International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8, Issue-1S5, June 2019

SMC and FOC: Comparative Investigation of Sliding Mode and Field Oriented Control of Induction Motor

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Abstract*: *The generalized model of Indirect Field Oriented control of Induction motor is described in this manuscript. The speed regulator of the closed loop system is simulated by Sliding Mode Controller (SMC) and the performance is equated with thatt of field-oriented control. The performance parameters of both the controllers are tabulated. The simulation of Sliding Mode Control shows superior characteristics in the variations of parameter and load changes.

Index Terms*: *Induction motor (IM), field-oriented control (FOC), sliding mode controller (SMC), speed control.

I. INTRODUCTION

The demand of high-performance electric drive increased due to the capacity of accurately executing torque, speed and position demands. In the past DC motor are extensively used in variable speed application where flux and torque are the function of filed and armature current respectively. Nevertheless, DC motor experienced its drawback like maintenance, sparking, problems in commutation at high current and voltage therefore it is normally limited to low power and low rates of speed.

Now a days in most of the industry induction motor is the key actuator. In reality, it has great power/mass proportion, simpler upkeep and comparatively economical than DC machine [1]. Though its main drawbacksare more complicated issue in its control, nonlinearity and its large coupled structure [3]. Moreover, the parameters of motor are time-fluctuating under the common procedure and the majority of the state variables are generally not quantifiable. The new approach known as Vector Control (VC) or Field-Oriented Control (FOC), the induction equipment becomes progressively more frequent. Such kind of control technique can offer similar performance like dc machine mainly because the speed of the motor, starting current and power factor are controlled easily achieved via individually excited switches of the inverter. In order to assess vector control, the active model of the induction machine is necessary in MATLAB.

The majority of the industrial application, DC motor unit isreplaced by induction engine due to the improvement of the vitality electronics region. Most of the studies are focused on the sensorless control of induction motor to reduce the price tag on sensor. The operation of sensorless control involves the assessment of internal variables within the machine. The calculation relies entirely upon measured port voltages and currents. The use of closed loop program and available loop program vary regarding correctness, strength, and limits of use.

In sensor less solution the induction motor is modeled as equivalent to dc motor by decoupling the effect of torque and flux. The controlled by number of algorithms to generate the control signal. The sliding mode control algorithm offer excellent dynamics of the IM drive. It progresses the performance of field-oriented control of induction motor.

II. CLOSED LOOP SPEED CONTROL

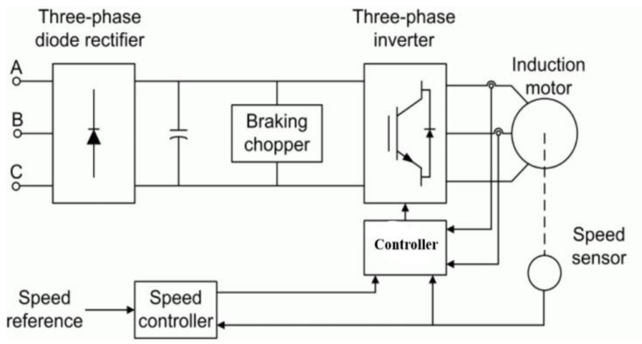

Fig. 1: Block diagram of closed loop control of IM

The fig .1 shows feedback control mechanism of induction motor. The main part of the drive is rectifier, inverter, controller and induction motor. The reference torque and rotor flux of the machine are getting from speed controller. The implementation of controller is done by using field-oriented control or sliding mode control algorithm. Compared to scalar control its offers fast dynamic response, independent control of flux and torque. The implementation level requires fast computing processor or DSP due to its computation complexity.

Revised Manuscript Received on May 30, 2019.

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III. MODELLING EQUATIONS OF INDUCTION MOTOR

The fixed stator d-q reference frame of a three-phase squirrel- cage induction machine is modelled from nonlinear differential equations. The equations are the function of electrical variables such as currents in stator, rotor flux and mechanical variable such as torque and speed. The modeling is done under the assumptions of magnetic circuit linearity, same mutual inductances, and no iron losses. Three phase voltages supplied to the motor are as follows.

$$V_{as} = V_m \sin(\omega_e t) \qquad (1)$$

$$V_{bs} = V_m \sin\left(\omega_e t - \frac{2\pi}{3}\right) \qquad (2)$$

$$V_{cs} = V_m \sin\left(\omega_e t + \frac{2\pi}{3}\right) \qquad (3)$$

Where, V_m is the amplitude of terminal voltage, and ω_e is the supply frequency.

By Park's transformation matrix, three phase stationary reference frame variable are changed into two phase stationary reference frame variables. The d-axis and q-axis voltages are formulated from equations.

$$V_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_e \varphi_{ds} \qquad (4)$$

$$V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_e \varphi_{qs} \qquad (5)$$

$$V_{qr} = 0 = R_s i_{qr} + \frac{d\varphi_{qr}}{dt} + \omega_e \varphi_{dr} \qquad (6)$$

$$V_{dr} = 0 = R_s i_{dr} + \frac{d\varphi_{dr}}{dt} - \omega_e \varphi_{qr} \qquad (7)$$

Based on Krause's model, the Flux linkage equations are given by

$$\frac{dF_{qs}}{dt} = \omega_b \left[V_{qs} - \frac{\omega_e}{\omega_b} F_{ds} - \frac{R_s}{x_{ls}}\left(F_{qs} - F_{mq}\right)\right] \qquad (8)$$

$$\frac{dF_{ds}}{dt} = \omega_b \left[V_{qs} + \frac{\omega_e}{\omega_b} F_{qs} - \frac{R_s}{x_{ls}}\left(F_{ds} - F_{md}\right)\right] \qquad (9)$$

$$\frac{dF_{ds}}{dt} = \omega_b \left[-\frac{\omega_e - \omega_r}{\omega_b} F_{dr} - \frac{R_r}{x_{lr}}\left(F_{mq} - F_{qr}\right)\right] \qquad (10)$$

$$\frac{dF_{dr}}{dt} = \omega_b \left[+\frac{\omega_e - \omega_r}{\omega_b} F_{qr} - \frac{R_r}{x_{lr}}\left(F_{md} - F_{dr}\right)\right] \qquad (11)$$

Mutual flux linkages are given as

$$F_{mq} = X_{ml}^{*}\left[\frac{F_{qs}}{x_{ls}} + \frac{F_{qr}}{x_{lr}}\right] \qquad (12)$$

$$F_{md} = X_{ml}^{*}\left[\frac{F_{ds}}{x_{ls}} + \frac{F_{dr}}{x_{lr}}\right] \qquad (13)$$

Stator current and rotor current in d and q axis are given by

$$i_{qs} = \frac{1}{x_{ls}}\left[F_{qs} - F_{mq}\right] \qquad (14)$$

$$i_{ds} = \frac{1}{x_{ls}}\left[F_{ds} - F_{md}\right] \qquad (15)$$

$$i_{qr} = \frac{1}{x_{lr}}\left[F_{qr} - F_{mq}\right] \qquad (16)$$

$$i_{dr} = \frac{1}{x_{lr}}\left[F_{dr} - F_{md}\right] \qquad (17)$$

Electromagnetic torque developed is given by

$$T_e = \frac{3}{2}\frac{p}{2}\frac{1}{w_b}\left(F_{ds} i_{qs} - F_{qs} i_{ds}\right) \qquad (18)$$

$$T_e = T_l + \frac{2}{p} J \frac{dw_r}{dt} \qquad (19)$$

Speed of the motor is given by

$$\omega_r(t) = \frac{p}{2J}\int (T_e - T_L)dt \qquad (20)$$

IV. FIELD ORIENTED CONTROL STRATEGY (FOC)

The fig.2 represents the control signal generation of FOC. In FOC, the d-q coordinate's reference frame is based on the rotor position. The flux in rotor rotating at an angular frequency which is same as stator frequency ω_e. The FOC ensure that torque and flux are autonomous variable so that it can autonomously controlled by the component of stator current i_{ds}, and $\mathbf{i_{qs}}$[2].The controller part embraces PI controller for engendering i_{ds}^{*} from the flux reference and actual rotor flux of induction motor, and torque-controlled signal i_{qs}^{*}

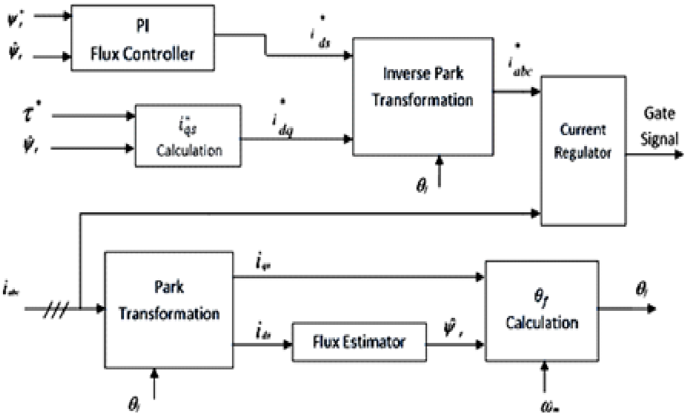


Fig.2: FOC controller

The q-axis stator current reference iqs* is calculated from reference torque input Te*as:

$$i_{qs}^{*} = \frac{2}{3}\cdot\frac{2}{P}\cdot\frac{L_r}{L_m}\cdot\frac{T_e^{*}}{|\psi_{est}|} \qquad (21)$$

Where $|\psi_{est}|$ is the estimated flux linkage of rotor

$$|\psi_{est}| = \frac{L_m\ i_{ds}}{1+\tau_{ds}} \qquad (22)$$

The d-axis stator current reference $\mathbf{i_{ds}}$***** is obtained from rotor flux reference of rotor $|\psi|_r^{*}$

$$i_{qs}^{*} = |\psi|_{r}^{*}/L_{m} \qquad (23)$$

The position of rotor flux θ_e, generated from the speed of rotor ω_m and slip frequency ω_{sl} is required for coordinates transformation.

$$\theta_e = \int(\omega_m + \omega_{sl})\,dt \qquad (24)$$

$$\text{Where } \omega_{sl} = \frac{L_m}{|\psi_r|_{est}} \cdot \frac{R_r}{L_r} \cdot i_{qs}^{*} \qquad (25)$$

The references current for the current controller ia*, ib*, ic* are generated from the current references i_{ds}^{*} and i_{qs}^{*} and it is compared with the measured current to build the inverter gating impulses.

V.SLIDING MODE CONTROLLER (SMC)

The variable structure control (VSC) is used as the key idea of SMC for the development of the control algorithm. A sliding area is defined in VSC and controller definitely forced move the drive to that area till the machine reached to the required stage [4]. Designing guidelines for sliding mode controller of induction motor is listed below. The SMC has two steps; set a surface for sliding in terms of error and generate a signal that control the machine to drive along the switching surface [5].

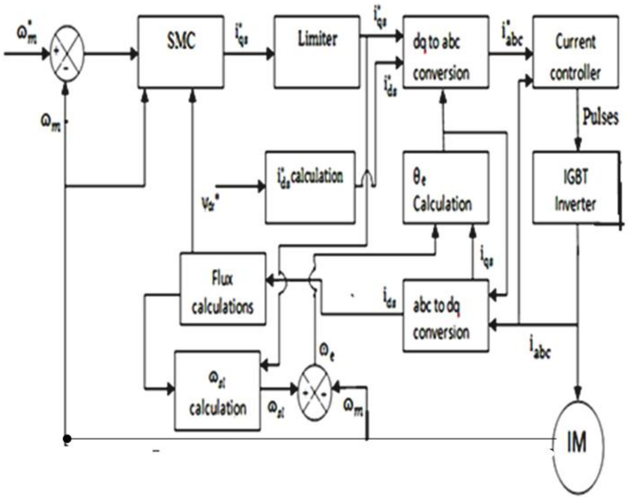


Fig. 3: SMC controller

The torque-controlled signal is created from the sliding mode controller but flux controlling signal is made same as FOC. The torque equation of the motor can be

$$T_{em} = K_T i_{qs}^{e} \qquad (26)$$

$$\text{Where } K_T = \frac{3}{2} * \frac{p}{2} * \frac{L_m}{L_r} * \lambda_{dr}^{e} \qquad (27)$$

The fundamental torque equation of the motor is

$$J\dot{\omega_m} + B\omega_m + T_L = T_{em} \qquad (28)$$

After substituting T$_{em}$ the equation become,

$$\dot{\omega_m} + a\omega_m + f = bi_{qs}^{e} \qquad (30)$$

$$\text{Where } a = \frac{B}{J}, b = \frac{K_T}{J}, f = \frac{T_L}{J}$$

If there is some uncertainties present in a, b and f then the equation can be written as

$$\dot{\omega_m} = (a + \Delta a)\omega - (f + \Delta f) + (b + \Delta b)i_{qs}^{e} \qquad (30)$$

The tracking speed error e(t)

$$e(t) = \omega_m(t) - \dot{\omega_m}(t) = -ae(t) + u(t) + d(t) \qquad (31)$$

Where $u(t) = bi_{qs}^{e} - a\dot{\omega}_m(t) - f(t) - \dot{\omega}_m(t)$ and

$$d(t) = -\Delta a\omega_m(t) - \Delta f(t) + \Delta bi_{qs}^{e}(t)$$

The sliding variable can be defined as

$S(t) = e(t) - \int_0^t (k - a)e(\tau)d\tau$; k is constant gain. (32)

The variable structure can be defined as

$$u(t) = ke(t) - \beta sgn(S) \qquad (33)$$

The assumption for obtaining the speed trajectory are the value of k<0 and β≥ $|d(t)|$

Therefore, current command signal can be written as

$$i_{qs}^{e} = 1/b\left[ke - \beta sgn(S) + a\omega_m^{*}(t) + \dot{\omega^{*}}_m(t) + f\right] \qquad (34)$$

VI.MODELLING OF IM, FOC AND SMC

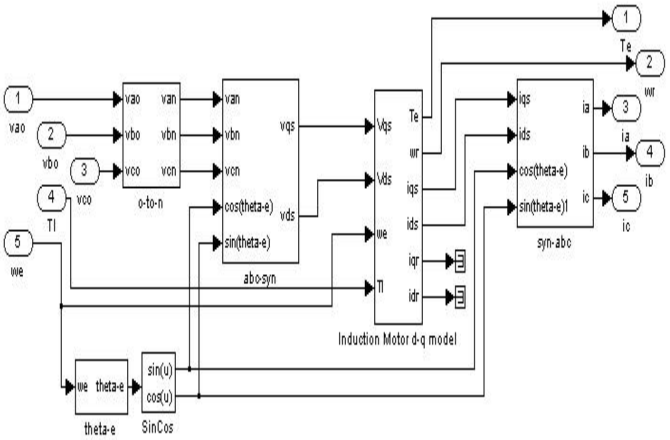
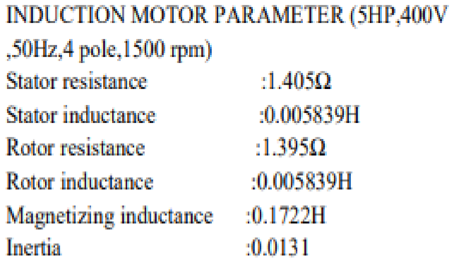


Fig.4: simulation model of IM

Table I: Parameter of induction motor



INDUCTION MOTOR PARAMETER (5HP,400V ,50Hz,4 pole,1500 rpm)	
Stator resistance	:1.405Ω
Stator inductance	:0.005839H
Rotor resistance	:1.395Ω
Rotor inductance	:0.005839H
Magnetizing inductance	:0.1722H
Inertia	:0.0131

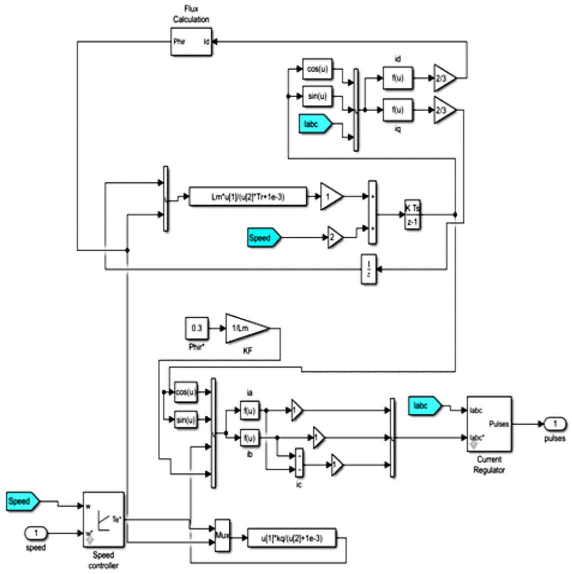


Fig .5: simulation of FOC

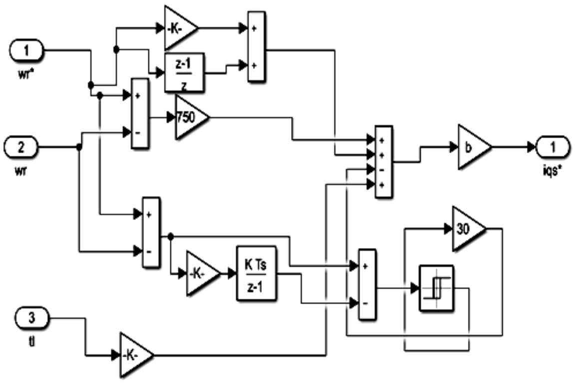


Fig.6: simulation of SMC

SIMULATION RESULT

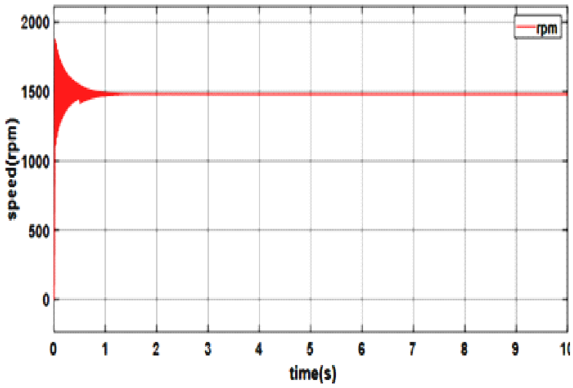


Fig.7:Speed vs time characteristics of IM

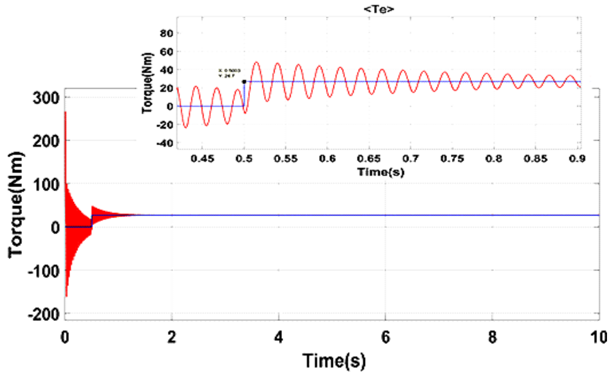


Fig.8:Torque vs Time characteristics of IM

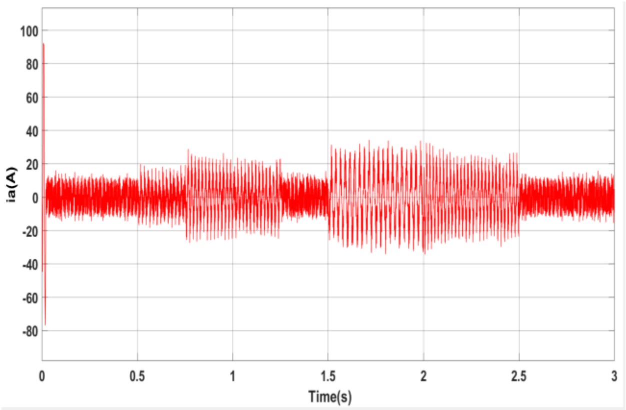


Fig .9: Current vs Time characteristics of FOC

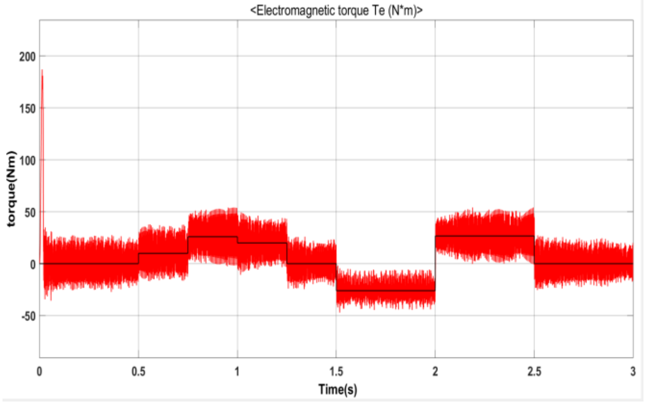


Fig .10:Torque vs time characteristics of FOC

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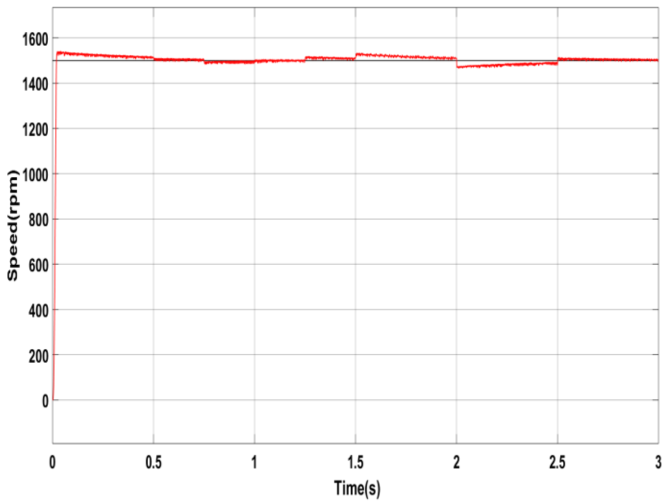

Fig.11:speed vs time characteristics of FOC

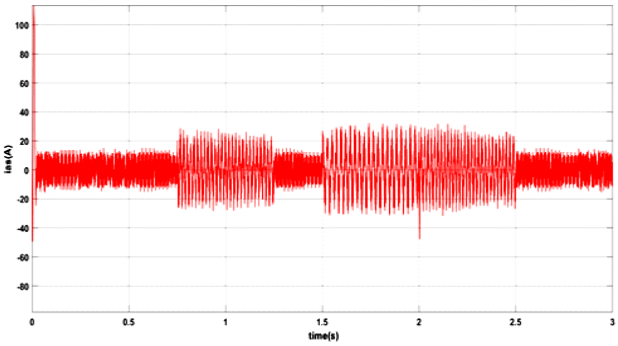

Fig.12 :Current vs Time characteristics of SMC

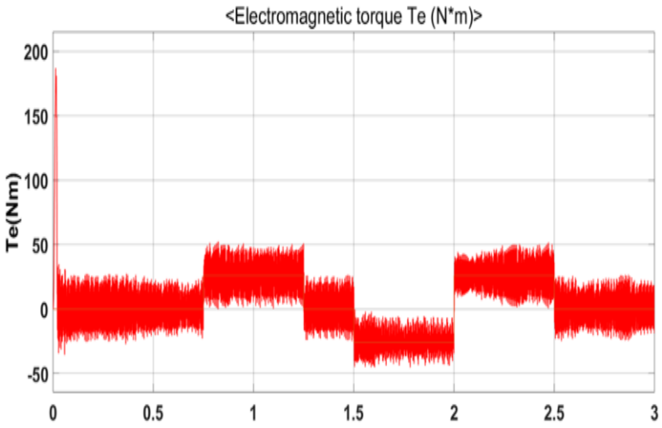

Fig.13: SMC: Torque vs time

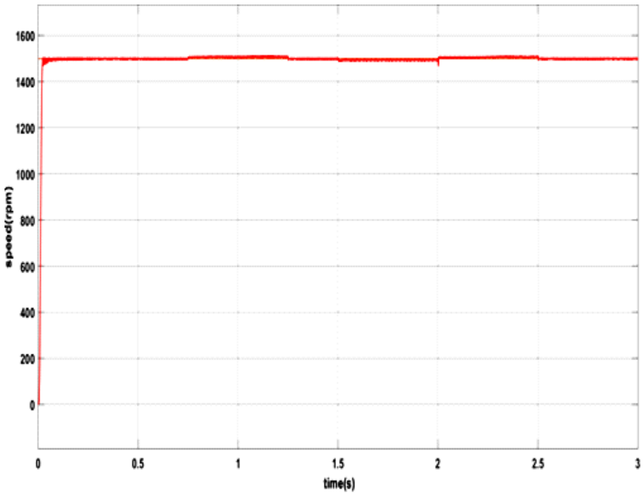

Fig 14: SMC: Speed vs time

VII.RESULT

The performance of SMC is compared with that of FOC of induction motor. The performance is evaluated in terms of load torque variations. The MATLAB/Simulink packages are used for the simulation. Before going to the controller part, the d-q modelling of induction motor is demonstrated and its performance is evaluated under rated load condition. The parameter used for the simulation are in Table I

A step signal is used as the load torque for the simulation. The investigation is focused on the torque and current ripple. The Fig.8 depicts the torque response of induction motor under normal operating condition. The rated torque of the motor was calculated as 26.7 Nm. Up to 0.5sec the motor load torque was zero and at 0.5 sec the rated torque of 26.7Nm was applied to the motor and an increase in the torque was observed from this instant. Up to 0.5 sec the motor is running under no load condition and on the application of rated load of 26.7 Nm the speed of the motor from Fig.7 is obtained as 1430 rpm at 0.5 sec.

The speed response of the FOC and SMC is evaluated by applying a load changes at different instant of time. The other parameter such as viscous friction, magnetizing inductance Lm and rotor inductance Lr are held constant. There is large fluctuation in speed response of FOC under various load condition are depicted in Fig.11and it has difficulty to attain desired speed at different load condition, therefore it is proven that FOC no robust against the changes of IM parameter. The Fig .14 shows sliding mode controller shows good speed response and always runs at its rated speed at different load condition. The torque response analysis, from Fig.10 and Fig .13 reveals the torque ripple is less in sliding mode controller compared to FOC

VIII.CONCLUSION

The control algorithm FOC and SMC are presented in this paper. From the comparative analysis the two controller shows nearly same response under no load condition. On the application of load torque SMC offers good response, less torque ripple and current ripple. The SMC controller strategy shows better performance than the FOC controller strategy in the face of system parameters variation and external load torque.

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