A Sliding Mode Control Approach for Improved Speed Performance in DTCHysteresis-Based Induction Motor

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Abstract— Recent development in power electronics and soft computing techniques made it possible to design and implement the sophisticated control strategies of AC motor drives. In this paper the Direct Torque Control (DTC) which is one of the most excellent control strategies of ac motors which give very good steady and dynamic response which is quite different from that of the field-oriented control is proposed. The proposed scheme is based on limit cycle control of both flux and torque using optimum PWM output voltage; a switching table is employed for selecting the optimum inverter output voltage vectors so as to attain as to attain as fast a torque response, as low an inverter switching frequency, and as low harmonic losses as possible. The current research directed towards the improving the performance of this technique by improving the speed performance. Sliding Mode Control technique is used to estimate the rotor speed. The main objective of this paper to improve the speed performance of the drive against uncertainties caused by load disturbances, an integral switching surface sliding mode speed controller is proposed. To verify the feasibility of the proposed method, simulation as well as comparison with the conventional DTC scheme is carried out.

Keywords: *DTC, Induction Motor, sliding mode control.*

I. INTRODUCTION

THE electric drives are machines used for motion control. At present around 75% of electric power consumed by electric drives. This electric drives are mainly DC and AC drives, later 18th century AC drives become more popular especially induction because of robustness, rugged structure ease of maintenance so widely used in industries. The Field Oriented Control (FOC) is very popular because of its good performance. Later 1980 when there was still a trend towards standardization of control systems based on FOC method [1]. The demonstration that an induction motor can be controlled like a separately excited dc motor, brought a renaissance in the high performance control of ac drives. Because of dc machine-like performance, vector control is also known as decoupling, orthogonal, or transvector control. The FOC method guarantees flux and torque decoupling [2]. However FOC drive scheme requires current controllers and coordinate transformations. Current regulated pulse width modulation (CRPWM) inverter and inner current loops degrade the dynamic performance in the operating regimes wherein the voltage margin is insufficient for the current control, particularly in the field weakening region. In FOC to design a high performance IM drive flux angle is needed for transformation, which is sensitive to identification. It has high complexity and calculations requiring trigonometric functions during dynamic flux& torque control.

DTC was introduced in Japan Takahasi and Nagochi in 1986 as an alternative to the field oriented control. The DTC having very good steady state and dynamic performance than vector control made scientists to make more research on this control strategy. The authors of the new control strategies proposed to replace motor decoupling and linearization via coordinate transformation, like in FOC, by hysteresis controllers, which corresponds very well to *on-off* operation of the inverter semiconductor power devices. These methods are referred to as *conventional* D*TC*. It controls flux and torque directly based on their instantaneous errors. Unlike field-oriented control, direct torque control does not require coordinate transformation and any current regulator [3]. It controls flux and torque directly based on their instantaneous errors [3]. In a direct torque controlled induction motor drive, supplied by a voltage source inverter, it is possible to control directly the stator flux linkage (or the rotor flux linkage, or magnetizing flux linkage) and the electromagnetic torque by the selection of optimum inverter switching modes. The selection is made to restrict the flux and torque errors within respective flux and torque hysteresis bands, to obtain fast torque response, low inverter switching frequency, and low harmonic losses. In addition to controlling the electromagnetic torque, the controlled flux linkage is the stator flux linkage. In spite of simplicity, direct torque control is capable of generating fast torque response. In addition, direct torque control minimizes the use of machine parameters [4], so it is very little sensible to the parameters variation. Hence this control algorithm is being widely used in the industry [5]. The main reason for its popularity is due to its simple structure, especially when compared with field-oriented control (FOC) scheme [6]. In CDTC the flux and torque are controlled independently by selecting one of the voltage space vectors of the VSI, in order to keep the stator flux and torque within the limits of the hysteresis bands.

One of the drawbacks of conventional DTC is disturbance in speed response during application of load torque. Industrial applications exhibit significant uncertainties, so that performance may deteriorate, if conventional controller such as PI controller is used. For this reasons it is worth to develop controllers that have capabilities of handling uncertainties caused by parameter variations. The sliding mode control can offer good performance against insensitivities to load disturbance [7], [8]. Hence, to improve the speed performance under uncertainties, a sliding mode speed controller is used for DTC in [9].

The main objective of this paper is to develop a high performance direct torque controlled induction motor drive for fast torque response. Also to improve the speed performance, under uncertainties, an integral switching surface sliding mode speed controller is developed, which is robust under uncertainties caused by load variations.

Modeling on Induction Motor is presented in Section II. DTC principle is described in Section III. In Section IV the speed performance of the drive against uncertainties caused by load disturbances are analyzed and integral sliding mode speed controller is defined. Simulation results are presented in Section V to demonstrate the performance improvements over CDTC that are obtained with proposed method. Finally conclusions are given in Section VI.

II. MODELLING OF INDUCTION MOTOR

The induction motor model can be developed from its fundamental electrical and mechanical equations. In stationary reference frame the voltage equations are given by

$$v_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt}$$
$$v_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt}$$
$$0 = R_r i_{dr} + \omega_r \Psi_{qr} + \frac{d\Psi_{dr}}{dt}$$
$$0 = R_r i_{qr} - \omega_r \Psi_{dr} + \frac{d\Psi_{qr}}{dt} \qquad (1)$$

Where p indicates the differential operator (d/dt).

The stator and rotor flux linkages are defined using their respective self leakage inductances and mutual inductance as given below

$$\Psi_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\Psi_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\Psi_{qr} = L_r i_{qr} + L_m i_{qs}$$
$$\Psi_{dr} = L_r i_{dr} + L_m i_{ds} \qquad (2)$$

III. PRINCIPLE OF CONVENTIONAL DTC

The basic block diagram representing the CDTC scheme is shown in Fig.1. The basic principle of CDTC can be explained as follows: In steady state conditions the stator and rotor flux linkage space vectors have the same angular speed and the angle δ_{sr} between these vectors determines the electromagnetic torque developed from a three-phase induction motor, according to the following expression

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\psi_r||\psi_s|\sin\delta_{sr} \qquad (3)$$

For a given induction motor, the parameters are constant and hence T_e is the function of stator flux (ψ_s), rotor flux (ψ_r) and δ_{sr}. As the rotor time constant is large for a normal squirrel cage induction motor, the rotor flux linkage can be assumed to be invariant in magnitude as well as in position for a small time interval. The stator flux is affected directly by impressed stator voltage $\overline{V_s}$.

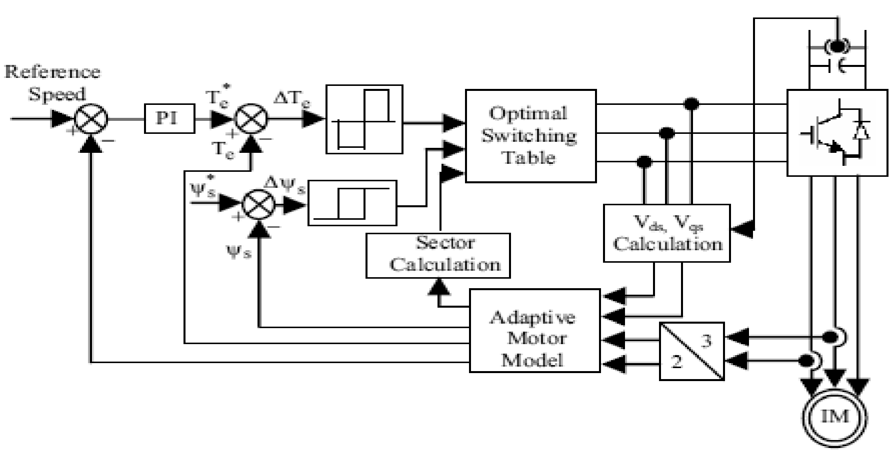

Fig.1 Block diagram of conventional DTC

A. Hysteresis Controllers

The estimated stator flux linkage and electromagnetic torque are compared with the reference values. The flux error and torque error are fed to the hysteresis controllers used for selecting appropriate voltage vector according to the switching table.

If a stator flux increase is require then, $H_{\psi} = 1$

If a stator flux decrease is required then, $H_{\psi} = 0$

The digitized output signals of the two level flux hysteresis controller are defined as

$$\text{If } \overline{\psi}_s \le \overline{\psi}_s^* - \Delta\psi_s \quad \text{then } H_{\psi} = 1$$

$$\text{If } \overline{\psi}_s \ge \overline{\psi}_s^* + \Delta\psi_s \quad \text{then } H_{\psi} = 0 \tag{4}$$

If a torque increase is required then $H_T = 1$

If a torque decrease is require then $H_T = -1$

If no change in the torque is required then $H_T = 0$

The digitized output signals of the three level torque hysteresis controller can be defined as
For the anticlockwise rotation or forward rotation

$$\text{If } T_e^* - T_e \ge \Delta T_e \quad \text{then } H_T = 1 \tag{5}$$

$$\text{If } T_e \ge T_e^* \quad \text{then } H_T = 0$$

For clockwise rotation or forward rotation

$$\text{If } T_e^* - T_e \le -\Delta T_e \quad \text{then } H_T = -1 \tag{6}$$

$$\text{If } T_e \le T_e^* \quad \text{then } H_T = 0$$

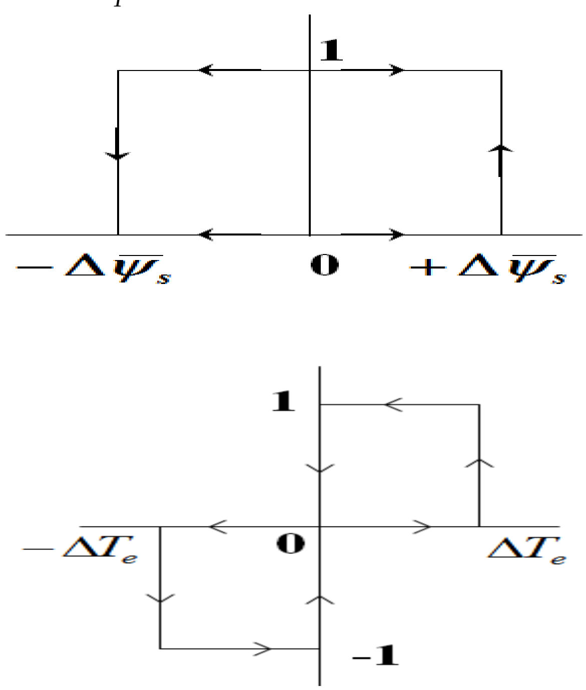

Fig.2. (a) Flux hysteresis comparator (b) Torque hysteresis comparator

B. Flux, torque estimation and sector selection

The components of the stator flux is given by

$$\psi_{ds} = \int (V_{ds} - R_{ds}\, i_{ds})dt$$

$$\psi_{qs} = \int (V_{qs} - R_{qs}\, i_{qs})dt \quad (7)$$

The stator flux linkage /phase is given by

$$\psi_s = \sqrt{\psi_{ds}^2 + \psi_{qs}^2} \quad (8)$$

The electromagnetic torque developed by the induction motor can be obtained from the knowledge of stator flux linkage and currents in stationary reference (i_{ds} and i_{qs}) frame as

$$T_e = \frac{3}{2}\frac{P}{2}\left[i_{qs}\psi_{ds} - i_{ds}\psi_{qs}\right] \quad (9)$$

Where, P is the number of poles.

Assuming the stator resistance voltage drop is small; the stator flux variation can be expressed as

$$\bar{V}_s = \frac{d\bar{\psi}_s}{dt} \text{ (or) } \Delta\bar{\psi}_s = \bar{V}_s \Delta t \quad (10)$$

Which means that $\bar{\psi}_s$ can be changed incrementally by applying stator voltage vector $\bar{V}_s$ with a time increment Δt. In order to make torque control easier, magnitude of stator flux is to be kept constant in DTC. Thus rapid changes of the electromagnetic torque can be produced by rotating the stator flux in the required direction, as directed by the torque command. The adaptive motor model takes motor currents and voltages to generate the flux, torque, speed and stator flux angle signals. The static motor data is also utilized in making calculations [5]. The estimated torque and flux are compared with their reference values in their corresponding hysteresis comparators.

The output of a three-phase voltage source inverter (VSI) has 8 possible voltage vectors, including 6 non-zero volt-age vectors (V1–V6) and 2 zero voltage vectors (V0, V7). The lines connecting the ends of the 6 non-zero voltage vectors constitute a hexagon. According to the positions of the non-zero voltage vectors, the *d–q* plane is divided into six sectors. The voltage vectors and the sectors are shown in Fig.2. Finally, the outputs of hysteresis controllers with the number of sector at which the stator flux linkage space vector is

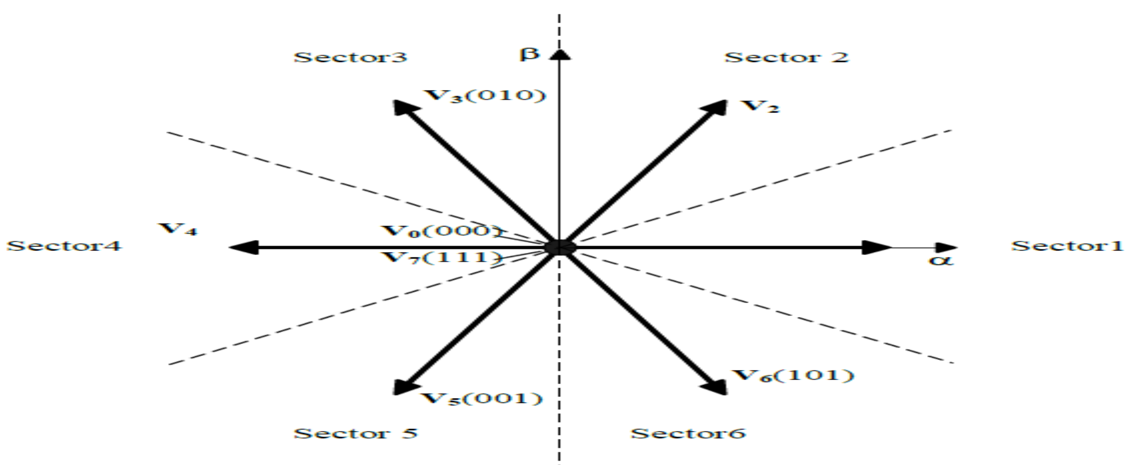

Fig 3. Eight VSI voltage vectors and six sectors

Table I: Optimum voltage vector switching table

H_ψ	H_{Te}	α(1)	α(2)	α(3)	α(4)	α(5)	α(6)
1	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_0	V_7	V_0	V_7	V_0	V_7
1	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_7	V_0	V_7	V_0	V_7	V_0
0	-1	V_5	V_6	V_1	V_2	V_3	V_4

located are fed to a switching table to select a suitable voltage vector to limit torque and flux errors within the hysteresis band, which results in a direct and decoupled control.

IV .INTEGRAL SLIDING MODE SPEED CONTROLLER

A sliding mode control (SMC) with a variable control structure is basically an adaptive control that gives robust performance of a drive with parameter variation and load torque disturbance. In an SMC, as the name indicates, the drive response is forced to track or "slide" along a predefined trajectory or "reference model" in phase plane by a switching control algorithm, irrespective of the plant's parameter variation and load disturbance. The control strategy detects the deviation of the actual trajectory from the reference trajectory and correspondingly changes the switching strategy to restore the tracking.

Control Approach:

To improve the speed performance, an integral switching surface sliding mode speed controller is proposed, whichis robust under uncertainties caused by load torque disturbances. In general, the electromechanical equation of an induction motor is described as

$$J\frac{d\omega_m}{dt} + B\omega_m + T_L = T_e \quad (11)$$

Where B and J denote the viscous friction coefficient and inertia constant of the motor respectively, *TL* is the external load torque and ω_m is the rotor mechanical speed in angular frequency. *Te* is the electromagnetic torque of induction motor, defined as

$$T_e = \frac{3}{2}\frac{P}{2}\left[i_{qs}\psi_{ds} - i_{ds}\psi_{qs}\right] \quad (12)$$

The electromechanical equation can be modified as

$$\dot{\omega}_m + a\omega_m + d = bT_e \quad (13)$$

Where a=$\frac{B}{J}$, b=$\frac{1}{J}$ and d=$\frac{T_L}{J}$

Now consider the above electromechanical equation with uncertainties as

$$\dot{\omega}_m = -(a+\Delta a)\omega_m - (d+\Delta d) + (b+\Delta b)T_e \qquad (14)$$

Δa, Δb and Δd represents the uncertainties of the terms *a*, *b* and *d* introduced by system parameters *J* and *B*.
Now let us define the tracking speed error further as

$$e(t) = \omega_m(t) - \omega*_m(t) \qquad (15)$$

Where ω_m* is the rotor reference speed command.
Taking derivative of (13) with respect to time yields

$$\dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}^*_m(t) = -ae(t) + f(t) + x(t) \qquad (16)$$

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

$$f(t) = bT_e(t) - a\omega^*_m - d(t) - \dot{\omega}^*_m(t) \qquad (17)$$

and the *x(t)*, lumped uncertainty, defined as

$$x(t) = -\Delta a\omega_m(t) - \Delta d(t) + \Delta bT_e(t) \qquad (18)$$

Now, the sliding variable with integral component, is defined as

$$S(t) = e(t) - \int_0^t (h-a)e(\tau)d\tau \qquad (19)$$

where *h* is a constant gain. Also in order to obtain the speed trajectory tracking, the following assumptions are made.
Assumtion-1: The *h* must be chosen so that the term (*h-a*) is strictly negative and hence *h<0*.
Then the sliding surface is defined as follows:

$$S(t) = e(t) - \int_0^t (h-a)e(\tau)d\tau = 0 \qquad (20)$$

based on the developed switching surface, a switching control that guarantees the existence of sliding mode, a speed controller is defined as

$$f(t) = he(t) - \beta\,\mathrm{sgn}(S(t)) \qquad (21)$$

Where β is the switching gain, *S(t)* is the sliding variable defined by (11) and *sgn(.)* is the sign function defined as

$$\mathrm{Sgn}(S(t)) = \begin{cases} +1 & \text{if } S(t)>0 \\ -1 & \text{if } S(t)<0 \end{cases} \qquad (22)$$

Assumtion-2: The gain β must be chosen so that $\beta \geq |x(t)|$ for all time.
When the sliding mode occurs on the sliding surface (19), then, $S(t) = \dot{S}(t) = 0$ and the tracking error *e(t)* converges to zero exponentially. Finally, the reference torque command T^*_e can be obtained by substituting (21) in (17) as follows.

$$T^*_e(t) = \frac{1}{b}\left[(h.e) - \beta\,\mathrm{sgn}(S) + a\omega^*_m + \dot{\omega}^*_m + d\right] \qquad (23)$$

V. SIMULATION RESULTS AND DISCUSSION

To validate the DTC Hysteresis based direct torque control of induction motor drive using sliding mode speed controller, a numerical simulation has been carried out using Matlab-Simulink platform. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 15 N-m. The induction motor used in this case study is a 1.5 KW, 1440 rpm, 4-pole, 3-phase induction motor having the following parameters:

R_s =7.83 ohm $R_r = 7.55$ ohm
L_m = 0.4535 H L_s = 0.475 H; L_r = 0.475 H
J = 0.06 Kg - m^2 B=0.01 N-m.sec/rad

For the proposed integral switching surface sliding mode speed controller, the values of h and β are chosen as h = -200 and β =10. Various conditions are simulated with and without sliding mode speed controller; the results are presented and compared to CDTC. The results for SMC based DTC are shown in Fig 4.1 to Fig 4.7.

The steady state torque plots of DTC controlled induction motor drive are shown in Fig 4.1. Fig 4.1 and Fig 4.2 show the speed, torque and current transients responses during the step change in load torque of 10 N-m without and with the proposed sliding mode speed controller. Moreover, the comparison of speed responses is shown in Fig 4.3, from which it can be observed that the speed performance has been improved with the help of proposed speed controller. Also, to validate the proposed controller, another load torque disturbance that consists of both step changes and sinusoidal disturbance as shown in Fig 4.4 has been applied on DSVM based DTC.

Fig 4.5 and Fig 4.6 show the transient responses during the new load disturbance with out and with the proposed speed controller and the comparison of speed responses is shown in Fig 4.7. From Fig 4.5, it can be observed that for sinusoidal varying load disturbances, the speed response is also varying sinusoidally. From Fig 4.3 and Fig 4.7, it can be concluded that though the load torque is added or removed the speed response is almost the same with the proposed speed controller. Thus, the speed tracking is not affected by the external load torque disturbances. Hence, the proposed speed controller is robust to the variation in load torque disturbances and provides the robustness for the drive.

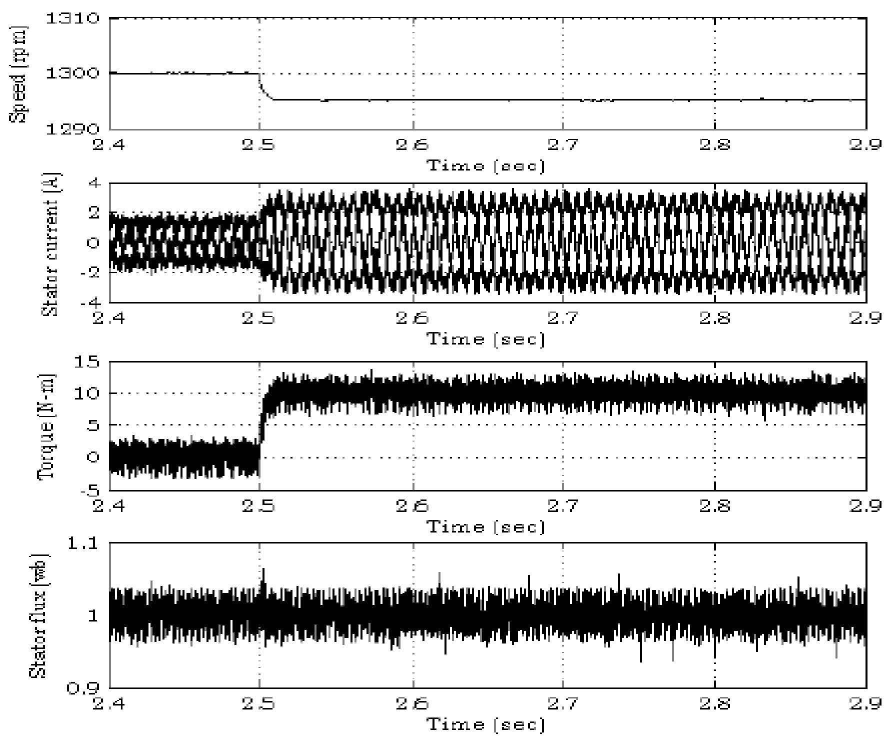

Fig.4.1. DSVM based DTC-Transients during step change in load without SMC: a 10 N-m load is applied at 2.5sec

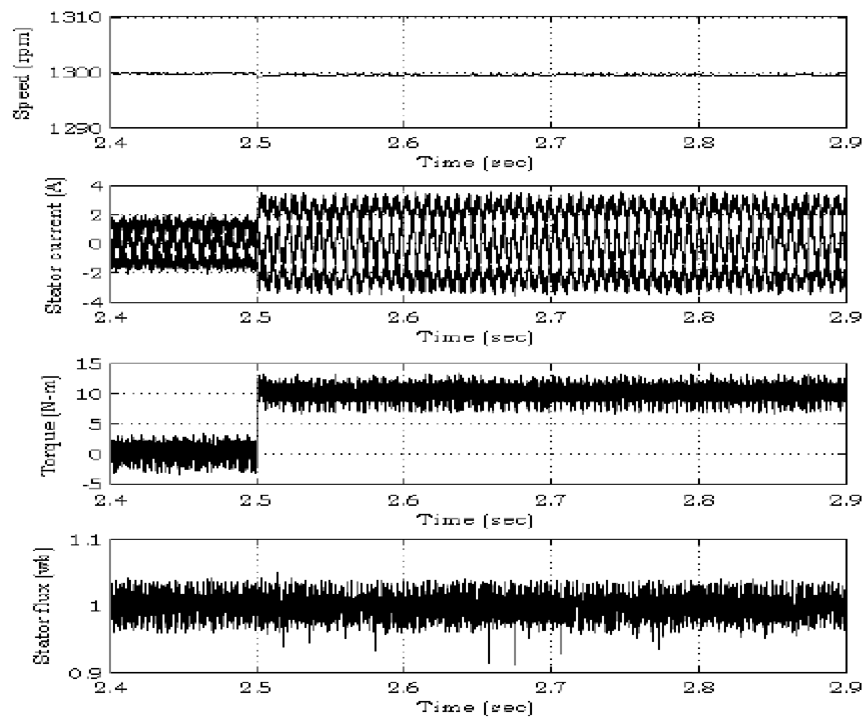

Fig.4.2. DSVM based DTC-Transients during step change in load with SMC: a 10 N-m load is applied at 2.5sec

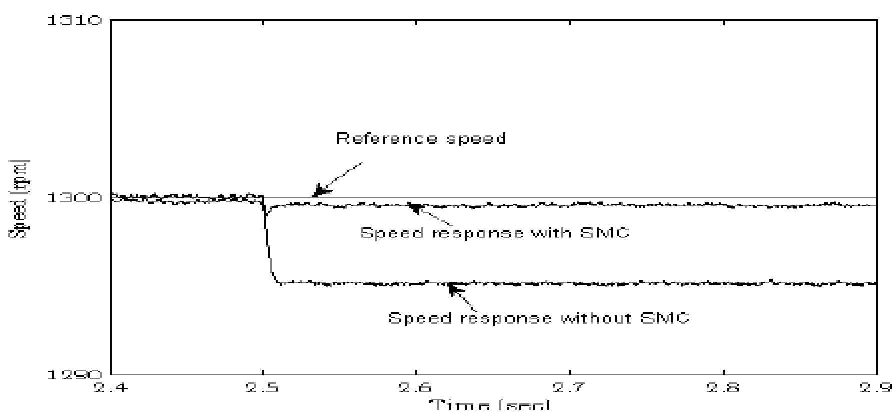

Fig.4.3 Comparison of speed responses during step change in load: a 10 N-m load is applied at 2.5 sec

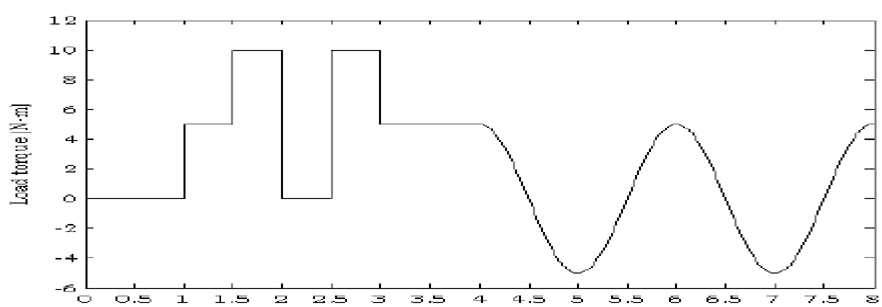

Fig 4.4 External load torque disturbance

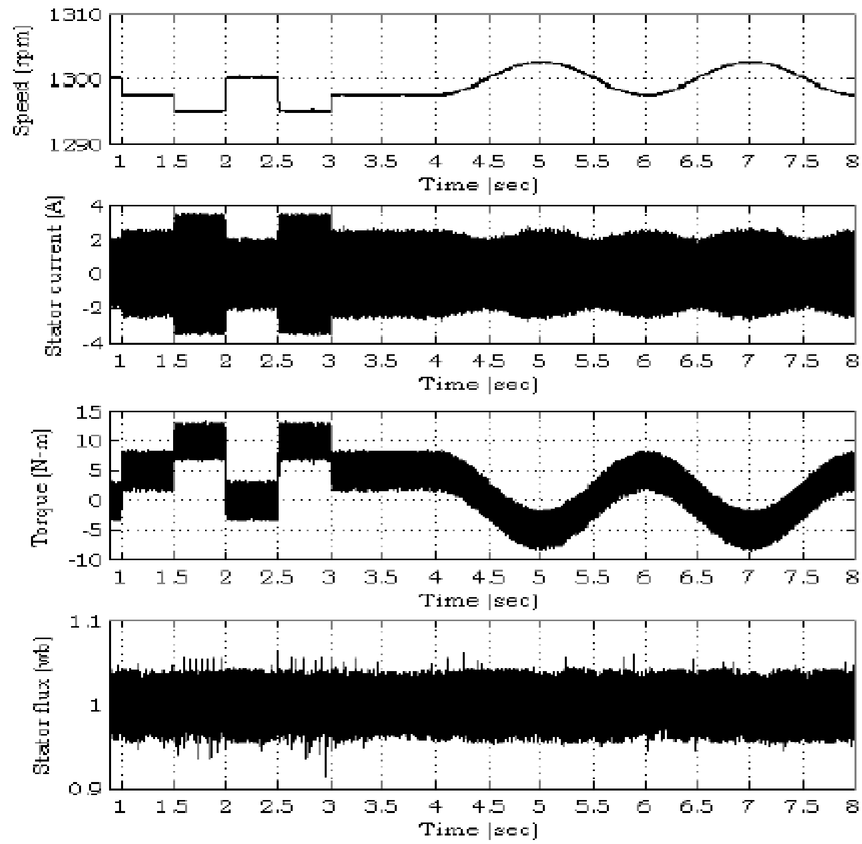

Fig 4.5 Transients during external load torque disturbances without SMC

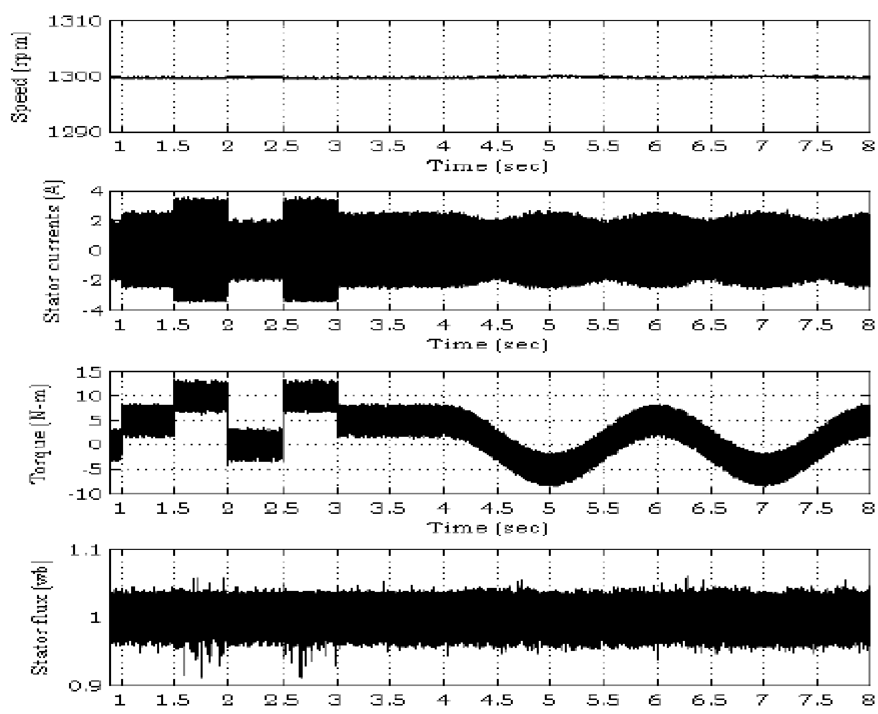

Fig 4.6 Transients during external load torque disturbances with SMC

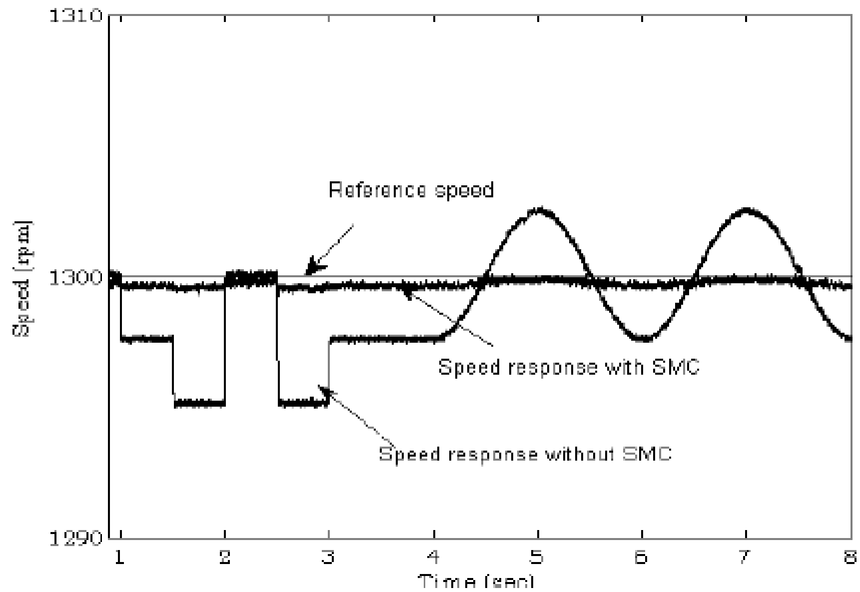

Fig. 4.7 Comparison of speed responses during external load torque disturbances

V. CONCLUSIONS

In CDTC, the steady state speed response is poor during external load torque disturbances. In order to improve the performance of CDTC in terms of speed response, in this paper SMC based DTC has been developed. Hence, it is possible to improve the response of the speed with simple control strategy with respect to basic DTC scheme. By analyzing the flux, current and torque waveforms, it has been shown that the load torque disturbance with deviation in speed response can be reduced with the Integral Sliding Mode Speed Controller. The simulations at different conditions have been carried out and the results prove the validity of the proposed control algorithm.

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