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AN IMPROVED PERFORMANCE OF VCIMD WITH SLIDING MODE CONTROLLER BASED LOOKUP TABLE STRATEGY FOR THE MITIGATIONS OF CMV

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Abstract:

This paper presents An improved Speed and Torque Performance of SMC (Sliding Mode Controller) incorporated with VCIMD (vector controlled induction motor drive) for the Mitigations of CMV (common mode voltage) with the switching tables for the generation of gating pulses through PWM signals. High performance induction motor (IM) drives require a better transient and steady state performance. The PWM procedure is a much more time consuming process. The proposed technique uses predetermined switching table to reduce the time consuming. This SMC based approach gives a quick torque response like DTC (direct torque control) and gives reduced ripple like FOC (field oriented control). The switching table is based on the conventional DTC principle, which gives good performance with reduced common mode voltage variations. To show the performance improvement in the proposed approach when compared with the conventional approach, simulation results using the SIMULINK software are presented. Results show that the performance of the proposed approach is better compared to conventional technique.

Key Words: Switching Table, FOC, CMV, SMC & IMD

1. Introduction:

To achieve good performance of IM drives, field oriented control is employed. The FOC or vector control gives an independent control of the flux and torque of the IM. The FOC was presented in a paper by F. Blaschke [1] in 1972. Hence, this control technique is becoming popular in many industrial applications. Decoupled control in FOC method requires phase transformation, the system becomes more complexity. In the literature there are so many papers able to increase the enactment of FOC [2-4]. In 1985, Takahashi introduced direct torque control (DTC) scheme [5]. In contrast to FOC, DTC method requires the knowledge of stator resistance only. Hence it decreases the associated sensitivity to parameters variation and the elimination of speed information. There is no need of phase transformation and PWM modulator in DTC as compared with FOC. Implementation of DTC is very simple because it has one lookup table and two hysteresis comparators to control both the flux and torque. A detailed comparison between FOC and DTC methods has given in [6]. Though, DTC gives fast dynamic response, it gives more current ripple at steady state for both the flux and torque responses. The conventional FOC strategy employs current controllers of hysteresis type to generate PWM signals. However, this can be achieved by using the switching tables also [7].

New proposed FOC scheme give remedies for disadvantages of both DTC & FOC, which combines the principles of both FOC & DTC. The proposed SMC based algorithm uses sophisticated switching tables to generate the PWM signals to the inverter. However new FOC scheme does not requires phase transformation and it provides better system enactment in both transient and steady state.

2. Reduced Common Mode Volatage:

Common mode voltage is the voltage between neutral terminal and the floating ground of DC bus. It is as shown in Figure 1.

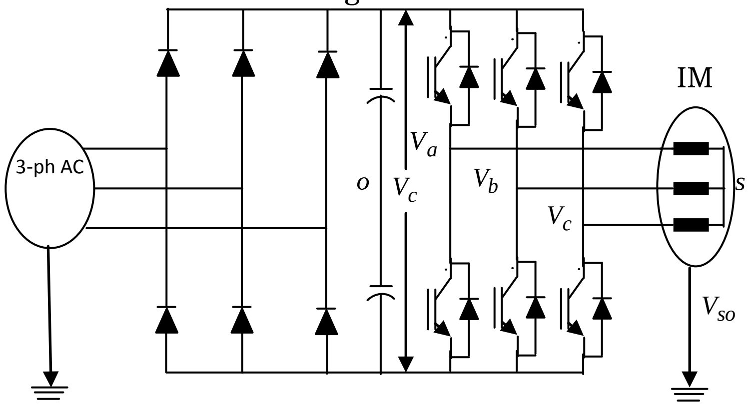

Figure 1: 3-phase VSI fed IM

The load voltage equation per phase is given in (1).

$$\begin{aligned} V_{an} &= V_{so} - V_{ao} \\ V_{bn} &= V_{so} - V_{bo} \\ V_{cn} &= V_{so} - V_{co} \end{aligned} \qquad (1)$$

Where, V_{ao}, V_{bo}, V_{co} = pole voltages of the inverter, V_{so} = CMV.

By adding equations in (1) and using $V_{an} + V_{bn} + V_{cn} = 0$, now the CMV is given as,

$$V_{com} = V_{so} = \frac{V_{ao} + V_{bo} + V_{co}}{3} \qquad (2)$$

Therefore V_{so} , in the induction motor becomes Zero when fed by balanced supply. Here induction motor fed by PWM inverter, so the power supply unbalanced and there exist V_{so} . A detailed analysis is given in various papers [8-14].

The CMV is decided by voltage of DC bus & state of switching. According to the inverter switching states the output voltage has eight vectors. The V_{SO} of inverter can be written in (3) by using inverter switching states.

$$V_{com} = V_{so} = \frac{V_{dc}}{3}(S_a + S_b + S_c) - \frac{V_{dc}}{2} \qquad (3)$$

Where, S_a, S_b, S_c = switching states of every phase.

The V_{so} of inverter for every switching state shown in Table 1,

Table 1: CMV and output voltage generated by every switching state

Switching State	Inverter Pole Voltages			V_{com}
	V_{ao}	V_{bo}	V_{co}	
V_0 (0 0 0)	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
V_1 (1 0 0)	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{6}$
V_2 (1 1 0)	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{6}$
V_3 (0 1 0)	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{6}$

V_4 (0 1 1)	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{6}$
V_5 (0 0 1)	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{6}$
V_6 (1 0 1)	$\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{6}$
V_7 (1 1 1)	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$	$\frac{V_{dc}}{2}$

The common mode voltage is $V_{dc}/3$ for transition switching vectors from odd to even (vice versa) and even (odd) to switching states. The V_{SO} is varied to $2V_{dc}/3$ when even (odd) voltage vector transition to seven voltage vector and V_{SO} is varied V_{dc} if voltage vectors transition seventh to zero (vice versa).

From the above discussion it is observed that the variation of V_{SO} worst if the voltage vectors transition from zero to zero or zero to seventh .So transition can be neglected.

3. Conventional FOC Algorithm:

As the IM has a construction which is simple, the coupling factor makes its mathematical more and more complex between a large number of variables and the non-linearities. Vector control computes the complex higher order equations. The main effectiveness of the FOC is the phase transformation. By using the FOC, stator current components are controlled. These currents are represented in synchronously rotating reference frame. The current component vector of the stator regulates the rotor flux linkages and the torque of IM. i_{ds}^* is the flux producing component and i_{qs}^* is the torque producing component. Vector of stator current is resolved as i_{ds}^* and i_{qs}^* synchronously rotating reference frame. The torque component is quadrature with flux component and these flux component lies in the direction of rotor flux linkages vector. This decouples the torque control from the flux control. The electromagnetic torque expression for an induction motor is given as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \quad (4)$$

In the independent control of FOC, the direct axis is aligned to flux and quadrature axis is aligned to torque component. The torque equation is given as in (5),

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs}\right) \quad (5)$$

Hence, the total flux of rotor can be written as in (6).

$$\psi_r = \psi_{dr} = L_m i_{ds} \quad (6)$$

From (3), it can be observed that the rotor flux is directly proportional to i_{ds}^* and is maintained constant. Hence, the torque linearly depends on i_{qs}^*, and provides a torque response as fast as the i_{qs}^* response. Then, the slip frequency can be evaluated from (7) and added to the rotor speed to generate unit vectors.

$$\omega_{sl} = \frac{L_m R_r}{L_r \Psi_r} i_{qs}^* \quad (7)$$

4. FOC Algorithm With DTC Strategy:

The electromagnetic torque expression for an induction motor can also be represented as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left|\overline{\Psi}_r\right|\left|\bar{i}_s\right|\sin\eta \qquad (8)$$

Where, η = the angle between rotor flux linkage vectors and vector of stator current is shown in Fig. 2.By (8), it is clear that the variations of torque depend on the variation of η. The torque of an IM can be controlled by changing the value of η. This is the basic principle of "proposed FOC". By rotating the direct and the quadrature axis components of the current vector, the direction of the torque is changed quickly and the T_e is produced. The rotor flux is constant in the transient period. Here, the direct and quadrature axis stator currents are fixed to the synchronously rotating reference frame. The approximate stator voltage expression can be represented as

$$\bar{v}_s = \frac{d\overline{\psi}_s}{dt} \qquad (9)$$

The stator flux linkage space vector can be represented as

$$\overline{\psi}_s = L_s\bar{i}_s + \frac{L_m}{L_r}\psi_r - \frac{L_m^2}{L_r}\bar{i}_s \qquad (10)$$

The voltage equation by keeping the vector of flux linkages of the rotor is given by (11)

$$\bar{v}_s = \frac{d\overline{\psi}_s}{dt} = \left(L_s - \frac{L_m^2}{L_r}\right)\frac{d\bar{i}_s}{dt} = \sigma L_s\frac{d\bar{i}_s}{dt} \qquad (11)$$

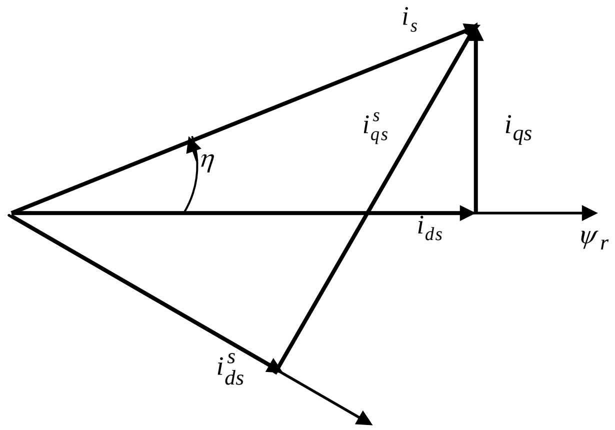

Figure 2: Representation of rotor flux linkage and stator current space vectors

Considering time Δt, expression of the stator current is given by (12).

$$\Delta\bar{i}_s = \frac{1}{\sigma L_s}\bar{v}_s\Delta t \qquad (12)$$

Thus, the space vector of stator current rotates at speed proportional to magnitude of SV (space vector) of stator voltage and moves by $\Delta\bar{i}_s$ along the space vector of stator voltage. The required direction of stator can be possible to change by selecting a suitable voltage vector. Independent control of the torque and flux is achieved by Vector Control. The control is achieved by the tangential and radial components which are $\bar{i}_{ds}$ and $\bar{i}_{qs}$ these are proportional to stator voltage vectors of same direction. The forward active voltage vector cause increase torque with η and rapid movement in I_s when assuming slow motion of the rotor flux linkage vector. The electromagnetic torque decrease and i_s becomes stationary if the zero voltage vector is utilized and the value of η decreases, because of the forward motion of rotor flux. The ratio of zero and non zero voltage vectors has to be changed for changing the speed of the stator current vector. In a three phase, two level VSI, there are eight voltage vectors, out of which two are zero state vectors and the remaining six are active state vectors as shown in Fig. 3(a). The position of the current of stator controls the stator current of direct and quadrature axis by switching the voltage vectors. The value of $\bar{i}_{ds}$ increases by the vectors $\bar{V}_2$ and $\bar{V}_6$ and decreases by vectors $\bar{V}_3$ and $\bar{V}_5$ in the same way $\bar{i}_{qs}$ increases by the vectors $\bar{V}_2$ and $\bar{V}_3$ also decreased by $\bar{V}_3$ and $\bar{V}_5$. It is as shown in Fig. 3(b). This is confined to a particular sector, in the same way other vectors of other sectors are selected. The torque and flux linkages of the stator errors are bounded in a hysteresis band. These are $2*\Delta\bar{i}_{ds}$ and $2*\Delta\bar{i}_{qs}$ in the DTC.

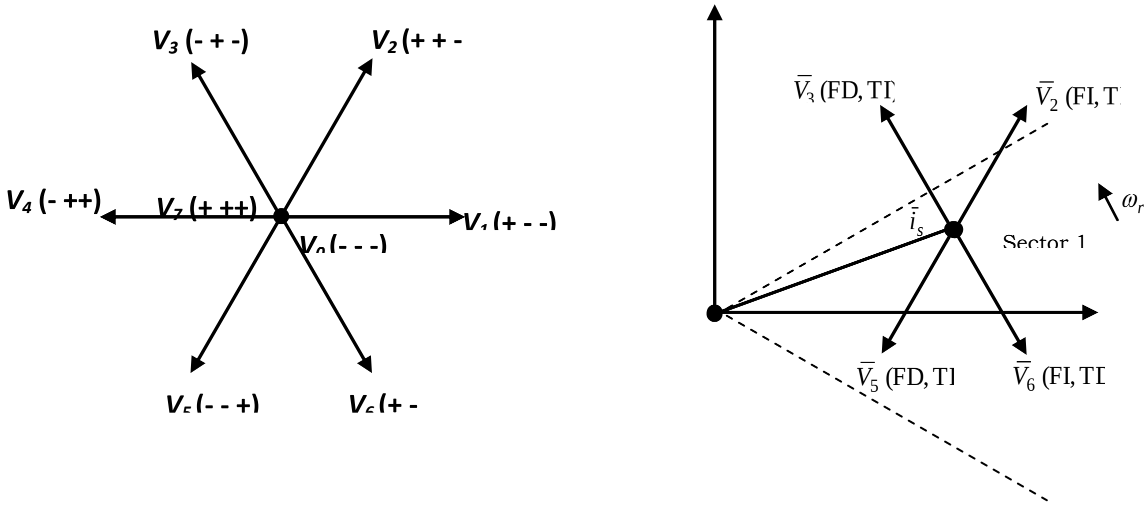

Figure 3: (a) & (b) Voltage space vectors of inverter and selection of suitable voltage space vector in sector I (-30⁰ to 30⁰) respectively

If a flux component current ($\bar{i}_{ds}$) rise is required then $S_d = 1$; if $\bar{i}_{ds}$ drop is necessary then $S_d = 0$. Two level FHC which uses digitalized output signals are defined as, $\bar{i}_{ds} \leq \bar{i}_{ds}^* - \Delta\bar{i}_s$ also $S_d = 1$ and if $\bar{i}_{ds} \geq \bar{i}_{ds}^* + \Delta\bar{i}_s$ then $S_d = 0$. If $\bar{i}_{qs}$ is increased, $S_q = 1$, if $\bar{i}_{qs}$ decrease is required then $S_q = -1$, and if no change in $\bar{i}_{qs}$ is required then $S_q = 0$. Three level THC which uses digitalized output signals for the anticlockwise rotation or forward rotation can be defined as if $\bar{i}_{qs}^* - \bar{i}_{qs} \geq \Delta\bar{i}_{qs}$ then $S_q = 1$, if $\bar{i}_{qs} \geq \bar{i}_{qs}^*$ then $S_q = 0$ and for clockwise rotation or backward rotation if $\bar{i}_{qs}^* - \bar{i}_{qs} \leq -\Delta\bar{i}_{qs}$ then $S_q = -1$ and if $\bar{i}_{qs} \leq \bar{i}_{qs}^*$ then $S_q = 0$. By using stator current vector position and S_d, S_q, the switching voltage vector which is suitable is selected from the switching table, which is given in Table 2.

Sector S_d	S_q	I	II	III	IV	V	VI
1	1	$\bar{V}_2$	$\bar{V}_3$	$\bar{V}_4$	$\bar{V}_5$	$\bar{V}_6$	$\bar{V}_1$
	-1	$\bar{V}_6$	$\bar{V}_1$	$\bar{V}_2$	$\bar{V}_3$	$\bar{V}_4$	$\bar{V}_5$
	1	$\bar{V}_3$	$\bar{V}_4$	$\bar{V}_5$	$\bar{V}_6$	$\bar{V}_1$	$\bar{V}_2$

0	-1	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$

Table 2: Optimum voltage vector switching table for reduced CMV

5. Sliding Mode Controller Based Lookup Table Strategy of Vector Controlled Induction Motor Drive:

A Sliding Mode Control (SMC) gives a robust performance of a IM with variation in the parameters and disturbances in the load torque. It is an adaptive control. In SMC the response of the IM is forced to tract sliding along a predefined trajectory by a reference model. It is done on the phase plane by control algorithm of switching in disturbances of load and variation in the parameters. The implementation of SMC is very simple. The applications of SMC are robot drives, servo with DC motors, synchronous motors and machine tool control etc.

The electromechanical equation of an induction motor is described as

$$J*\frac{d\omega_m}{dt}+B*\omega_m+T_L=T_e \qquad (13)$$

Where J = Inertia constant
B = The coefficient of viscous friction
T_L = Load torque
T_e = Electromagnetic torque of induction motor
ω_m = Rotor mechanical speed in angular frequency,

The rotor electrical speed in electrical form is given by $\omega_m=\frac{2\omega_r}{P}$.

Equation (13) can be written as in (14),

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

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

By taking (14) with disturbances,

$$\dot{\omega}_m=-(a+\Delta a)\omega_m-(d+\Delta d)+(b+\Delta b)T_e \qquad (15)$$

By considering the moment of inertia and viscous friction coefficients the disturbances of a, b and d are Δa, Δb and Δd respectively. The speed error is given by (16).

$$e(t)=\omega_m(t)-\omega_m^*(t) \qquad (16)$$

Where ω_m^* is the rotor reference speed. Then, by taking the derivative of (16) w.r.t. yields

$$\dot{e}(t)=\dot{\omega}_m(t)-\dot{\omega}_m^*(t)=-a*e(t)+f(t)+x(t) \qquad (17)$$

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

$$f(t)=b*T_e(t)-a*\omega_m^*-d(t)-\dot{\omega}_m^*(t) \qquad (18)$$

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

$$x(t)=-\Delta a*\omega_m(t)-\Delta d(t)+\Delta b*T_e(t) \qquad (19)$$

Now, the sliding variable with integral component can be defined as

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

Where, h = constant gain,

When the sliding mode occurs on the sliding surface, then, $S(t)=\dot{S}(t)=0$ and the tracking error $e(t)$ converges to zero exponentially.

$$T_e^*(t)=\frac{1}{b}\left[(h*e)-\beta*\mathrm{sgn}(S)+a*\omega_m^*+\dot{\omega}_m^*+d\right] \qquad (21)$$

Even though the load torque of DTC induction motor drive is with some uncertainties, speed tracking problem can be solved by proposed sliding mode speed control.

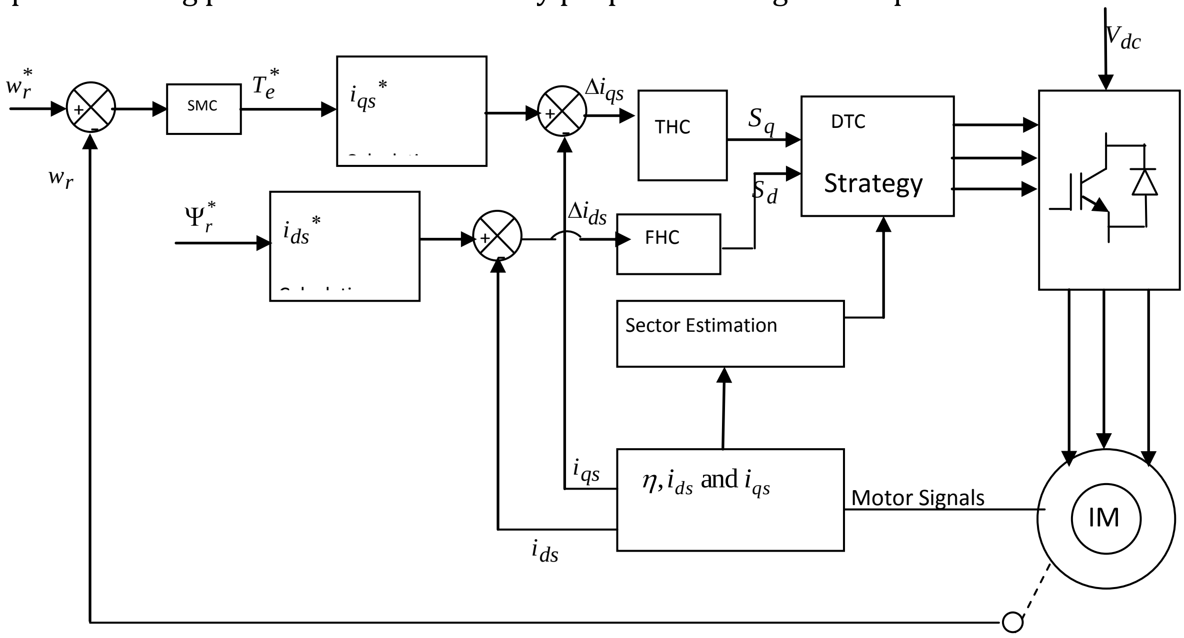

Figure 4: Block diagram of SMC based lookup table strategy of vector controlled induction motor drive

6. Results:

Matlab-Simulink environment is used to validate numerical simulation studies and proposed algorithm. The dc link voltage is taken as 600V for the simulation studies. In The Simulation induction motor parameters are chosen as R_s =1.57ohm, R_r=1.21ohm, L_m=0.165H, L_s=0.17H, L_r=0.17H and J=0.089Kg-m^2. The results of simulation are shown from Fig. 5 – Fig. 9.

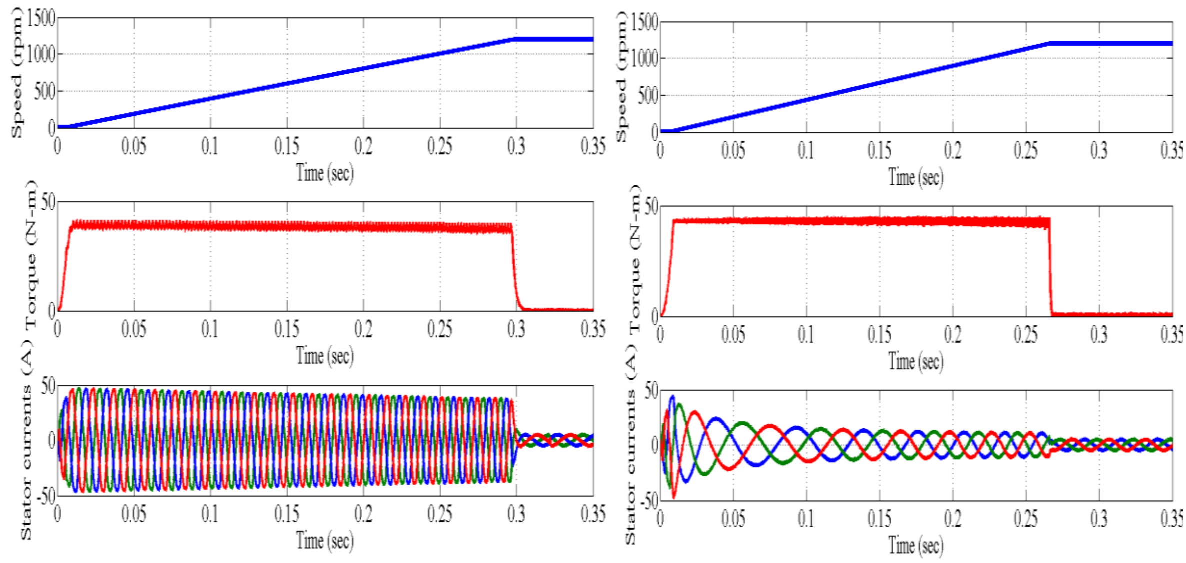

Figure 5: Starting transients of conventional and SMC based vector controlled induction motor drive respectively

It is observed that starting transients with conventional FOC are upto 0.3 secs but with SMC based FOC they are upto 0.26 secs. So there is an improvement in the transient behaviour with SMC based FOC induction motor drive.

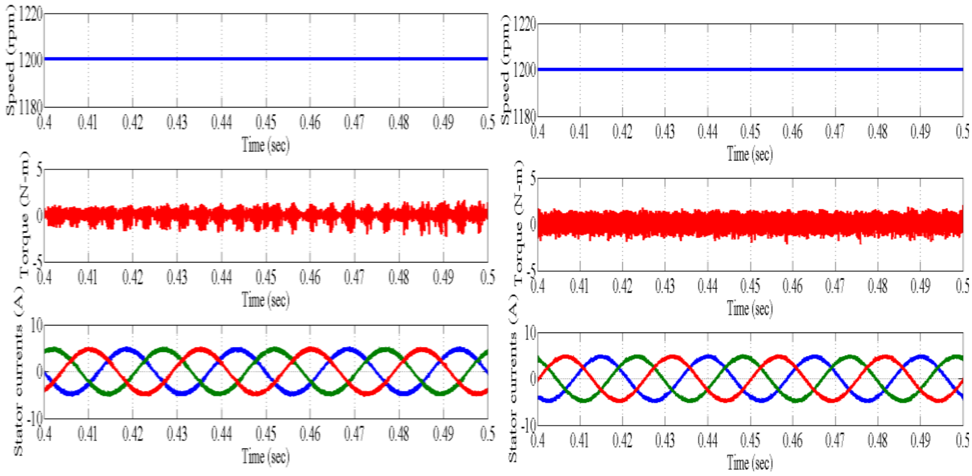

Figure 6: Steady state performance of conventional and SMC based vector controlled induction motor drive respectively

It is observed that the torque ripple is SMC based vector controlled induction motor drive is uniform when compared to conventional FOC drive.

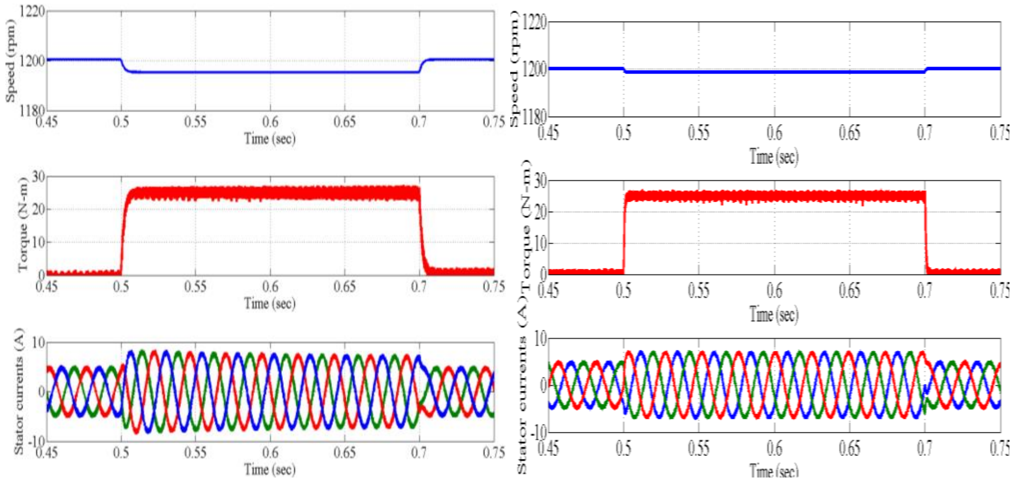

Figure 7: performance during step change in load torque conventional and SMC based vector controlled induction motor drive respectively

The response during change in load torque command (the load torque of 25 N-m is applied at 0.5 sec and removed at 0.7 sec) is shown in Fig. 7. The momentary speed decrease with SMC based vector controlled induction motor drive less when compared to conventional FOC drive

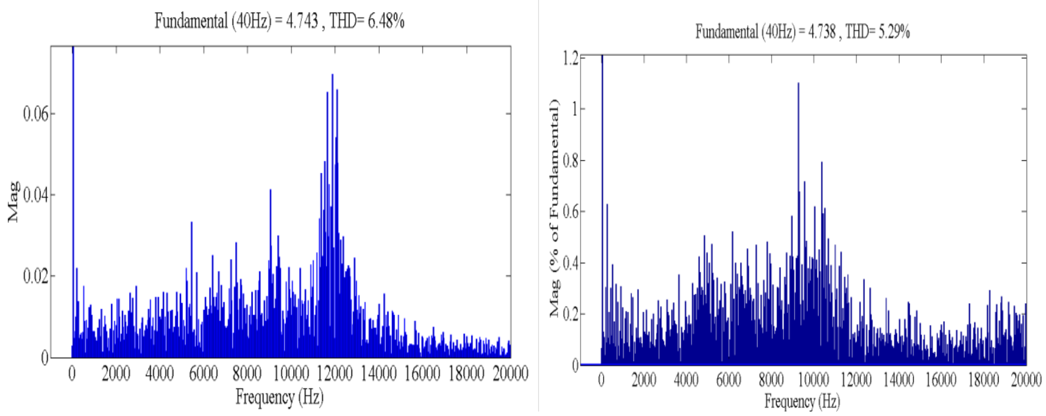

Figure 8: Harmonic spectra of line current of conventional and SMC based vector controlled induction motor drive respectively

From the simulation results it can be observed that SMC based vector controlled induction motor drive will provide good performance when compared to conventional drive.

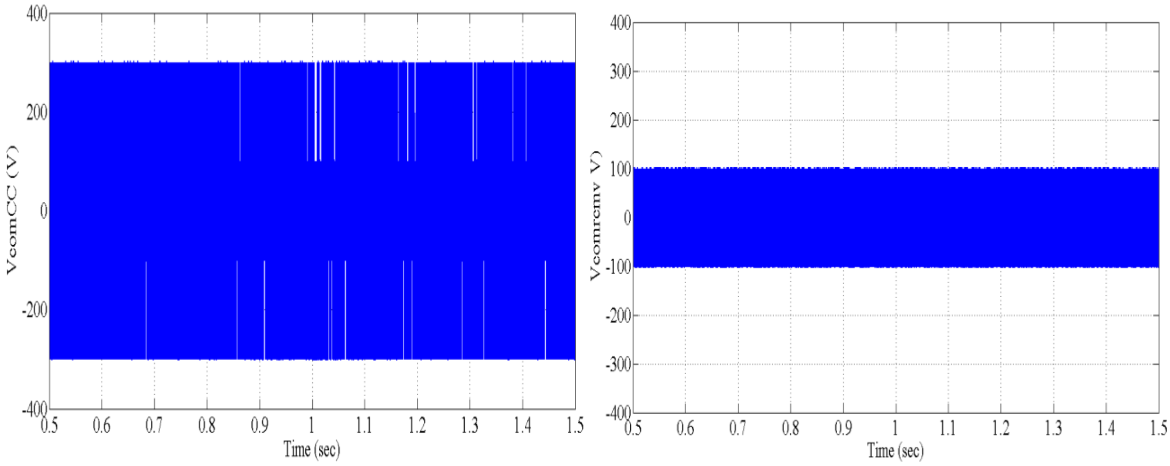

Figure 9: The variations of common mode voltage (CMV) conventional and SMC based vector controlled induction motor drive respectively

It is observed that the CMV is reduced drastically in SMC based vector controlled induction motor drive when compared to conventional FOC drive.

7. Conclusion:

The proposed approach combines the basic FOC principle and DTC algorithms with SMC controller. It uses the instantaneous errors in d-and q axes stator currents and sector information to select suitable vector of voltage. Hence, the time consuming problem in PWM technique id eliminated by using predetermined switching table in the proposed algorithm. In this paper, zero voltage vectors are not applied to reduce the variations in CMV. It is observed from the simulations results the drive shows good performance at the time of starting due to the proposed algorithm. When there is a step change in the load torque, the momentary decrease in speed with the proposed method is less. Finally the proposed method will provide less THD in steady state current ripple and drastic reduction in CMV variations when compared to the conventional FOC approach.

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