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VSI fed IM drive employing look –up tables with 6&12 sectors

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Abstract: Since the IM drives play a vital role for variable speed applications from fractional horse power to multi Mega-watt power, the control and estimation of induction motor drives constitute a vast subject. Nowadays, vector control and direct torque control (DTC) are popular for high performance drives. Even though these methods give better performance, the vector control method needs reference frame transformations and direct torque control gives large steady state ripples. To overcome these problems in the above methods mentioned, this paper presents an advanced vector control method for voltage-source inverter fed induction motors using sophisticated look-up tables. This method uses a predetermined look-up table instead of a much more time consuming pulse width modulation (PWM) procedure in conventional vector control for generating inverter gate signals. This approach gives faster torque response like in vector control methods and it also reduces ripples as in DTC method. To validate the proposed method numerical simulations have been carried out and compared with the existing algorithms. The simulation results confirm the effectiveness of the proposed method.
Key Words— Induction Motor Drive, Look-up table, Vector Control

1. Introduction

High performance induction motor drives require decoupled torque and flux control. This control is commonly provided through vector control. Vector control schemes require reference frame transformation. DTC as compared to FOC is advantageous in aspects such as absence of co-ordinate transformation and PWM modulator. DTC is also very simple in its implementation as it needs only two hysteresis comparators and a lookup table for both flux and torque control. A detailed comparison between vector control and DTC has given in. Though, DTC gives fast transient response, it gives large ripple in steady state. Hence to overcome the drawbacks of vector control and DTC, this paper presents a new vector control scheme, which combines the principles of both vector control and DTC. For the current controllers, several look-up tables have given in. This paper also presents, a sophisticated look-up table based vector control algorithm. The proposed method does not require reference frame transformations and give good steady state and transient responses.

2. Mathematical Modeling of Induction Motor

The voltage expressions of a three-phase induction motor in stator reference frame are given as in (1)

$$\bar{v}_s = R_s\bar{i}_s + \frac{d\bar{\lambda}_s}{dt} \quad (1)$$

$$\bar{v}_r = R_r\bar{i}_r - j\omega_r\bar{\lambda}_r + \frac{d\bar{\lambda}_r}{dt} \quad (2)$$

The dynamic equations of the induction motor can be represented by using flux linkages as variables, which involves the reduction of a number of variables in the dynamic equations. The stator and rotor flux linkages in the stator reference frame are defined as in (2).

$$\overline{\lambda}_s = L_s \bar{i}_s + L_m \bar{i}_r \quad (3)$$

$$\overline{\lambda}_r = L_m \bar{i}_s + L_r \bar{i}_r \quad (4)$$

The electromagnetic torque and electromechanical expressions of the induction motor are given by

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

And $T_e = T_L + J\dfrac{d\omega_m}{dt} = T_L + \dfrac{2}{P}J\dfrac{d\omega_r}{dt}$ (6)

3. Vector Control of Induction Motor

The induction motor's dynamic model equations are non-linear and multi-variable. Also, an additional non-linearity is seen in the machine model due to variation of machine parameters with saturation temperature and skin effect. There are also coupling effects between input and output variables i.e., both torque and flux are functions of voltage and frequency. In the vector control algorithm, the machine torque and rotor flux linkage are controlled through stator current vector control. The stator current vector is divided into a torque producing component (i_{qs}^*) and flux producing component (i_{ds}^*) in a rotating frame of reference. The flux component i_{ds}^* is along the machine flux linkage vector and the torque component i_{qs}^* is perpendicular to the flux component. This represents the decoupling effect between torque and flux. The electromagnetic torque expression for an induction motor is given by

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\mathrm{Re}\left(j\overline{\lambda}_r \cdot \bar{i}_s^{\,*}\right) = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}\right) \quad (7)$$

For decoupling control, the q-axis flux component must be made equal to zero. Then the torque expression can be modified as given in (8).

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\lambda_{dr} i_{qs}\right) \quad (8)$$

Hence, the total rotor flux equal to $\lambda_r = \lambda_{dr}$ and given as in (9).

$$\lambda_r = \lambda_{dr} = L_m i_{ds} \quad (9)$$

From (9), 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 faster torque response than the current (i_{qs}) response. Then, the slip frequency ω_{sl} is added to the rotor speed to generate unit vectors. The block diagram of indirect vector controlled induction motor drive is as shown in Fig.1.

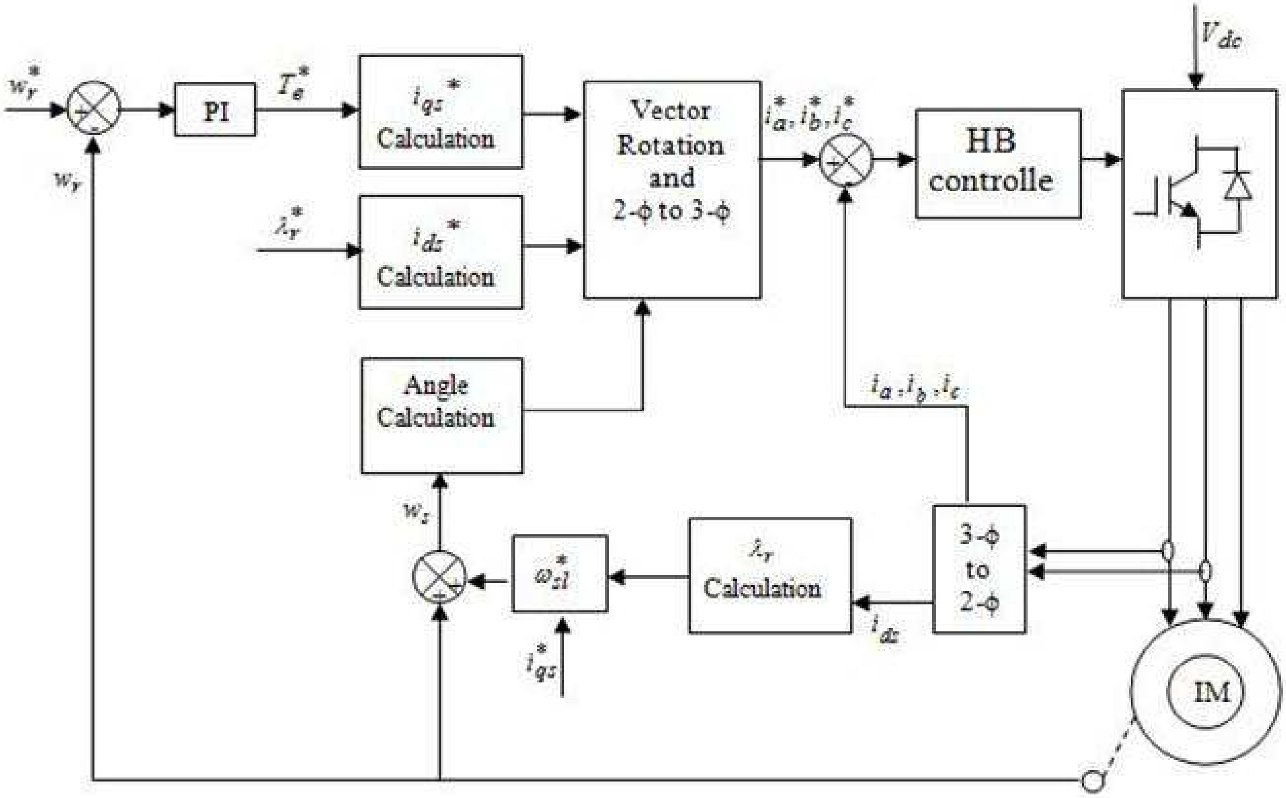

Fig. 1 Block diagram of indirect vector controlled induction motor drive

The d-q axes currents then transformed from rotating to stationary and then converted from two-phase to three-phase currents. Then, the reference three-phase currents are compared with the actual three-phase stator currents in the hysteresis band type current controller, from which the pulses can be generated and given to the voltage source inverter.

4. Proposed Vector Control Algorithm for Induction Motor

The electromagnetic torque expression for an induction motor, which is given in (7), can be represented as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left|\bar{\lambda}_r\right|\left|\bar{i}_s\right|\sin\eta \tag{10}$$

where η is the angle between stator current and rotor flux linkage vectors as shown in Fig. 2.

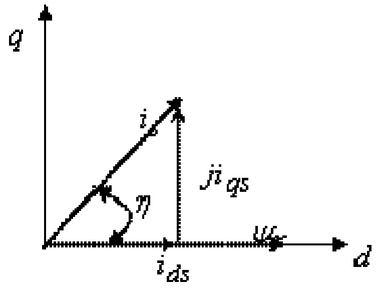

Fig. 2 Representation of stator current vector and rotor flux linkage space vectors

From (10), it can be observed that the torque dynamics depends on the variation of η. Hence, fast torque control can be achieved by rapidly changing 'η' in the required direction. This is the basic objective of "proposed vector control". During a short transient, the rotor flux remains almost unchanged, thus rapid changes of electromagnetic torque can be produced by rotating the d and q components of stator current vector in the required direction. By ignoring the stator resistance drop, the stator voltage expression can be represented as

$$\bar{v}_s \cong \frac{d\bar{\lambda}_s}{dt} \tag{11}$$

From (3) and (4), the stator flux linkage space vector can be represented as given in (12).

$$\bar{\lambda}_s = L_s \bar{i}_s + \frac{L_m}{L_r}\lambda_r - \frac{L_m^2}{L_r}\bar{i}_s \tag{12}$$

Then the stator voltage expression can be represented as given in (13).

$$\bar{v}_s = \frac{d\bar{\lambda}_s}{dt} = L_s \frac{d\bar{i}_s}{dt} + \frac{L_m}{L_r}\frac{d\bar{\lambda}_r}{dt} - \frac{L_m^2}{L_r}\frac{d\bar{i}_s}{dt} \tag{13}$$

As the rotor time constant is high, the rotor flux linkage space vector will move slowly. Hence, for short time durations, the rotor flux linkage vector is assumed as constant. This simplifies the voltage expression as follows.

$$\bar{v}_s = \frac{d\bar{\lambda}_s}{dt} = \left(L_s - \frac{L_m^2}{L_r}\right)\frac{d\bar{i}_s}{dt} = \sigma L_s \frac{d\bar{i}_s}{dt} \tag{14}$$

For a short time interval of Δt, the stator current expression can be represented as given in (15).

$$\Delta\bar{i}_s = \frac{1}{\sigma L_s}\bar{v}_s \Delta t \tag{15}$$

Thus, the stator current space vector moves by $\Delta\bar{i}_s$ in the direction of the stator voltage space vector at a speed proportional to magnitude of voltage space vector (i.e. dc link voltage). By selecting the appropriate stator voltage vector step-by-step, it is then possible to change the stator current in the required direction. Decoupled control of the torque and stator flux is achieved by acting on the radial (flux component current $\bar{i}_{ds}$) and tangential components (torque component current $\bar{i}_{qs}$) of the stator current vector in the locus.

Considering the three-phase, two-level, six pulse voltage source inverter (VSI), there are six non-zero active voltage space vectors and two zero voltage space vectors as shown in Fig.3. The six active voltage space vectors can be represented as

$$\bar{V}_k = \frac{2}{3}V_{dc}\exp\left[j(k-1)\pi/3\right] \qquad k = 1,2,\ldots,6 \tag{16}$$

Depending on the position of stator current vector, it is possible to switch the appropriate voltage vectors to control both d and q axes stator currents. As an example if stator current vector is in sector I, then voltage vectors $\bar{V}_2$ and $\bar{V}_6$ can increase $\bar{i}_{ds}$ and $\bar{V}_3$ and $\bar{V}_5$ can decrease the $\bar{i}_{ds}$. Similarly $\bar{V}_2$ and $\bar{V}_3$ can increase the torque component current $\bar{i}_{qs}$ and $\bar{V}_5$ and $\bar{V}_6$ can decrease the $\bar{i}_{qs}$. Similarly the suitable voltage vectors can be selected for other sectors.

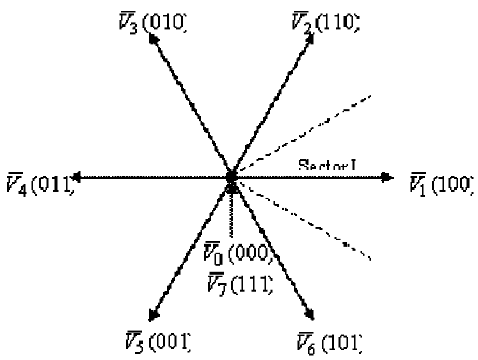

Fig. 3 Inverter voltage space vectors with 6-sector division

Table 1. Optimum voltage Switching vector look up table with 6-sectors

N		1	2	3	4	5	6
$S_d = 1$	$S_q = 1$	110	010	011	001	101	100
	$S_q = 0$	111	000	111	000	111	000
	$S_q = -1$	101	100	110	010	011	001
$S_d = 0$	$S_q = 1$	010	011	001	101	100	110
	$S_q = 0$	000	111	000	111	000	111
	$S_q = -1$	001	101	100	110	010	011

The proposed vector controlled induction motor drive block diagram s shown in fig.4

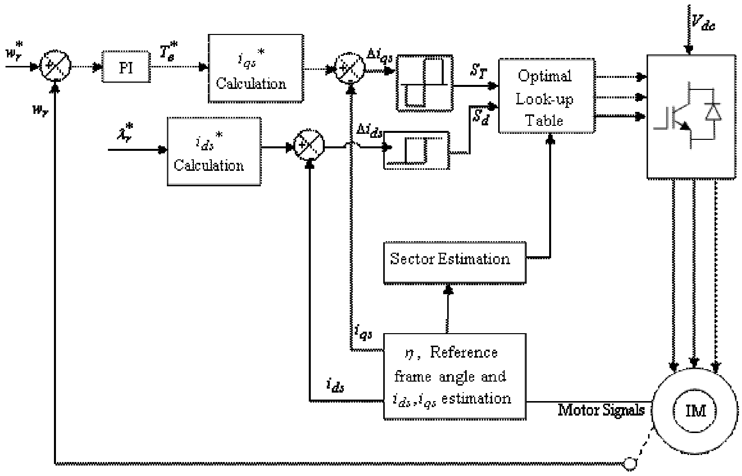

Fig. 4 Block diagram of proposed vector controlled induction motor drive

As in conventional vector control, the proposed vector control algorithm generates d- and q- axes commands. Then as in DTC, the proposed algorithm uses hysteresis current controllers and switching table. Thus, the proposed algorithm eliminates time consuming PWM procedure. The generated d and q axis current commands are compared with their actual current values obtained from the measured phase currents. The current errors are used to produce d and q flags as inputs to the switching table. A third input to the table determines the sector through which the current vector is passing. It is produced by having the d and q axis currents and the rotor position. The switching table provides the proper voltage vectors by deciding on the status of the inverter switches. In field oriented control, the current decoupling network is a feed forward (indirect) method to produce flux orientation. In proposed control system, Current decoupling means to determine the reference current space phasor i_{ds}^*, i_{qs}^*, based on reference rotor flux λ_r^* and torque T_e^*. Based on the outputs of hysteresis controllers and position of the stator current vector, the optimum switching table will be constructed. This gives the optimum selection of the switching voltage space vectors for all the possible stator current vector positions. As in DTC, the stator flux linkage and torque errors are restricted within their respective hysteresis bands, which are $2\Delta\bar{i}_{ds}$ and $2\Delta\bar{i}_{qs}$ respectively. For the current control strategy it is enough to analyze only signs of voltage vector components $\bar{V}_{sd}$ and $\bar{V}_{sq}$. In order to utilize all six active states per sector the stator flux locus is divided into twelve sectors instead of six. This novel stator flux locus is introduced in Fig. 5. However, it is necessary to define small and large variations. It is observed that V1 will produce a large increase in flux and a small increase in torque in sectorS12. In contrast to this,V2 will increase the torque in large proportion and the flux in a small one. The hysteresis block should consist of four levels so that the torque error can be divided in the number of intervals that are measured later. The look up table for 12-sector is shown in Table.2

Table 2 Optimum voltage switching vector lookup table

Sector / F	T	1	2	3	4	5	6	7	8	9	10	11	12
FI	TI	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
FI	TsI	*V_2	V_2	*V_3	V_3	*V_4	V_4	*V_5	V_5	*V_6	V_6	*V_1	V_1
FI	TsD	V_1	*V_1	V_2	*V_2	V_3	*V_3	V_4	*V_4	V_5	*V_5	V_6	*V_6
FI	TI	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
FD	TI	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3
FD	TsI	V_4	*V_4	V_5	*V_5	V_6	*V_6	V_1	*V_1	V_2	*V_2	V_3	*V_3
FD	TsD	V_7	V_5	V_0	V_6	V_7	V_0	V_0	V_2	V_7	V_3	V_0	V_4
FD	TI	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5

5. Simulation Results and discussions

To verify the proposed algorithm, a numerical simulation has been carried out using MATLAB-Simulink. The induction motor parameters are: R_s = 4.1Ω, R_r = 2.5 Ω, L_s = 0.545 H, L_r = 0.542 H, L_m = 0.51 H, number of poles = 4 and J = 0.04 Kg-m^2. The results of conventional vector control and proposed vector control algorithms are presented and compared. The simulation studies have been carried for various conditions such as starting, steady state, load change and speed reversal with a PI type speed controller. The results of conventional vector control algorithm are given in Fig. 7 – Fig. 12 and the results of proposed algorithm for 6-sectors are given in Fig.13–Fig.18 andfor12-sectorsaregiveninFig.19–Fig.24

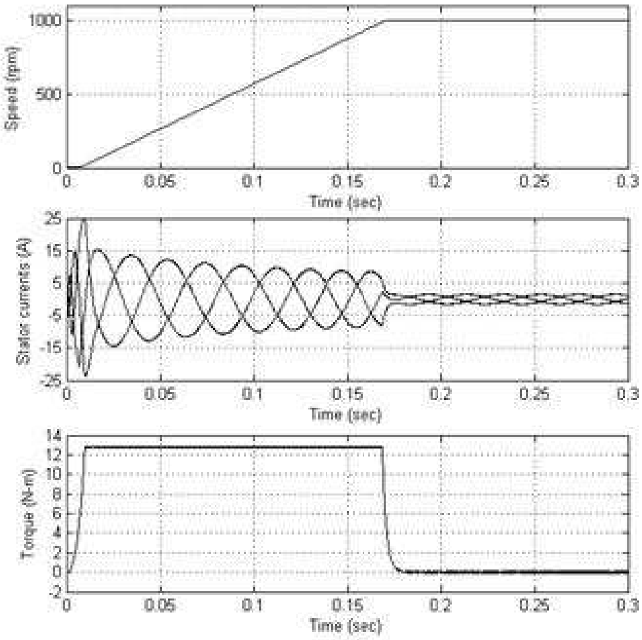

Fig.7 starting transients in conventional vector control algorithm

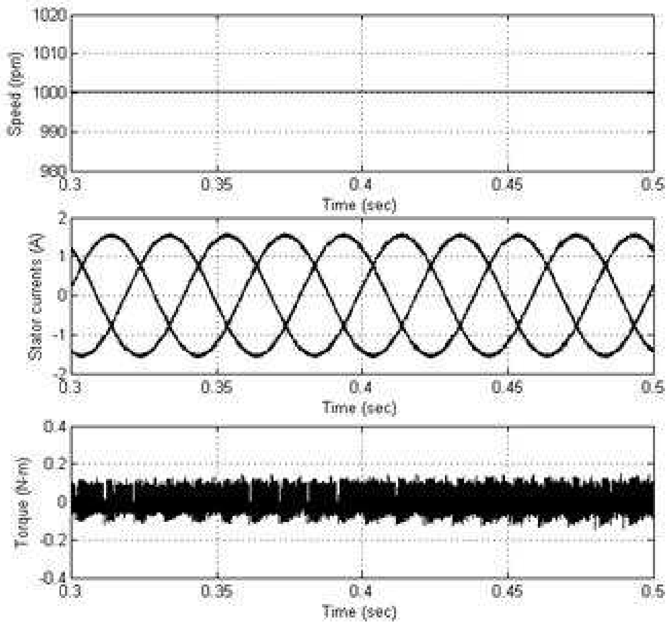

Fig.8 steady state plots in conventional vector control algorithm

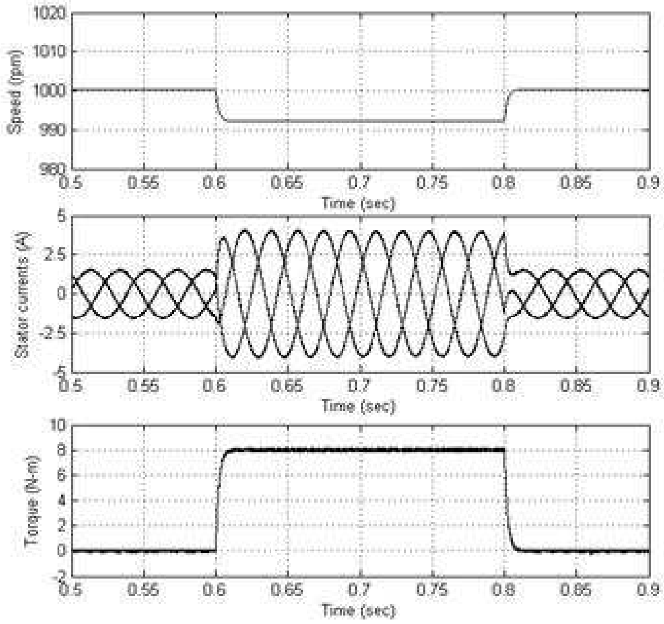

Fig.9 transients during load change in conventional vector control algorithm

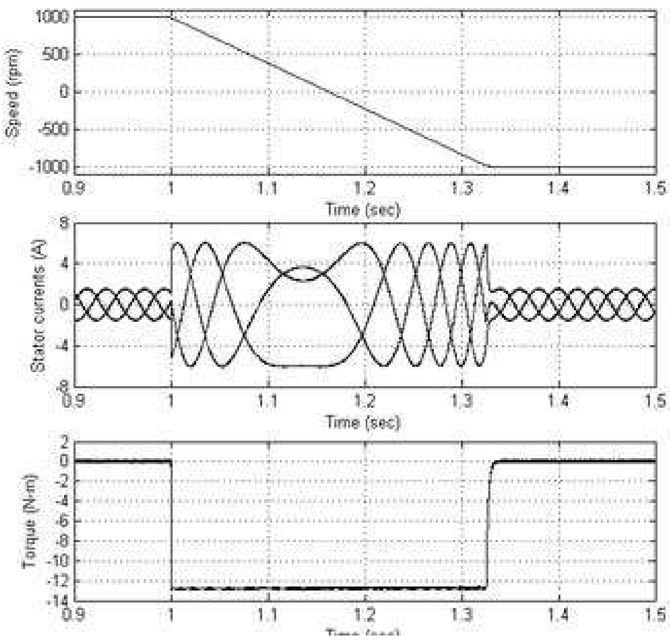

Fig.10 transients during speed reversal (speed is changed from +1000 rpm to -1000 rpm)

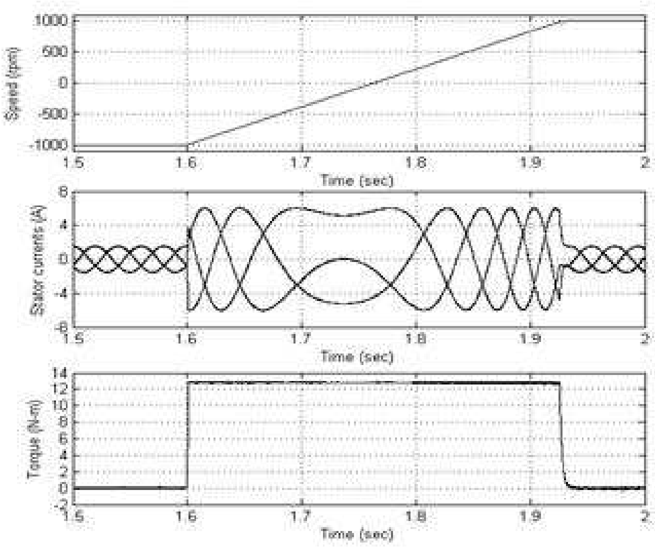

Fig.11 transients during speed reversal (speed is changed from -1000 rpm to +1000 rpm)

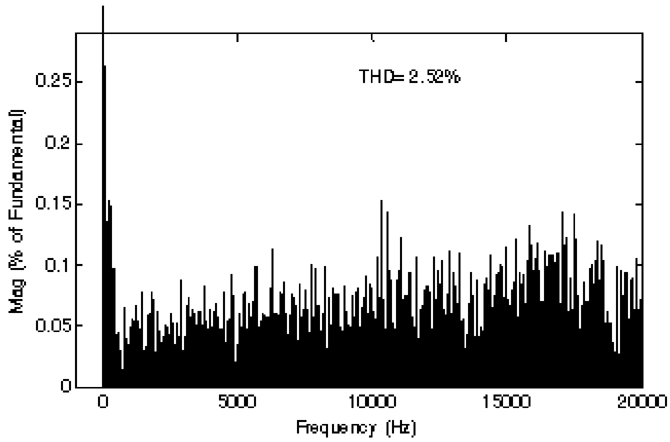

Fig.12 Harmonic distortion of stator current in conventional vector control algorithm

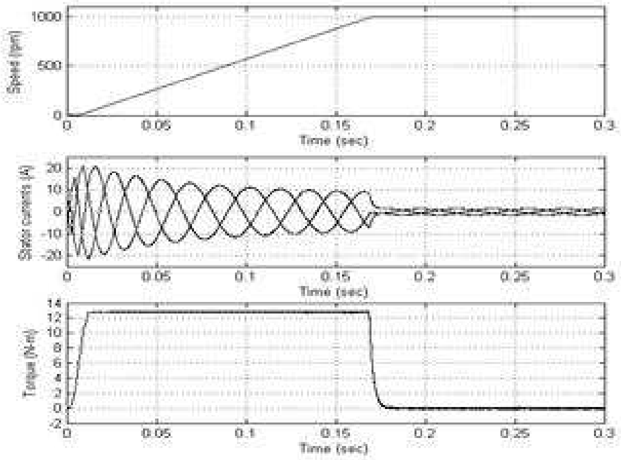

Fig.13 Motor speed, stator current and torque during the starting period with 6-sectors

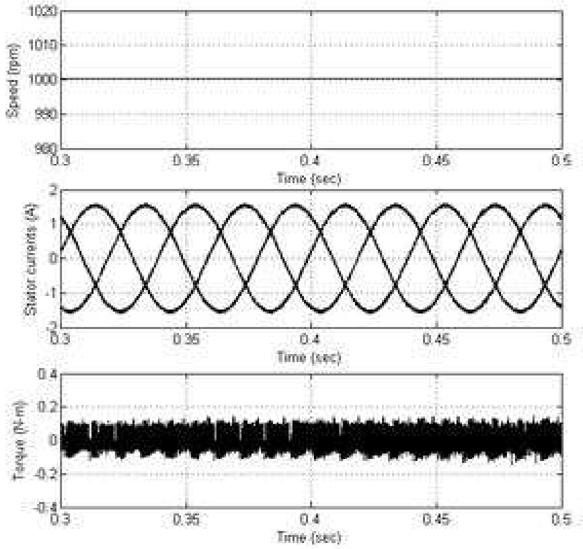

Fig.14 Motor speed, stator current and torque during the steady state period with 6-sectors

6. Conclusions

A novel vector control algorithm is presented in this paper for the VSI-fed induction motor drive. The proposed algorithm combines the basic principles of vector control and direct torque control algorithms. It uses the instantaneous errors in d-and q axes stator currents and sector information to select the suitable voltage vector. Hence, the proposed algorithm uses a predetermined look-up table instead of a much more time consuming PWM procedure in conventional vector control algorithm. The proposed algorithm is validated through simulation results. From the results, it can be concluded that the proposed method is simple and gives good transient performance with slightly increased steady state ripple in stator current.

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