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Sliding Mode Controller Vs PID Controller For Induction Motor - A Comparative Study

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***Abstract*— In this paper Mathematical model of Indirect Field Oriented control of Induction motor is described. The speed control of the closed loop system is simulated by Sliding Mode Controller (SMC) and the performance is compared with that of conventional PID controller. A detailed study is done on the frequency response and time response of the closed loop system by linearising the Induction motor model. The complete system is simulated using MATLAB / Simulink and the results with sliding mode controller and classical PID controller are compared. The performance parameters of both the controllers are tabulated. The simulation results show the superior performance of Sliding Mode Controller in the presence of parameter variations and load disturbances.**

***Index Terms*— Sliding Mode Control, Linearising, PID controller, frequency response, time response**

Symbols used-

$S(t)$	- Sliding surface.
i_{ds}, i_{qs}, V_{ds}, V_{qs}	- Direct and quadrature axis components of stator currents and stator voltages
ψ_{rd}, ψ_{rq}	- Direct and quadrature axis components of rotor flux.
R_s, R_r	- Stator and rotor resistance of Induction motor.
L_s, L_r & L_m	- stator, rotor and mutual inductances.
ω_r	- Rotor speed.
ω_e	- Synchronous speed.
ω_{sl}	-Slip speed.
T_e	-Torque developed in the Induction motor.
P	- Number of poles.
J , B	- Moment of Inertia and coefficient of viscous friction of the Induction motor respectively

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I. INTRODUCTION

Induction motors have many advantages compared to DC motor, such as reliability, robustness, high efficiency, low cost etc. After the invention of Field oriented control, which provides high performance control for Induction motor drives, most of the variable speed drives are operating with Induction motor. The Field Oriented Control or Vector control, which is based on the rotor field orientation, provides the decoupling between the torque and flux in the Induction motor similar to that of DC motor. Therefore Field oriented control of Induction motor provides the dynamic characteristics similar to that of DC motor. There are two methods to implement Field Oriented Control, the direct or feedback method and indirect method or feed forward method [1]. In the last few decades the PID controllers were widely used in the vector control of induction motors due to its good performance and simple structure. But the control performance of the closed loop system is still influenced by the uncertainties which are due to unpredictable parameter variations, external load disturbances and nonlinear dynamics. Therefore many studies such as optimal control, adaptive control, Variable Structure control, fuzzy and neural control etc [4, 5, 8] have been done in order to maintain the better performance of Induction motor in the presence of uncertainties.

In the recent years, the variable structure control using Sliding Mode has received more attention in the area of control of electrical drives [2]. The most important feature of Sliding Mode Control (SMC) is its robustness, fast dynamic response and insensitivity to parameter variations. In electric drives the parameter variations can happen due to temperature variations in windings, switching effects of converters, saturation, unknown loads etc.

In this paper a Sliding Mode Control strategy is explained for the speed control of Induction motor. The proposed closed loop system is simulated with different loads, sudden change in reference speed and with parameter variations.

II. VECTOR CONTROLLED INDUCTION MOTOR MODEL

The dynamic model of the Induction motor in synchronously rotating d-q reference frame is given below as state model [4]. The state variables selected are i_{ds}, i_{qs}, ψ_{dr}, ψ_{qr}.

$$\dot{x} = Ax + Bu$$

Where $x = \begin{bmatrix} i_{ds} & i_{qs} & \psi_{dr} & \psi_{qr} \end{bmatrix}$

$u = \begin{bmatrix} V_{ds} & V_{qs} \end{bmatrix}$

$$A = \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right) & \omega_e & \frac{L_m}{\sigma L_s L_r \tau_r} & \frac{L_m \omega_r}{\sigma L_s L_r} \\ \omega_e & -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right) & \frac{L_m \omega_r}{\sigma L_s L_r} & \frac{L_m}{\sigma L_s L_r \tau_r} \\ \frac{L_m}{\tau_r} & 0 & \frac{1}{\tau_r} & (\omega_e - \omega_r) \\ 0 & \frac{L_m}{\tau_r} & -(\omega_e - \omega_r) & -\frac{1}{\tau_r} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 \end{bmatrix}^T$$

Selecting i_{ds} and i_{qs} as output variables,

$y = Cx$

Where $C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$

$$T_e = \frac{3P}{4}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \qquad (1)$$

$\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage coefficient.

$\tau_r = \frac{L_r}{R_r}$ is the rotor time constant.

In the field oriented control, for decoupling of torque and flux, i_{qs} should be oriented in the direction of flux ψ_r and i_{ds} should be perpendicular to it. Then current i_s can be controlled by means of i_{qs} without affecting flux ψ_r and ψ_r is controlled by means of i_{ds} without affecting the current i_{qs}.
This condition is satisfied if $\psi_{qr} = 0, \psi_{dr} = \psi_r$.
Then dynamic equations are simplified to

$$\frac{di_{ds}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right) i_{ds} + \omega_e i_{qs} + \frac{L_m}{\sigma L_s L_r \tau_r}\psi_{dr} + \frac{1}{\sigma L_s} V_{ds}$$
$$\frac{di_{qs}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma\tau_r}\right) i_{qs} + \omega_e i_{ds} + + \frac{L_m \omega_r}{\sigma L_s L_r}\psi_{dr} + \frac{1}{\sigma L_s} V_{qs}$$
$$\frac{d\psi_{dr}}{dt} = \frac{L_m}{\tau_r} i_{ds} + \frac{1}{\tau_r}\psi_{dr}$$
$$0 = \frac{L_m}{\tau_r} i_{qs} - (\omega_e - \omega_r)\psi_{dr} \tag{2}$$
$$T_e = \frac{3P}{4}\frac{L_m}{L_r}(\psi_{dr} i_{qs})$$
$$T_e = K_T i_{qs} \tag{3}$$
$$\text{Where} \quad K_T = \frac{3P}{4}\frac{L_m}{L_r}\psi^*_{dr}$$

Where ψ^*_{rd} is the command rotor flux.

From (2), $\omega_{sl} = \omega_e - \omega_r = \frac{L_m}{\tau_r}\frac{i_{qs}}{\psi_{dr}}$ (4)

In Indirect Field Oriented Control the signal ω_{sl} thus obtained is added with speed signal ω_r to generate frequency signal ω_e which is then integrated to obtain θ_e. The unit vectors $cos\ \theta_e$ and $sin\ \theta_e$ are generated from θ_e.

$$\omega_e = \omega_r + \omega_{sl} \quad , \quad \theta_e = \int \omega_e \, dt$$

III. Sliding Mode Controller

Sliding Mode Control is a nonlinear control technique which has remarkable features like accuracy, robustness and easy implementation [3]. The design of SMC involves two steps. The first step is to choose the sliding surface *S(t)* in terms of tracking error and second step is to choose the control input *u(t)* which will drive the system state to switching surface . The typical choice of *S(t)* is ,

$$S = \lambda e + \dot{e} \tag{5}$$

Where e is the tracking error, $e = \omega_m - \omega_m$ (6)

Where ω_m is the rotor mechanical speed, ω_m is the reference rotor speed, λ is a positive constant.
When the trajectory reaches sliding surface tracking error converges to zero as long as error vector stays on the sliding surface. Fig 1 shows the mechanism that happens in phase plane. There are two modes in sliding mode approach. The first mode called reaching mode is the step in which the phase trajectory (e, $\dot{e}$) is attracted towards the switching surface S=0. In the second mode known sliding mode, the phase trajectory slides on the surface until it reaches the equilibrium point (0, 0)
After choosing the sliding surface the next step is to choose the control law *u(t)* that will allow the error vector (e, $\dot{e}$) to reach the sliding surface. For that the control law should be designed in such a way that the condition,

$$S.\dot{S} < 0 \ , \square \ t \tag{7}$$

is met. The above condition is called reaching law.
In order to satisfy the above condition, in conventional SMC, $\dot{S}$ is typically chosen as

$$\dot{S} = -\varepsilon Sign(S), \quad t, \ \varepsilon > 0 \tag{8}$$

The term $-\varepsilon$ will drive the state towards the sliding surface rapidly. Therefore higher value of ε will reduce the time of reaching mode. But larger value of ε induces more chattering.

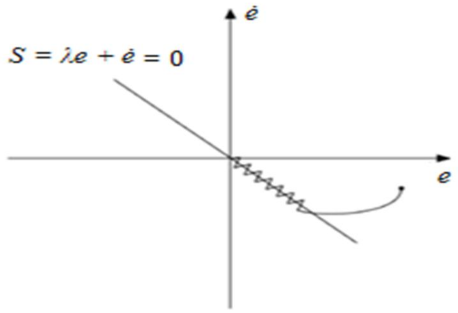

Figure1. The phase trajectory of the system with SMC.

The mechanical equation of an Induction motor is given by

$$T_e = J\,\dot{\omega}_m + B\omega_m + T_L \quad (9)$$

J and B are the Inertia constant and viscous friction constant of the Induction motor respectively. T_L is the external load applied. ω_m is the rotor mechanical speed and is related with rotor electrical speed ω_r by the relation,

$$\omega_m = \frac{2\omega_r}{P} \quad (10)$$

T_e is torque generated by the Induction motor.
Equating (3) and (9) we get,

$$J\,\dot{\omega}_m + B\omega_m + T_L = K_T i_{qs} \quad (11)$$

As per (2) i_{sq} is the control signal *u(t)* which controls the rotor speed.
Differentiating (5),

$$\dot{S} = \lambda\dot{e} + \ddot{e} \quad (12)$$

Where $\dot{e} = \dot{\omega}_m - \dot{\omega}_m^*$, $\ddot{e} = \ddot{\omega}_m - \ddot{\omega}_m^*$ (13)

$\dot{\omega}_m^*$, $\ddot{\omega}_m^*$ are zero as the reference speed is considered as constant.
Equating (8) and (12) and using (9) and (13),

$$i_{sq} = \left(-\varepsilon Sign(S) - \ddot{\omega}_m + \frac{\lambda B}{J}\omega_m + \frac{\lambda}{J}T_L\right)\frac{J}{\lambda K_T} \quad (14)$$

It is seen that the control signal $u = i_{qs}$ has two parts equivalent control and discontinuous control.

$u = u_{eq} + u_{disc}$

$$u_{eq} = \left(-\ddot{\omega}_m + \frac{\lambda B}{J}\omega_m + \frac{\lambda}{J}T_L\right)\frac{J}{\lambda K_T} \quad (15)$$

$$u_{disc} = -\varepsilon Sign(S)\frac{J}{\lambda K_T} \quad (16)$$

The discontinuous control with signum function is responsible for chattering.
Fig 2. Shows the block diagram of the Sliding Mode Controlled speed control of Indirect Field Oriented controlled Induction motor. As shown in fig.2, the power circuit consists of DC supply of 220V and IGBT two level inverter. A hysteresis band current controller is used. The speed control loop generates the torque component of current i_{qs}^*. The flux component of current i_{ds}^* for the desired rotor flux ψ_{dr}^* is generated. The slip frequency ω_{sl} is generated from i_{qs}^* in the feedforward manner. Signal ω_{sl} is added with speed signal ω_m to generate the frequency signal ω_e. The signal θ_e is obtained by integrating ω_e. Both i_{qs}^* and i_{ds}^* generates three phase reference currents i_a^*, i_b^*, and i_c^* through Park transformation which is then compared with the sensed winding currents i_a, i_b and i_c of the Induction motor. The errors in current are used by the Hysteresis current controller to generate switching signals for Voltage source inverter.

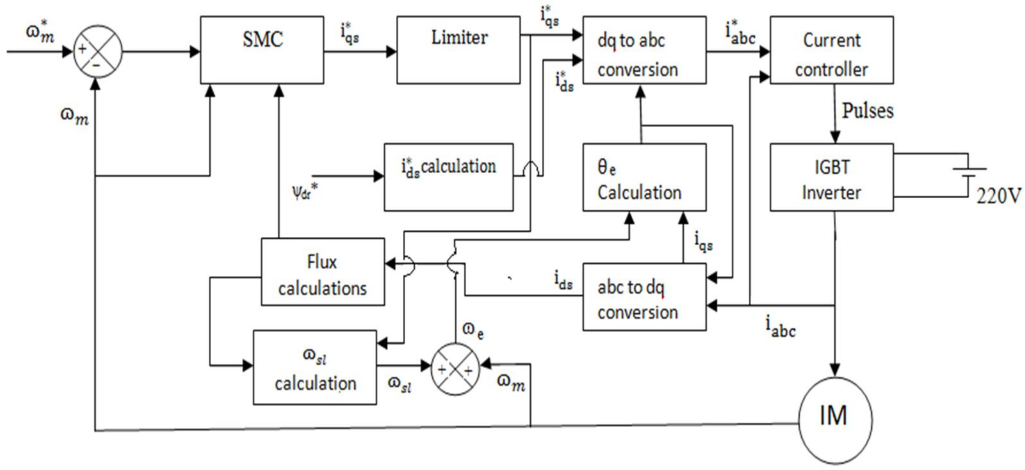

Figure 2. Block diagram representation of the system with SMC

IV. ILLUSTRATIVE CASE STUDY

The simulation of indirect field orient controlled induction motor is done using a 1HP (746W), 220V, 50 Hz, 4 Pole Squirrel cage induction motor. The simulation is done with conventional PID controller and Sliding Mode Controller. For simulation MATLAB 7.10(R2010a) /SIMULINK is used. Powergui tool in simpower systems toolbox is used for simulation. The parameters of the Induction motor used for simulation are 3A, 220V, 50Hz, 4P, R_s = 6.37Ω, R_r = 4.3 Ω, L_m = 0.24H, L_s = 0.26H, L_r = 0.26H, J = 0.0088Kg/m^2. The PID controller is designed with K_p = 45, K_i = 0.1 and K_d = 0.5. For the design of Sliding Mode Controller, λ = 100 and ε = 400 are used.

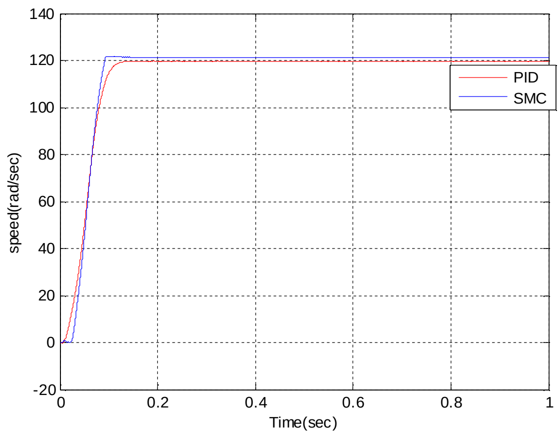

Figure 3.Speed vs Time response of PID and SMC without load

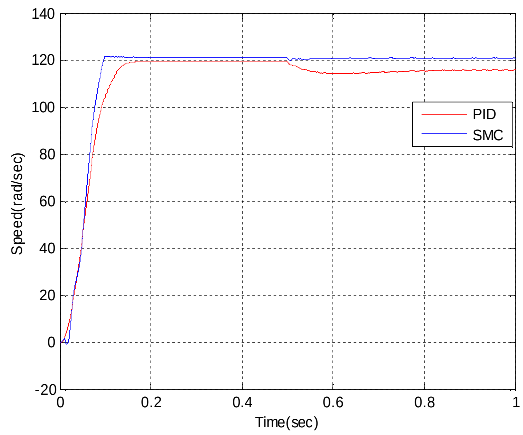

Figure 4.Speed vs Time response of PID and SMC with load of 4Nm applied after 5secs.

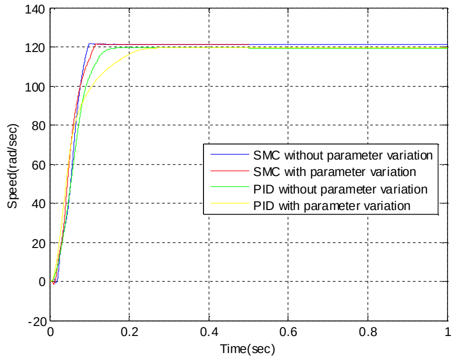

Figure 5.Speed vs Time response of PID and SMC with and without parameter variations

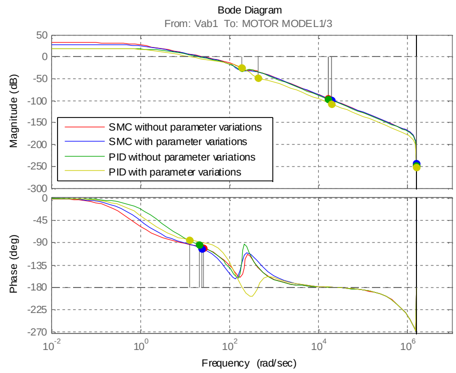

Figure 6. Frequency response (Bode plots) of PID and SMC with and without parameter variations

TABLE 1
COMPARISON OF PID AND SMC PERFORMANCES IN THE PRESENCE OF PARAMETER VARIATIONS

Controller description	Rise time (secs)	Settling time (secs)	Gain Margin (dB)	Phase Margin (deg)
SMC without parameter variations	0.1	0.1	95.3	77.9
SMC with parameter variations	0.11	0.11	95.3	77.9
PID without parameter variations	0.14	0.16	96.5	85.5
PID with parameter variations	0.24	0.25	47.6	95.4

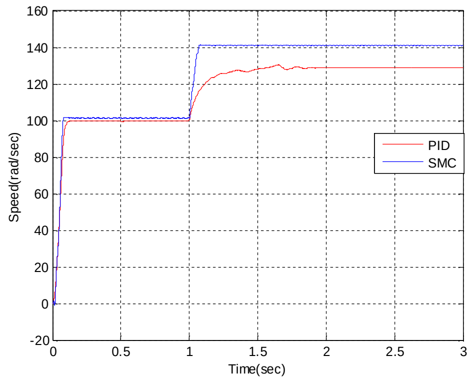

Figure 7.Speed vs Time response of PID and SMC for step change in reference speed, from 100 to 140 at 1 sec.

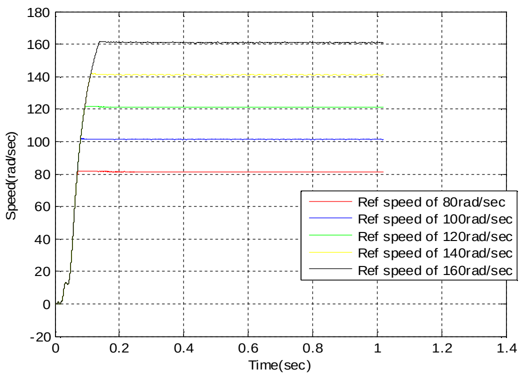

Figure 8. Speed vs Time response of SMC for different reference speed

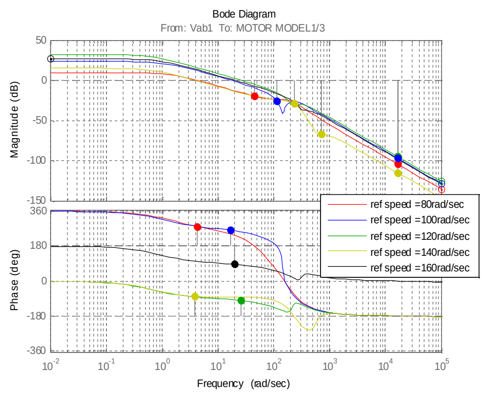

Figure 9. Frequency response (Bode plots) of SMC with different reference speeds

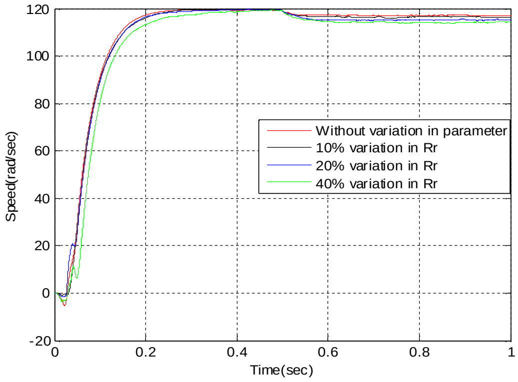

Figure 10. Speed vs Time response of PID controller with variation in parameters.

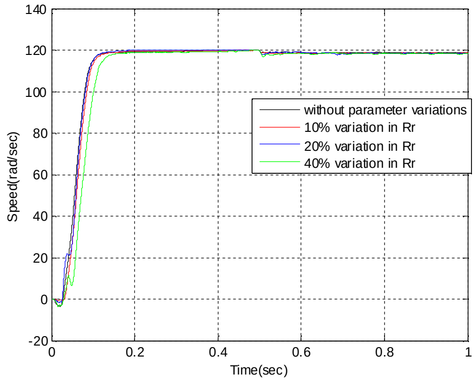

Figure 11. Speed vs Time response of SMC with variation in parameters

TABLE II
COMPARISON OF SMC PERFORMANCES FOR DIFFERENT REFERENCE SPEEDS

Reference speed(rad/secs)	Rise time (secs)	Settling time(secs)	Gain Margin(dB)	Phase Margin(deg)
80	0.06	0.06	20	102
100	0.08	0.08	25.3	81.3
120	1	1	97.4	79.2
140	1.1	1.1	66.8	101
160	1.4	1.4	-26.7	-94.5

Figure 3 shows the Speed – Time response of PID controller and Sliding Mode Controller at noload. It is seen that rise time and settling time is less with SMC. Figure 4 shows the Speed – Time response of PID controller and Sliding Mode Controller with load suddenly applied after 0.5secs. We can see that the speed of SMC system is robust compared to that of PID controlled system. Figure 5 and 6 show the time and frequency response of SMC and PID controllers with parameter variations. The rotor resistance of Induction motor is varied. The different performance parameters are tabulated in Table 1. It is seen that performance of SMC is stable even with parameter variations. Figure 7 shows the performance of SMC and PID controllers when there is a sudden change in reference speed from 100 rad/secs to 140 rad/sec. It is seen that Sliding Mode controller tracks the reference speed with minimum time and less steady state error. Figure 8 and 9 show the time and frequency response of Sliding Mode Controller for different reference speeds. The performance parameters tabulated in table 2 shows that the controller performance is better near the synchronous speed (157 rad/sec). Above the synchronous speed (160 rad/sec) the system become unstable. Figure 10 and 11 show the performance of SMC and PID controllers in the presence of parameter variations. The rotor resistance is varied by 10%, 20% and 40%. The performance shows the robustness of SMC compared to that of PID controller.

V. CONCLUSION

In this paper a speed control for vector controlled induction motor using Sliding Mode Controller is presented. The complete mathematical model of Indirect Field Oriented Controlled Induction motor and Sliding Mode Controller is described and simulated. From the simulation results it is seen that performance of Sliding Mode Control is superior than that of PID controller in the presence of uncertainties like parameter variations, load disturbances and sudden change in reference speed.

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