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Robust Speed Control of Vector Controlled Induction Motor Drives Using Sliding Mode Controller

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Abstract: In this paper speed control of an Indirect Field Oriented Controlled (IFOC) Induction Motor with sliding mode controller has been developed and simulated. In this work the complete mathematical model of field oriented controlled Induction Motor and sliding mode controller is described and simulated in MATLAB/SIMULINK. For studies a 1 HP (746w) squirrel cage type IM has been considered. The comparative study is done between PID controller and the sliding mode controller. The simulation results show that the proposed sliding mode controller (SMC) provides a good performance in the presence of external load disturbances.

Keywords—IFOC, IM, PID, SMC

I. INTRODUCTION

Induction motors were used in the past mainly in applications requiring constant speed. This is because the conventional methods of their speed control were either been expensive or highly inefficient. The Variable speed applications have been dominated by dc drives. The speed control of DC motors can be carried out in a simple way, because the torque and flux are decoupled in DC motors. But they have the disadvantages of more expensive, higher rotor inertia and maintenance problems associated with commutators and brushes. Because of the availability of thyristors, power transistors, IGBT and GTO, in recent years the speed control of induction motors is becoming inexpensive. So now a days it is increasingly replacing the DC motors in high performance electrical motor drives [1]. However the technique of vector control or field oriented control (FOC) based on the rotor field orientation applied to the induction motor provides the decoupling between the torque and flux in a similar way to the DC machine [2]. Apart from this Induction motor offers many attractive features such as ruggedness, low cost and high efficiency. Therefore with the integration of power electronics and low cost and high speed microcontrollers the induction motor drives have reached a competitive position compared to DC machines. The least expensive and most widely used induction motor is the squirrel cage induction motor. In the last decades the PID controllers has been widely used in the vector control of induction motors due to its good performance and simple structure.

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However in some applications the PID controller may not meet the concerned robustness under parameter variations and external load disturbances. For this reason there have been many studies made with the idea of maintaining the good performance of induction motor with uncertainties, such as optimal control, variable structure control, and adaptive control, fuzzy and neural control. In the past decade and present, the variable structure control strategy using the sliding mode has been focused on many studies and research for the control of AC motor drive system. The sliding mode control (SMC) is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to "slide" along a cross section of the systems normal behavior. SMC offers many good properties such as, good performance against unmodelled dynamics, insensitivity to parameter variations, rejection of external disturbance and fast dynamic response [3]. These advantages of SMC may be employed in the position and speed control of an AC drive system.

In this paper, a robust approach for induction motor speed control is presented. The proposed sliding mode controller may overcome the system uncertainties and load disturbances that are present in real systems.

II. VECTOR CONTROL OR FIELD ORIENTED CONTROL (FOC):

F. Blaschke in 1972 has introduced the principle of field orientation to realize dc motor like characteristics in an induction motor derive. For the same, he used decoupled control of torque and flux in the motor and gives its name transvector control. Because of the interactions between the stator and the rotor fluxes, an AC machine is not so simple. The orientations of rotor and stator fluxes are not held at 90 degrees but vary with the operating conditions. We can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the field and armature fluxes in an AC machine by orienting the stator current with respect to the rotor flux so as to get independently controlled flux and torque. Such a control scheme is called field oriented control or vector control [1]. This method is applicable to both induction motors and synchronous motors. The vector control approach needs more calculations than other standard control schemes, but has the following advantages.

- full motor torque capability at low speed
- better dynamic behaviour
- higher efficiency for each operating point in a wide speed range

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- decoupled control of torque and flux
- short term overload capability
- four quadrant operation

PRINCIPLES OF VECTOR CONTROL

The basic principles of vector control implementation can be explained with the help of fig. 1 where the machine model is represented in a synchronously rotating reference frame. The inverter is not included in the figure, assuming that its current gain is unity. It generate currents i_a, i_b, and i_c as dictated by the corresponding command currents i_a*, i_b*, and i_c* from the controller. The machine terminal phase currents i_a, i_b, and i_c are converted to i_{ds}^s and i_{qs}^s components by $3\Phi/2\Phi$ transformation. 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_e-q_e machine model. The controller makes two stages of inverse transformation so that the control currents i_{ds}* and i_{qs}* correspond to the machine currents i_{ds} and i_{qs} respectively. Also the unit vector ensures the correct alignment of current i_{ds} with the flux vector $\hat{\psi}_r$ and i_{qs} perpendicular to it.

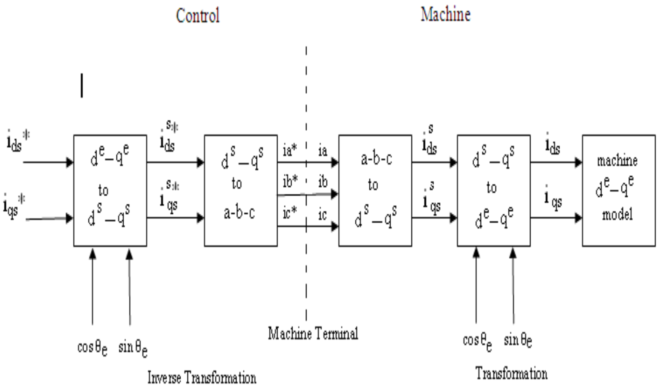

Fig 1. Vector control implementation principle with d_e-q_e machine model

The following two methods have been used in field oriented control.

1) Direct field oriented control (DFOC)
2) Indirect field oriented control (IFOC)

In Direct Field Oriented Control strategy rotor flux vector is either measured by using a flux sensor mounted in the air-gap or mathematically by using the voltage equations starting from the electrical machine parameters. In Indirect Field Oriented Control strategy rotor flux vector is estimated using the field oriented control equations (current model) requiring a rotor speed measurement. IFOC is more popular than DFOC due to its implementation simplicity and has become the industrial standard.

III. INDIRECT FIELD ORIENTED CONTROL (IFOC)

In the indirect field oriented control method, the rotor flux angle and thus the unit vectors $\cos\theta_e$ and $\sin\theta_e$ are indirectly obtained by summation of the rotor speed and slip frequency. The IFOC method is essentially same as the direct field oriented control except that the rotor angle is generated in an indirect manner using the measured speed ω_r and the slip speed ω_{sr}. To implement the IFOC strategy, it is necessary to take the following dynamic equations into consideration with respect to the phasor diagram of Indirect Field oriented Control method of induction motor, which is shown in Fig.2.

The phasor diagram suggests that for decoupling control, the stator flux component of current i_{ds} should be aligned on the *de* axis, and the torque component of current i_{qs} should be on the *qe* axis as shown in Fig 2[7].

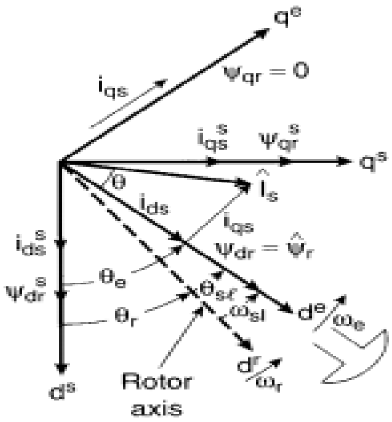

Fig.2 Phasor diagram of indirect field oriented control method of Induction motor.

For decoupling control, the rotor equations can be written as

$$\frac{d\psi_{dr}}{dt} + R_r i_{dr} - (\omega_e - \omega_r)\psi_{qr} = 0 \quad (1)$$

$$\frac{d\psi_{qr}}{dt} + R_r i_{qr} + (\omega_e - \omega_r)\psi_{dr} = 0 \quad (2)$$

The rotor flux linkage expressions are

$$\Psi_{dr} = L_r i_{dr} + L_m i_{ds} \quad (3)$$
$$\Psi_{qr} = L_r i_{qr} + L_m i_{qs} \quad (4)$$

From the above expressions we can write

$$i_{dr} = \frac{1}{L_r}\Psi_{dr} - \frac{L_m}{L_r} i_{ds} \quad (5)$$

$$i_{qr} = \frac{1}{L_r}\Psi_{qr} - \frac{L_m}{L_r} i_{qs} \quad (6)$$

By substituting (5) and (6) in (1) and (2) the inaccessible rotor currents can be eliminated.

$$\frac{d\psi_{dr}}{dt} + R_r\frac{1}{L_r}\Psi_{dr} - \frac{L_m}{L_r} R_r i_{ds} - \omega_{sl}\psi_{qr} = 0 \quad (7)$$

$$\frac{d\psi_{qr}}{dt} + R_r\frac{1}{L_r}\Psi_{qr} - \frac{L_m}{L_r} R_r i_{qs} + \omega_{sl}\psi_{dr} = 0 \quad (8)$$

Where $\omega_{sl} = (\omega_e - \omega_m)$

Also for decoupling control,

$$\Psi_{qr} = 0 \quad (9)$$

And

$$\frac{d\psi_{qr}}{dt} = 0 \quad (10)$$

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So that the rotor flux $\hat{\psi}_r$ is directed on the *de* axis. Substituting these equations in (7) and (8), we get

$$\frac{Lr}{Rr}\frac{d\hat{\psi}r}{dt} + \hat{\psi}r = L_m i_{ds} \quad (11)$$

And $\omega_{sl} = \frac{Lm}{\hat{\psi}r}\frac{Rr}{Lr} i_{qs}$ (12)

The electromagnetic torque developed,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{Lm}{Lr}\hat{\psi}_r i_{qs} \quad (13)$$

The signal ω_{sl} thus obtained is added with speed signal ω_m to generate frequency signal ω_e which is then integrated to obtain θ_e. The unit vectors *cos* θ_e and *sin* θ_e are generated from θ_e.

IV. Sliding Mode Controller (SMC)

In sliding mode controller, which is a varable structure method, the trajectories always move toward an adjacent region with a different control structure and will slide along the boundaries of the control structures. The motion of the system as it slides along these boundaries is called sliding mode and the geometric locus consisting of the boundaries is called the sliding surface. The design of SMC involves two parts. The first part involves the design of a sliding surface and the second part is concerned with the selection of control law that will make the switching surface attractive to the trajectories. With sliding mode controller, the system is controlled in such a way that the error in the system state always moves toward a sliding surface. The sliding surface is defined with the tracking error (e) of the speed and its rate of change (ė) as variables. Fig 3 shows the phase trajectory of the system being stabilized by SMC. After the initial reaching phase, the system enters into sliding phase along the surface S=0. The distance of the error trajectory from the sliding surface and its rate of convergence are used to decide the control input u(t) to the plant. The sign of the control input must change at the intersection of the tracking error trajectory with the sliding surface. In this way the error trajectory is always forced to move towards the sliding surface.

The mechanical equation for induction motor can be written as,

$$J\dot{\omega}_m + B\omega_m + T_L = T_e \quad (14)$$

Where J is the moment of inertia and B is the coefficient of friction.

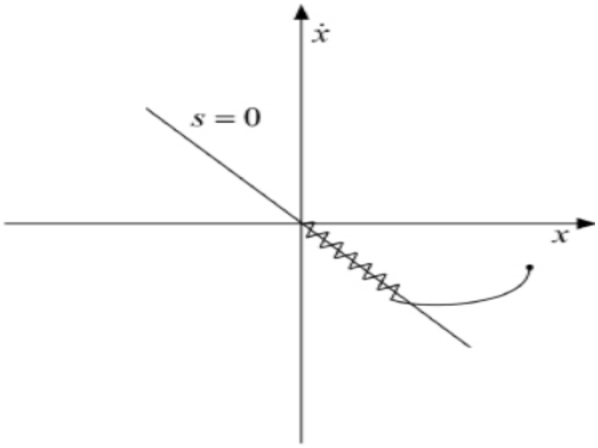

Fig.3 The phase trajectory of the system being stabilized by SMC.

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{Lm}{Lr}\hat{\psi}_r i_{qs} = K_T i_{qs} \quad (15)$$

The mechanical equation can be written as

$$\dot{\omega}_m + a\omega_m + f = bi_{qs} \quad (16)$$

Where a = B/J ; b = K_T/J ; f = T_L/J

Let the uncertainities in a, b and f are Δa, Δb and Δf respectively. Then,

$$\dot{\omega}_m = -(a + \Delta a)\,\omega_m - (f + \Delta f) + (b + \Delta b)\, i_{qs} \quad (17)$$

Let the error in speed is

$$e(t) = \omega_m(t) - \omega_m^*(t) \quad (18)$$

Where $\omega_m^*(t)$ is the speed command.

$$\dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}_m^*(t)$$

$$= u(t) + d(t) \quad (19)$$

Where $u(t) = bi_{qs}(t) - a\omega_m(t) - f(t) - \dot{\omega}_m^*(t)$
$d(t) = -\Delta a\,\omega_m(t) - \Delta f(t) + \Delta b\, i_{qs}(t)$

The sliding variable S(t) is defined as,

$$S(t) = \dot{e}(t) + Ke(t) \quad (20)$$

Where K is a positive constant .

Then sliding surface is defined as,

$$S(t) = \dot{e}(t) + Ke(t) = 0 \quad (21)$$

Sliding mode controller is defined as,

$$u(t) = -K\dot{e}(t) - K_i\, e(t) - \beta Sgn(S(t)) \quad (22)$$

where β is the switching gain,
S(t) is the sliding variable defined in (21)

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Then

$$i_{qs}^*(t) = \frac{1}{b}[-K\dot{e}(t) - K_i e(t) - \beta Sgn(S(t)) - a\omega_m + \dot{\omega}_m + f(t)] \quad (23)$$

β must be chosen such that $\beta \geq d(t)$, which represents all the disturbances.

It is seen that the variable structure control signals may produce the so called chattering phenomena caused by the discontinuity that appear in (23) across the sliding surface. Chattering is an undesirable practice since it involves high control activity and further may excite high frequency dynamics. To some extent the high frequency changes in electromagnetic torque will be filtered by the mechanical system inertia. In order to reduce chattering the sliding gain β can be adjusted. Fig4. Shows the complete block diagram of the system which uses sliding mode controller.

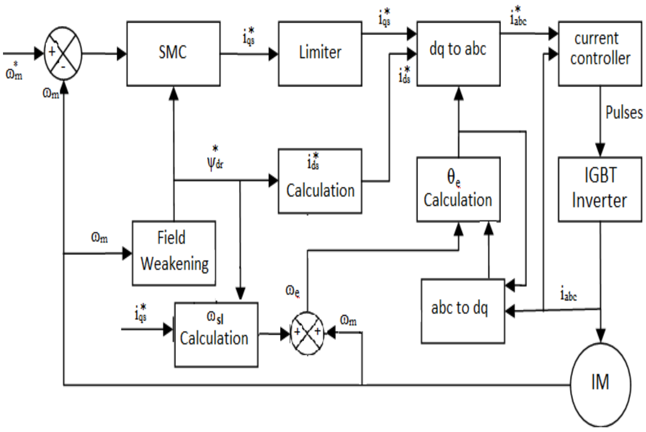

Fig 4. Block diagram for sliding mode control of indirect field orient controlled Induction motor.

V. SIMULATION RESULTS

The simulation of indirect field orient controlled induction motor is done using a 1HP (746W) squirrel cage induction motor. The simulation is done with PID controller and sliding mode controller. For simulation MATLAB 7.10(R2010a) /SIMULINK is used. Powergui tool in simpowersystems toolbox is used for simulation. Figures 5,6,7,8 show the simulation results for different conditions.

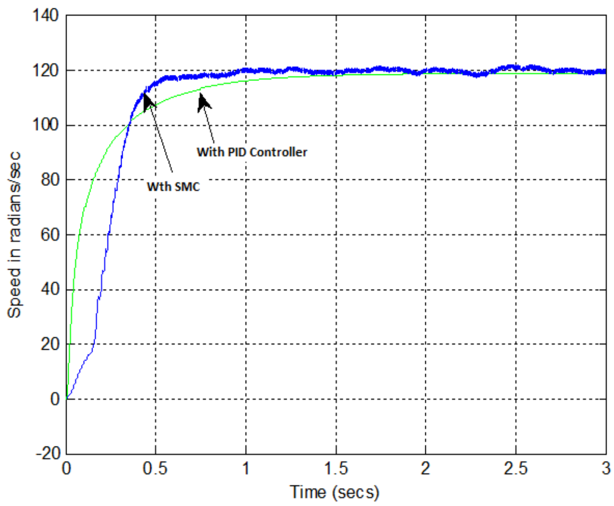

Fig 5. Speed response of PID and SMC for a command speed of 120 rad/secs with load torque $T_L = 0$

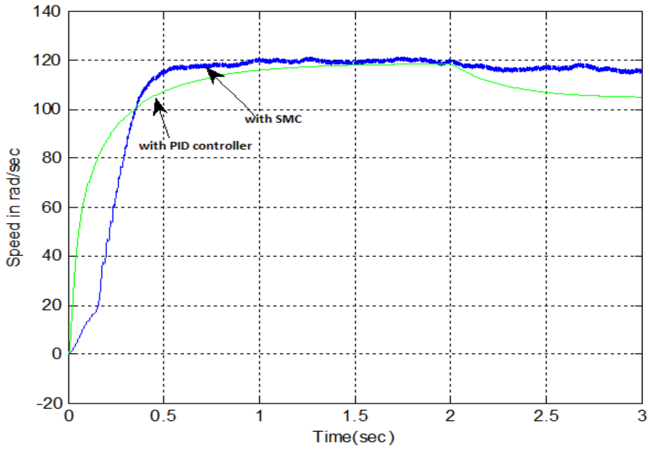

Fig 6. Speed response of PID and SMC for a command speed of 120 rad/secs with load torque T_L = 2Nm after 2 secs.

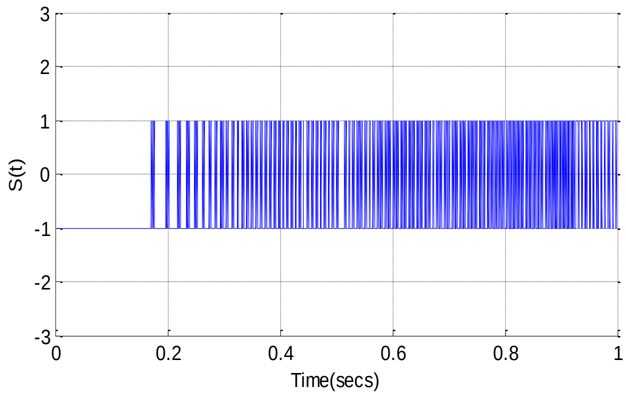

Fig 7. Sliding variable S(t) for a speed command of 120rad/secs.

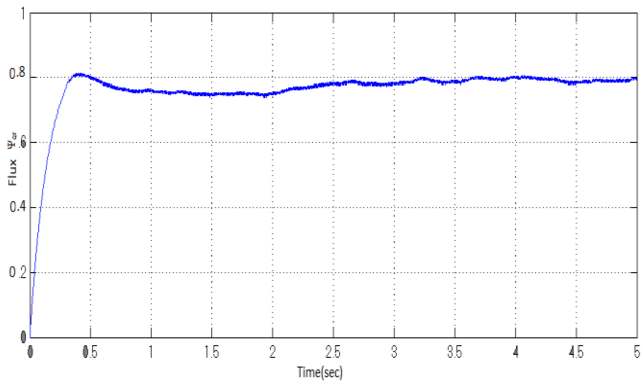

Fig 8. Variation of rotor flux Ψ_r after applying load torque T_L = 2Nm after 2 secs

VI. CONCLUSION

In this paper a robust speed control for vector controlled induction motor is presented. The complete mathematical model of Indirect Field Oriented Controlled Induction motor is described and simulated. From the simulation results it is seen that with Sliding Mode Control the speed response of Induction Motor can be made robust compared to PID controller in the presence of load disturbances.

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The control technique using SMC are very much suitable for real time implementation due to their simplicity, robustness and the ease of tuning. The chattering phenomena which is the main drawback of Sliding Mode Control is reduced to some extent by adjusting the gain β. It can be reduced further by applying adaptive algorithms. The speed sensors can be replaced by state estimators which estimates the actual speed from the machine terminal voltage and current.

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