

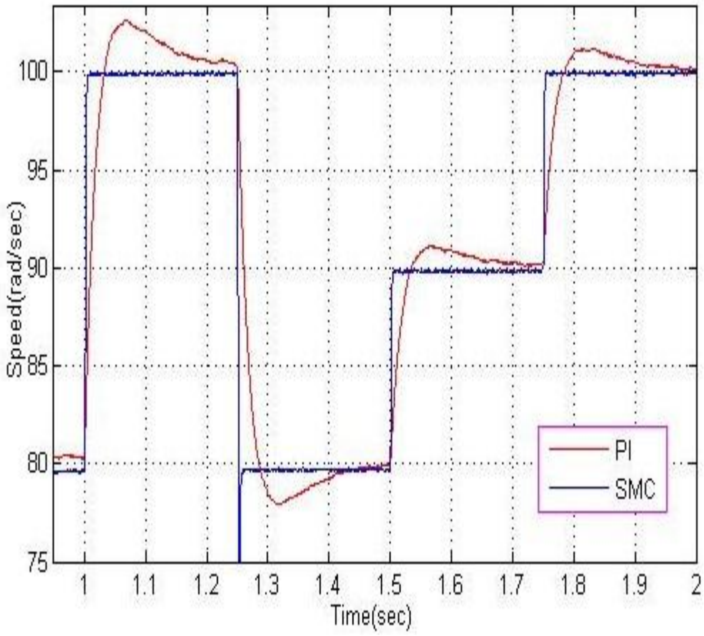

Fig -6: Speed responses for step changes of PI and SMC controllers.

Comparison of PI controller and sliding mode controller in term of maximum overshoot, rise time and settling time without any load is given in the table- 1. Also in the table-2 performance of PI controller and sliding mode controller for change in load torque is compared in terms of percentage of rotor speed drop after load applied.

Table -1: Comparative Results of PI and SMC.

Controller	%max. overshoot (M_p)	Rise Time (T_r)	Settling Time (T_s)
PI Controller	11.89	38.7 msec	0.8021 sec
Sliding Mode Controller	-	22.2 msec	0.0362 sec

Table -2: Performance of Controllers for change in Load at 1.5 sec after simulation begins.

Controller	%drop rotor speed for Load of 10 N-m	%drop rotor speed for Load of 15 N-m
PI Controller	14.11	21.31
Sliding Mode Controller	0.036	0.071

7. CONCLUSIONS

The Sensorless control of induction motor using vector control technique is simulated on MATLAB to apply the control techniques. Performance of sliding mode controller and PI controller on the induction motor drive has been observed. By using various simulations the performance of the controllers has been examined. Under the case such as load torque variations, the designed sliding mode controller gives satisfactory response, as well as have good trajectory tracking performance. Comparative study conclude that the sliding mode controller gives better dynamic behavior than PI controller. And the comparison between the speed control of an induction motor against parameter variations and external load torque by the sliding mode controller and PI controller clearly shows that the sliding mode controller gives better performance than the PI controller.

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