Comparative Study for Speed Control of Three-Phase Induction Motor Drive Using PI and Sliding Mode Controller

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Abstract: - Induction motor drives are now extensively used in position and variable speed control applications due to simple construction, low weight and advances in power electronics and micro-processors. This paper is concerned with the comparative study for speed control of induction motor with Proportional plus Integral (PI) and Sliding Mode Controller (SMC). PI controller is simple but sensitive to parameter variations and external disturbance. Due to the robustness of Sliding Mode Control, especially against parameters variations and external disturbances, and also its ability in controlling linear and nonlinear systems; a three phase induction motor sliding mode speed controller technique is proposed in this paper. Performance of these controllers has been verified through simulation results using MATLAB/SIMULINK software. The simulation results showed that SMC was a superior controller than PI controller for speed control of an induction motor.

Keywords: - d-q axis frame, Induction motor drive, MATLAB simulation, PI controller, Sliding mode controller

I. INTRODUCTION

Induction motors have been gradually utilized in place of DC motors due to high reliability, low weight and simple construction. Moreover, because of the advances in power electronics and micro-processors, induction motor drives used in position and variable speed control have become more attractive in industrial processes such as robot manipulators, steel & textile mills, plant automation etc. However, since the induction motors are characterized by highly non linear, complex and time varying dynamics and inaccessibility of some of the states and outputs for measurement, its control is considered as a challenging engineering problem. In the past years, many techniques for the control of induction motor have been investigated. Induction motors are generally controlled by conventional PI controllers, since they can be designed easily, have low cost, inexpensive maintenance and effectiveness. With the classical PI controller applied to control an Induction motor, a good performance characteristic of the controller can be obtained, if all the model parameters of induction motor and operating conditions such as external load torque, disturbances are exactly known. However, the performance of PI controller for speed or position regulation degrades under external disturbances and machine parameter variations. Furthermore, the PI controller gains have to be carefully selected in order to obtain a desired response. This makes the use of traditional PI controller a poor choice for industrial variable speed drive applications where higher dynamic control performance with little overshoot and high efficiency is required.

The above issues can be solved by advanced control techniques such as sliding mode control. Sliding mode control was first proposed in early 1950's in Soviet Union by Emelyanov and several co-researchers. After seventies, SMC has become more popular control strategies and powerful control technology to deal with the nonlinear uncertain system. Sliding mode control is one of the effective non linear robust control approaches since it provides system dynamics with an invariant property to uncertainties once the system dynamics are controlled in the sliding mode. It provides a systematic approach to the problem of maintaining stability and satisfactory performance in the presence of modeling imperfections. The salient feature of this controller is that it is computationally simple as compared to adaptive controllers with parameter estimation and also robust to parameter variations. But the sudden and large change of control variables leads to high stress for the system to be controlled that result in chattering of the system states which the limitation of this control technique is. Several solutions have been proposed in the research literature to eliminate or reduce the chattering.

II. STATE SPACE MODEL OF INDUCTION MOTOR

An induction motor model is used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period. These calculated voltage equations are then synthesized using the space vector modulation. A dynamic model of the induction motor subjected to control must be prepared to understand and design the vector controlled drives. Such a model can be obtained by stationary Reference Frame theory of electrical machines as explained. Reference frames rotating at an arbitrary speed are here after called arbitrary reference frames. The relationship between the stationary reference frames denoted by d and q axes and the arbitrary frames denoted by dc and qc axes.

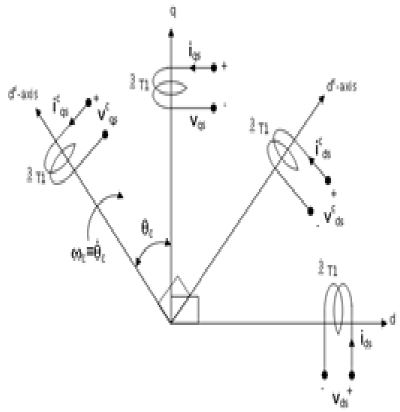

Fig 1 Stationary and arbitrary reference frame

The induction motor model in arbitrary reference frame is obtained as

$$\begin{bmatrix} V^c_{qs} \\ V^c_{ds} \\ V^c_{qr} \\ V^c_{dr} \end{bmatrix} = \begin{bmatrix} R_s + L_sP & \omega_c L_s & L_mP & \omega_c L_m \\ -\omega_c L_s & R_s + L_sP & -\omega_c L_m & L_mP \\ L_mP & (\omega_c - \omega_r) L_m & R_r + L_rP & (\omega_c - \omega_r) L_r \\ -(\omega_c - \omega_r) L_m & L_mP & -(\omega_c - \omega_r) L_r & R_r + L_rP \end{bmatrix} \begin{bmatrix} i^c_{qs} \\ i^c_{ds} \\ i^c_{qr} \\ i^c_{dr} \end{bmatrix}$$

where

$$\dot{\theta}_r = \omega_r$$

The EM Torque is an important output variable that determines such mechanical dynamics of the machine as the rotor position and speed. The above equation can be written as

$V = [R]i + [L]pi + [G]\, \omega_r i + [F]\, \omega_C i$
$Pi = itV = it\,[R]i + it\,[L]pi + it\,[G]\, \omega_r\, i + it\,[F]\, \omega_C\, i$

Where the [R] matrix consists of resistive elements, the [L] matrix consists of the coefficients of the derivative operator p, the [G] matrix has elements that are the coefficients of the electrical rotor speed ω_r, and [F] is the frame matrix in terms of the coefficients of the reference speed ω_C. The term it [R]i gives stator and rotor resistive losses. The term it [F] ω_Ci is the reference frame power and upon expansion comes to be zero because there cannot be a power associated with a fictitious element. The term it[L]pi denotes the rate of change of stored magnetic energy. Therefore, the term left must be equal to the air-gap power which is associated with torque by the following expression:

$$\omega_m\, Te = Pa = it\,[G]\, i \;\; X \;\; \omega_r$$

Substituting for ω_r in terms of ω_m leads to electromagnetic orque as

$$Te = P/2\ it\,[G]\, i$$

By substituting for [G] from above equation, the EM torque is obtained as

$$T_e = \frac{3}{2}\frac{P}{2} L_m (i^c_{qs} i^c_{dr} - i^c_{ds} i^c_{qr})$$

III. BASIC CONCEPT OF SLIDING MODE CONTROL

It is a nonlinear control method that alters the dynamics of a nonlinear system by application of a high-frequency switching control. The state-feedback control law is not a continuous function of time. Instead, it switches from one continuous structure to another based on the current position in the state space. The multiple control structures are designed so that trajectories always move toward a switching condition, and so the ultimate trajectory will not exist entirely within one control structure. Instead, the ultimate trajectory will slide along the boundaries of the control structures. The motion of the system as it slides along these boundaries is called a sliding mode and the geometrical locus consisting of the boundaries is called the sliding (hyper) surface. Figure 1 shows an example trajectory of a system under sliding mode control.

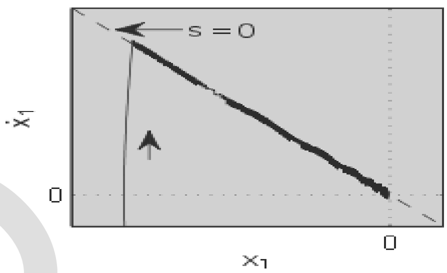

Fig 2 Phase plane trajectory of a system being stabilized by a sliding mode controller

The features of this controller can be compiled as:

- The main strength of sliding mode control is its robustness. Because the control can be as simple as a switching between two states (e.g., "on"/"off" or "forward"/"reverse"), it will not be sensitive to parameter variations that enter into the control channel.
- Since the control law is not a continuous function, the sliding mode can be reached in finite time which is better than asymptotic behavior.
- Sliding mode control gives the optimal controller for a broad set of dynamic systems.

IV. SLIDING MODE CONTROLLER FOR SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

The sliding mode controller design approach usually consists of two steps. First, the sliding or switching surface(s) is designed such that the system motion in sliding mode satisfies design specifications. Second, a control law is designed making the switching surface attractive to the system state. Sliding surface can be either linear or nonlinear. For simplicity, only a linear sliding surface is used in this paper.

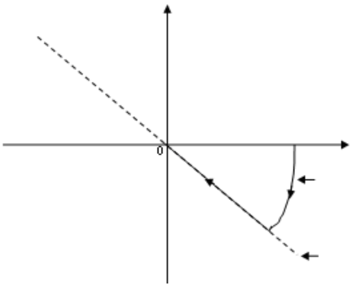

Fig 3 Phase portrait of a sliding motion

Slotine proposed a form of general equation to determine the sliding surface which ensures the convergence of a variable towards its desired value as:

$$s = \left(\frac{d}{dt} + \lambda\right)^{n-1} e$$

where *n* is the system order, e is the tracking error, and *é* is a strictly positive constant that determine the bandwidth of the system. Having chosen the sliding surface at this stage, the next step would be to choose the control law (u) that will allow the error vector (*e*, *é*) to reach the sliding surface. To do so, the control law should be designed in such a way that the following condition, also named reaching condition, is met:

$$s\dot{s} < 0$$

In order to satisfy this condition, the basic discontinuous control law of sliding mode control is given by:

$$u = -K sign(s)$$

where K is a positive constant known as the hitting control gain or parameter, s is the sliding surface, and sign is the signum function defined as:

$$\text{sign (s)} = \begin{cases} 1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases}$$

The discontinuous control law described presents high robustness, insensitive to parameter fluctuations and disturbances. However, using a sign function often causes chattering phenomenon in practice. Several solutions have been proposed in research literature to alleviate the chattering phenomenon. In controller design of induction motor, we consider a second order system

$$\ddot{x}(t) = f(x,t) + u(t)$$

where f(x,t) is generally nonlinear and/or time varying and is estimated as f'(x,t) , u(t) is the control input, and x(t) is the state to be controlled so that it follows a desired trajectory x_d(t) . The estimation error on f(x,t) is assumed to be bounded by some known function F=F(x,t), so that

$$\left|\hat{f}(x,t) - f(x,t)\right| \le F(x,t)$$

We define a sliding variable according to:

$$s(t) = (\frac{d}{dt} + \gamma)\tilde{x}(t) = \dot{\tilde{x}}(t) + \gamma\tilde{x}(t)$$

$$\dot{s}(t) = \ddot{x}(t) - \ddot{x}_d(t) + \gamma\dot{\tilde{x}}(t)$$

$$\dot{s}(t) = f(x,t) + u(t) - \ddot{x}_d(t) + \gamma\dot{\tilde{x}}(t)$$

The approximation of control law u'(t) to achieve s(t)=0 is

$$\hat{u}(t) = -\hat{f}(x,t) + \ddot{x}_d(t) - \gamma\dot{\tilde{x}}(t)$$

To account for the uncertainty in f while satisfying the sliding condition:

$$\frac{1}{2}\frac{d}{dt}(s(t)^2) \le -\eta\left|s(t)\right|, \qquad \eta > 0$$

Take the control law as:

$$u(t) = \hat{u}(t) - k(x,t)\,\mathrm{sgn}(s(t))$$

By choosing k(x,t) large enough, such that

$$k(x,t) = F(x,t) + \eta$$

ensures the satisfaction of following condition:

$$\frac{1}{2}\frac{d}{dt}(s(t)^2) = \dot{s}(t)s(t) = (f(x,t) - \hat{f}(x,t))s(t) - k(x,t)\left|s(t)\right| \le -\eta\left|s(t)\right|$$

$$\eta > 0$$

Hence, we ensure the system trajectory will take finite time to reach the surface S(t), after which the errors will exponentially go to zero

.

V. CHATTERING REDUCTION

An ideal sliding mode exists only when the state trajectory x(t) of the controlled plant agrees with the desired trajectory at every t > t_1 for some t_1 . This may require infinitely fast switching. In real systems, a switched controller has imperfections which limit switching to a finite frequency. The representative point then oscillates within a neighborhood of the switching surface. This oscillation, called chattering, is illustrated on fig 4

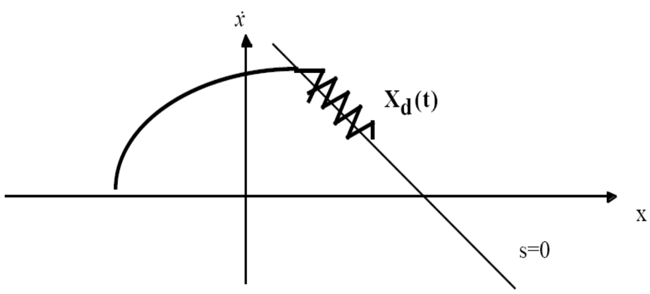

FIG 4 Chattering effect

VI. SIMULATION RESULTS

The induction motor used in this system is three phase, 50 Hz, 50 W, 4 pole, 220 V/3A, 1440 rpm type. Here the overall model of Three-phase Induction Motor with sliding mode control was implemented in MATLAB/Simulink. Simulation results of the SMC were compared with the PI controller. Simulations were based on the facts that whether the sliding mode controller is better and more robust than the PI controller or not. All the parameters are chosen to achieve the superior transient control performance in both the simulation and experimentation considering the requirement of stability, the limitation of control effort, and the possible operating conditions. The results of induction motor drive system with sliding mode controller are compared with the results of the same system with PI controller and their comparative study is given below:

(i) Change in reference speed

The reference speed is changed from 1000 rpm to 1200 rpm at time, t=1sec, and again 1200 rpm to 1500 rpm at time t=3sec. The reference d-axis rotor flux linkage is kept at 0.45 Vsec and load torque is kept at zero. The simulation responses for PI controller and sliding mode controller are given in following figures. From the figures it is clear that in case of sliding mode controller, the speed error of the system comes to zero faster than PI controller.

(ii) Trapezoidal Tracking of reference speed

A periodic trapezoidal reference speed is used to study the tracking performance of the drive system. The command peed is increased linearly from 0 at t=0.6 sec to 157 rad/sec at t=1.1 sec. It is kept constant at 157 rad/sec till t= 2.6 sec, and decreased linearly to zero at t =5.6 sec. The speed tracking performance is studied for both PI and sliding mode controller and the results are compared. Results comparison shows that speed tracking performance of sliding mode controller is much better than PI controller.

(iii) Variation in Load Torque

The response of controllers during variation of load torque is carried which shows that the PI controller speed response is affected by the load disturbance, where as the sliding mode controller have proved its robustness against load variations.

The simulation results show that the SMC realized a good dynamic behaviour of the motor with a rapid rise time and settling time, and had better performance than the PI controller. But the comparison between the speed control of a induction motor by the sliding mode controller and PI controller showed clearly that the sliding mode controller gives better performance than the PI controller against parameter variations and external load torque. The simulation results are shown:

Fig 5(a), (b), (c) and (d) follows:

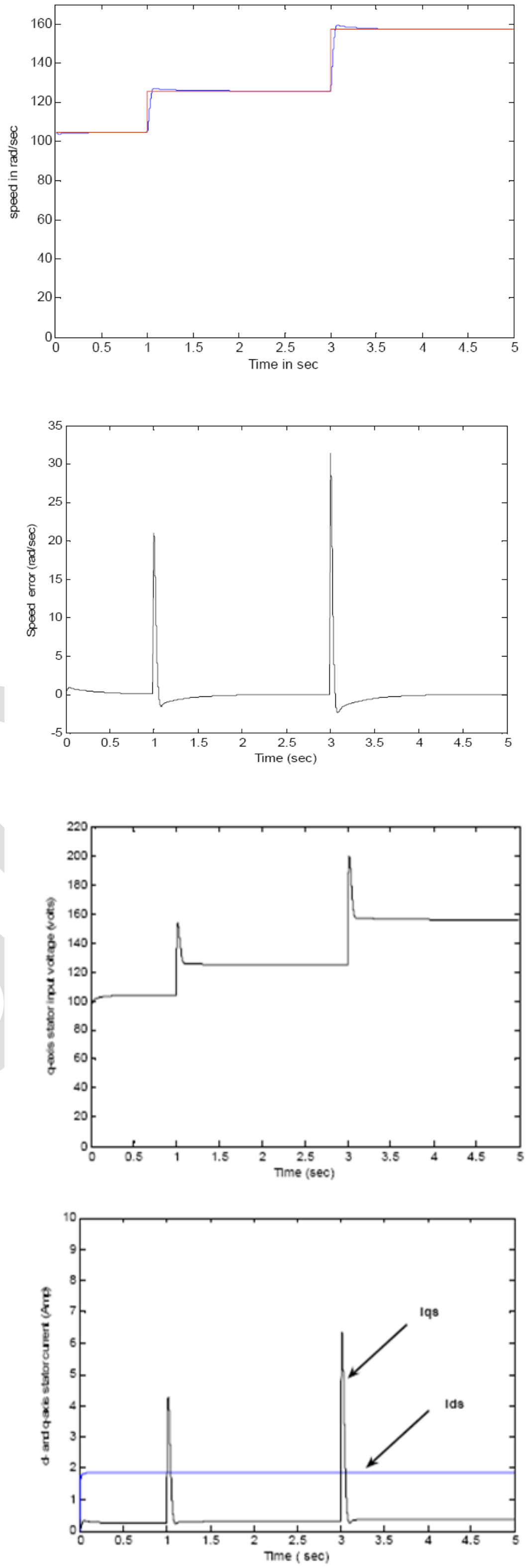

Fig 5 Step change in reference speed with P-I controller
(a) Speed ,
(b) Speed error,
(c) stator input voltage at q-axis
(d) stator current at d- and q- axis

Fig 6(a), (b), (c) and (d) follows:

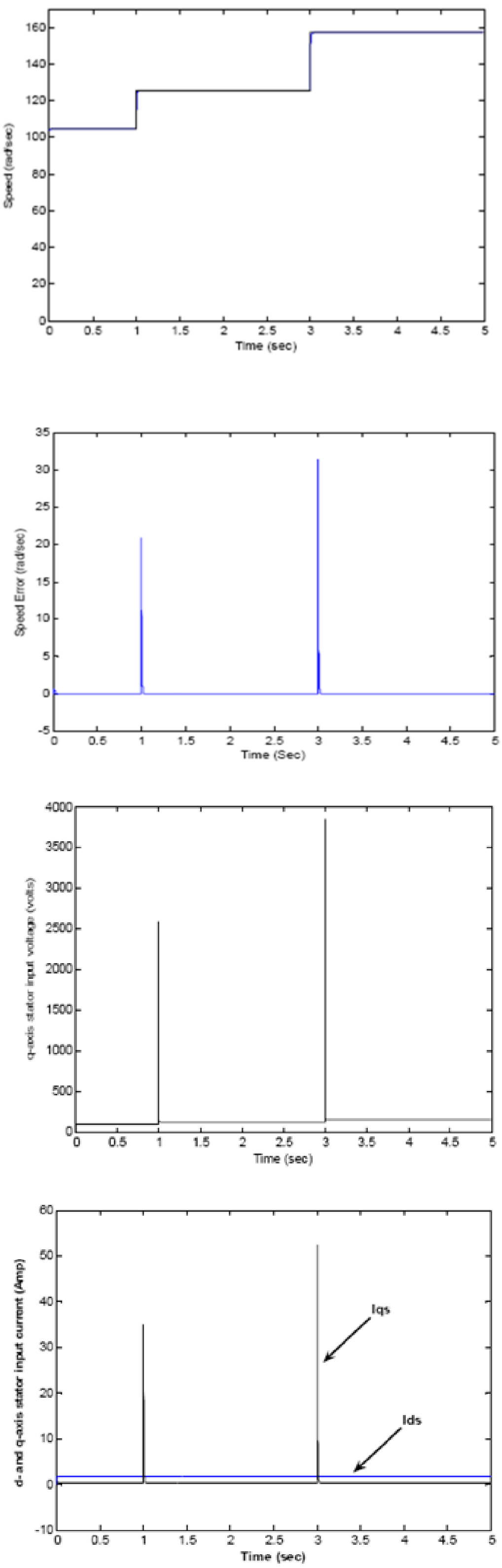

Fig 6 Step change in reference speed with SMC controller

(a) Speed ,
(b) Speed error,
(c) stator input voltage at q-axis
(d) stator current at d- and q- axis

CONCLUSION

This study involves the implementation of sliding mode control technique for the rotor speed control of an induction motor drive. In order to enhance the robust control performance of the field-oriented induction motor drive, a sliding mode controller is designed in accordance with Lyapunov stability theory. Some simulation tests under various operating conditions were carried to illustrate the effectiveness and robustness of the developed methodology. From the simulations results it is concluded that the speed tracking error of the sliding mode controller system converges quickly. The response of the system under disturbances is satisfactory in terms of good trajectory tracking performance and the speed regulation is also satisfactory.

FUTURE WORK

The effectiveness and the robustness of this controller is tested on a small rating induction motor drive system with the system uncertainty as load disturbance. As a future work, this controller can be applied to any higher rating induction motor drive system where parameter variation effect can be studied. Advanced control techniques such as Fuzzy logic principle or Neural networks can be incorporated to make this controller more efficient and robust.

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