Computer Engineering and Intelligent Systems www.iiste.org
ISSN 2222-1719 (Paper) ISSN 2222-2863 (Online)
Vol 2, No.6, 2011

Application of sophisticated look-up tables with 12-sectors for vector control of induction motor drive

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Abstract: The control of Induction motor drives constitutes a vast subject and with the advent of latest technologies like vector control, direct torque control etc., these drives have been playing a vital role in the industries for variable speed applications. The control strategies of induction motor drives are more complex than DC drive control strategy. This is because in AC drives variable frequency, variation of machine parameters occurs. The various control strategies for the inverter fed induction motor have provided good steady state but poor dynamic response. To overcome the problem of undesired ripples in current, torque and flux during steady state in FOC, a new method is employed in this paper that generates the stator current more accurately by applying the active voltage vector or zero voltage vectors using switching table within a sampling interval. Based on the output of controllers and position of stator current, an optimum look-up table is constructed. 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

Many of the industrial applications cannot utilize the line power directly and requires various devices to processes the power according to application requirements. This has led to the development of the power electronic field. With the advent of DSP kits which can operate at a processing rate of up to several hundred Mega Hertz., it is possible to have real time digital control of power converters. But, for medium and low power range applications it is more desirable and economical to use pulse width modulated voltage source inverter. A variable frequency is required because the motor shaft speed depends on the rotating magnetic field speed. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has been limited by means of the supply voltage. 3-phase Voltages of variable frequency and variable amplitude can be produced by employing PWM techniques for switching the devices in a voltage source inverter. Vector control over Induction motor drives will provide decoupling effect between torque and flux for better performance. With this proposed vector control strategy, the complexity of induction motor drives is reduced. This proposed work of vector control of Induction motor using sophisticated lookup tables is quite advantageous than conventional control techniques like PWM, SVPWM etc. This method proposes a new vector control method that uses a predetermined switching table instead of a Pulse Width Modulation (PWM) procedure to produce inverter gate signals.

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).

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

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

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

3. Vector Control of Induction Motor

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

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

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

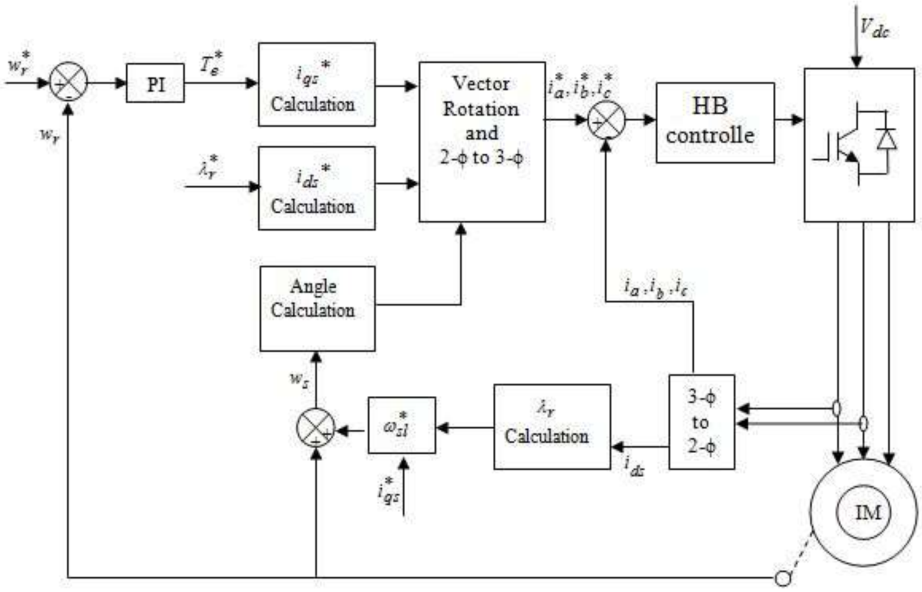

Fig. 1 Block diagram of indirect vector controlled induction motor drive

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

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

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

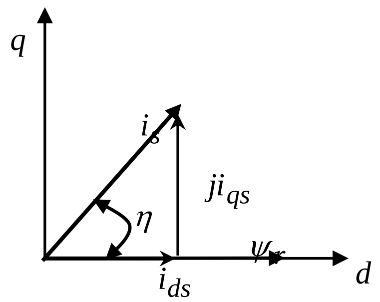

Fig. 2 Representation of stator current vector and rotor flux linkage space vectors

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. These two components are directly proportional to the components of the stator voltage vector in the same directions. By assuming a slow motion of the rotor flux linkage space vector, if a forward active voltage vector is applied then it causes rapid movement of $\bar{i}_s$ and torque increases with 'η'. On the other hand, when a zero voltage vector is used, the $\bar{i}_s$ becomes stationary and the electromagnetic torque will decrease, since $\bar{\lambda}_r$ continues to move forward and the angle 'η' decreases. If the duration of zero voltage space vector is sufficiently long, then the rotor flux linkage space vector exceeds the stator current vector, the angle 'η' will change its sign and the torque will also change its direction. Thus, it is possible to change the speed of stator current vector by changing the ratio between the zero and non-zero voltage vectors.

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

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

(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

$\overline{V}_2$ and $\overline{V}_3$ can increase the torque component current $\bar{i}_{qs}$ and $\overline{V}_5$ and $\overline{V}_6$ can decrease the $\bar{i}_{qs}$. Similarly the suitable voltage vectors can be selected for other sectors.

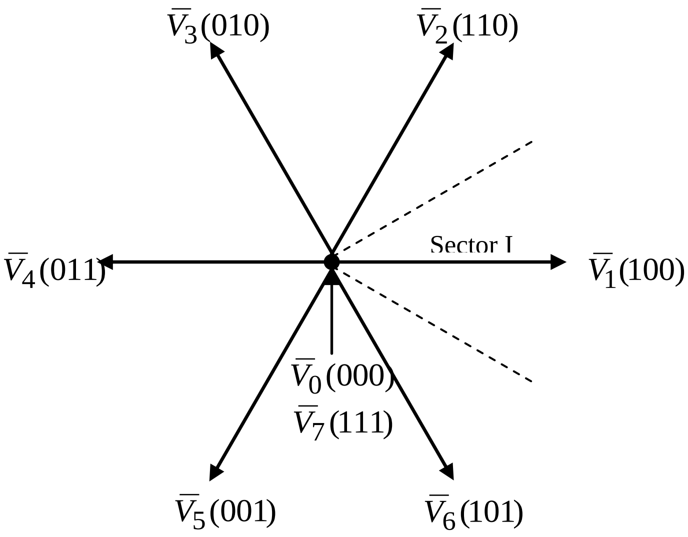

Fig. 3 Inverter voltage space vectors

The block diagram of proposed vector control algorithm is as shown in Fig.4.

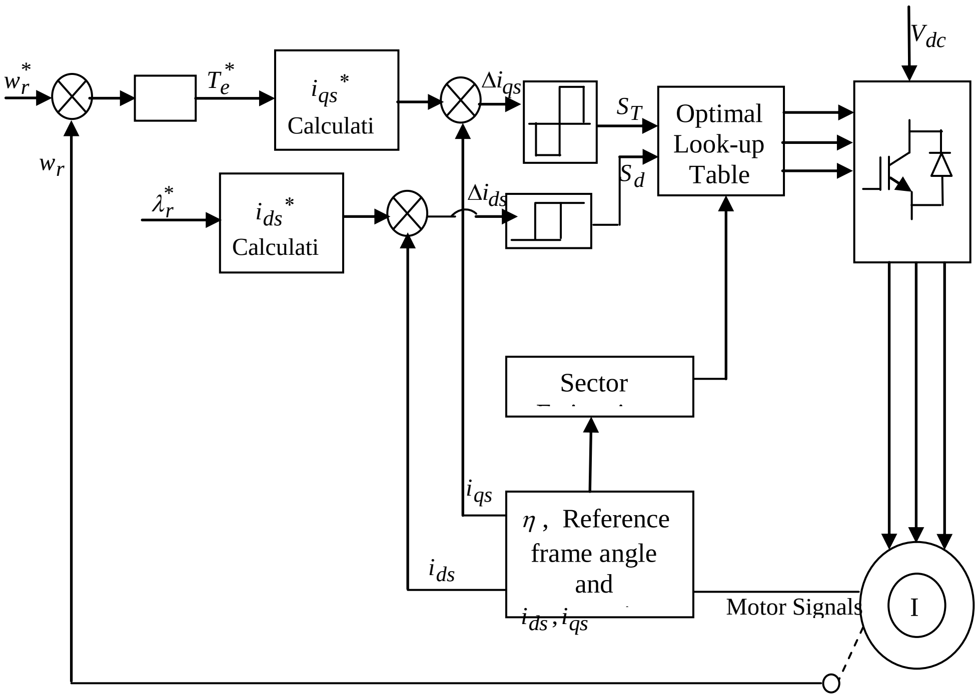

Fig. 4 Block diagram of proposed vector controlled induction motor drive

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.1

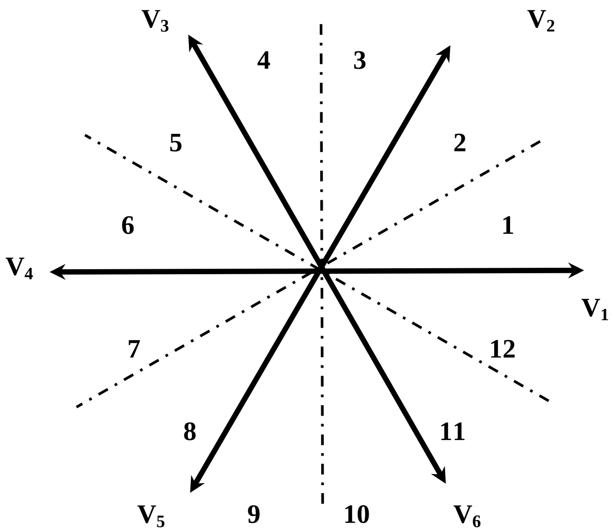

Fig. 5 Inverter voltage space vectors divided into 12-sectors

Table 1 Optimum voltage switching vector lookup table

Sector F	Sector 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

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. 6 – Fig. 11 and the results of proposed algorithm are given in Fig.12 – Fig.17.

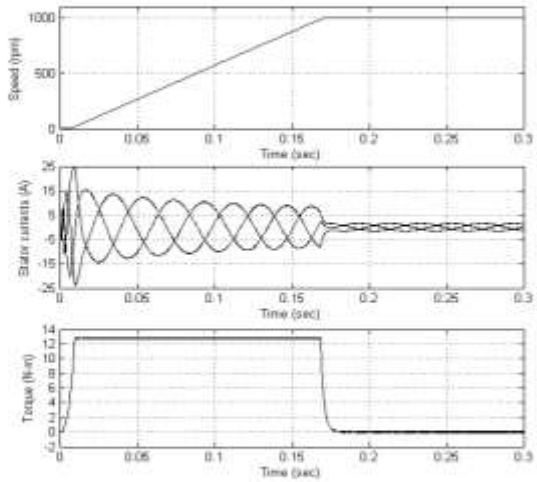

Fig.6 starting transients in conventional vector control algorithm

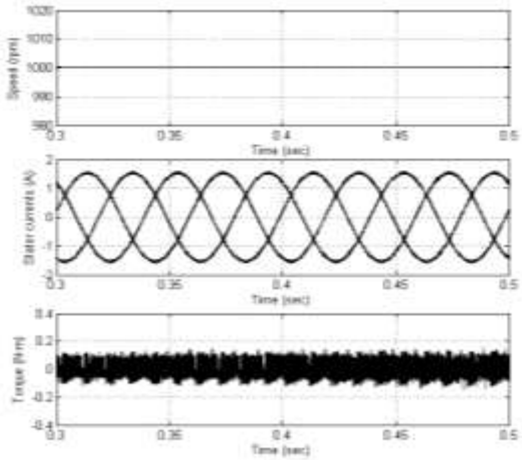

Fig.7 steady state plots in conventional vector control algorithm

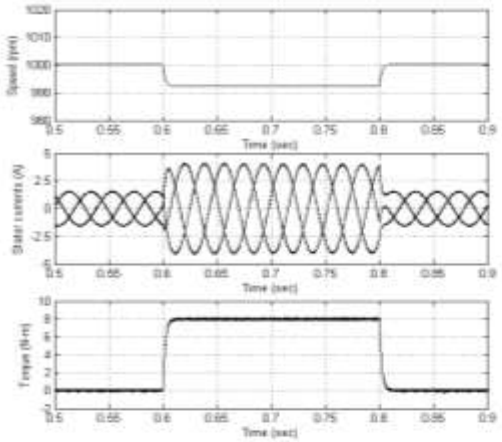

Fig.8 transients during load change in conventional vector control algorithm

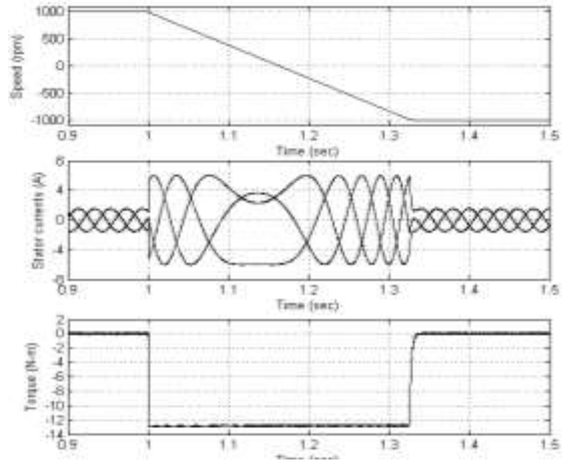

Fig.9 transients during speed reversal (speed is changed from +1000 rpm to -1000 rpm)

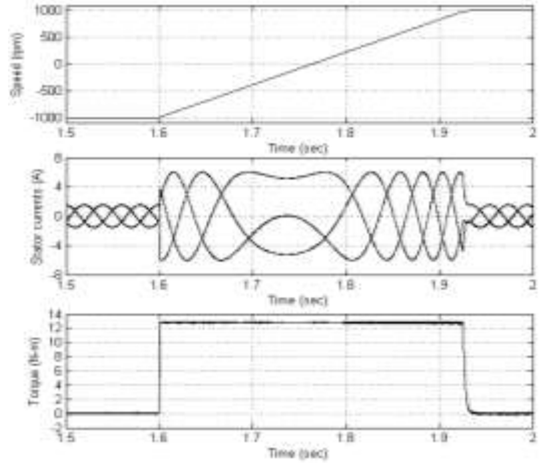

Fig.10 transients during speed reversal (speed is changed from -1000 rpm to +1000 rpm)

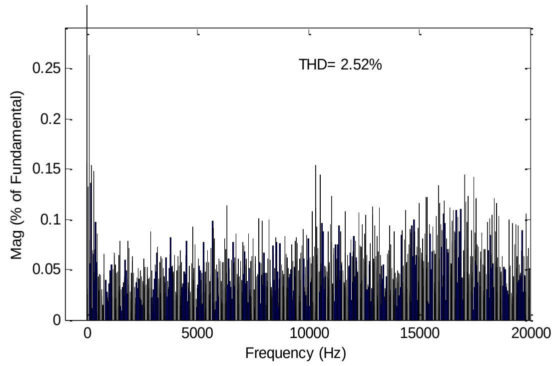

Fig.11 Harmonic distortion of stator current in conventional vector control algorithm

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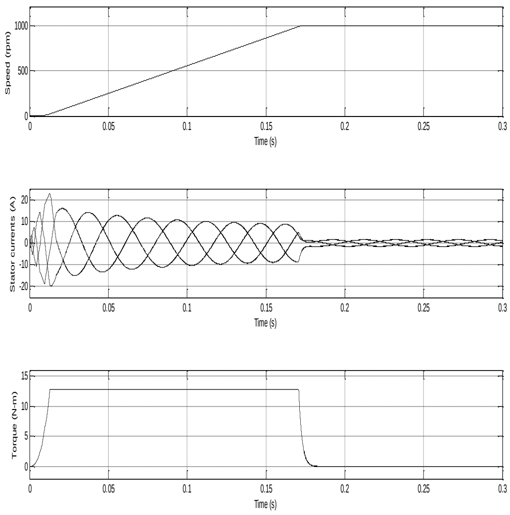

Fig.12 starting transients in proposed vector control algorithm

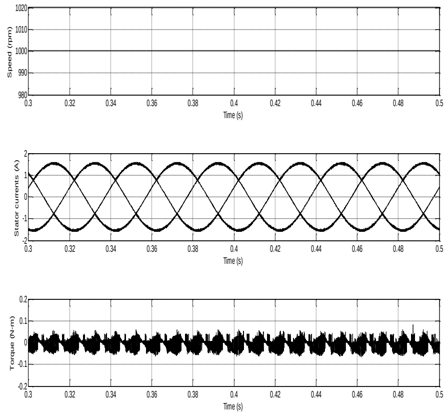

Fig.13 steady state plots in proposed vector control algorithm

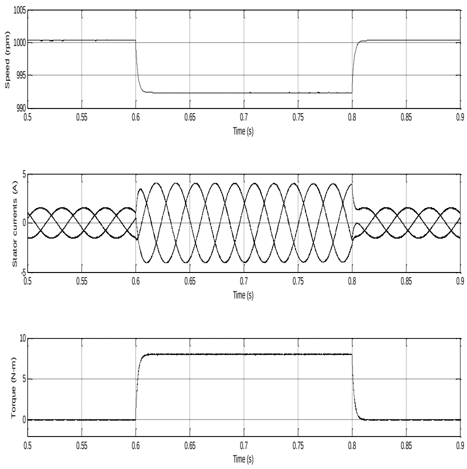

Fig.14 transients during load change in proposed vector control algorithm

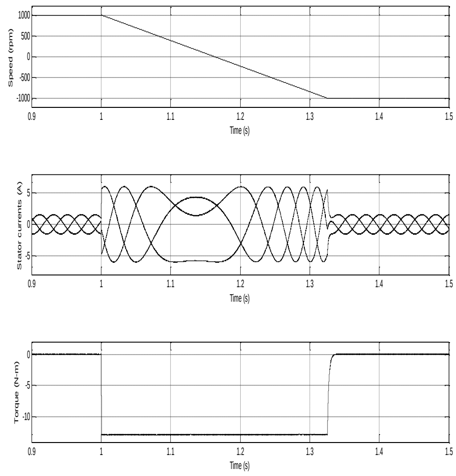

Fig.15 transients during speed reversal (speed is changed from +1000 rpm to -1000 rpm)

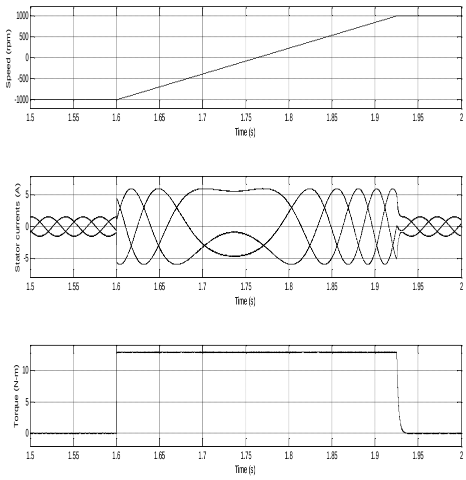

Fig.16 transients during speed reversal (speed is changed from -1000 rpm to +1000 rpm)

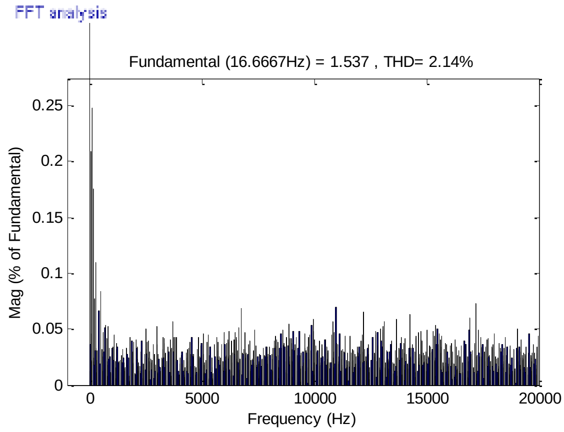

Fig.17 Harmonic distortion of stator current in proposed algorithm

1. From the results shown, it can be observed that for 2 cases of conventional control and using look up tables with 12 sectors. The starting period is considered from time t = 0 – 0.3 sec. Initially speed increases linearly till 0.17 sec., and goes to steady state after overcoming the rotor inertia. The stator current is initially high and decreases slowly. The torque linearly increases and rapidly reaches to maximum point at 0.02 sec till 0.17 sec., and then decreases to zero and remains same. But the starting transients are reduced in stator currents using look up tables compared with that of conventional control.

2. The steady state period is considered from time t = 0.3 to 0.5 seconds and in the 2 cases, the motor speed, stator current and electro magnetic torque are maintained constant. The main advantage of using look up table with 12 sectors is that the **torque ripples are reduced** which are found to be high in conventional control.

3. The case of load variation is considered from t = 0.5 – 0.9 sec. The step load is applied at t = 0.6 sec., and removed at 0.8 seconds. During this period, the speed decreases, the stator current and torque increases as they are directly proportional to each other but speed is inversely proportional to load. After 0.8 sec., all parameters came to original state. In conventional control, the stator current decreases and came to original state but using look up table with 12 sectors the stator current directly comes to original state with any change and some ripples are observed in torque due to the presence of stator torque.

4. In case of speed reversal from positive to negative during t = 0.9 – 1.5 seconds. The speed varies from positive to negative during t = 1 – 1.33 sec., the stator current increases but torque decreases. But the value of current I_a during the period is higher in case of proposed algorithm with 12 sectors and the current I_b remains in steady state for more time than in conventional vector control.

5. The case of speed reversal from negative to positive at t = 1.5 – 2 sec. During t=1.6 – 1.93 sec., the speed varies from negative to positive, the sector current and torque increases. The current I_a. is small in case of proposed algorithm with 12 sectors and the current I_c remains in steady state for less time than in conventional vector control.

6. It is observed that with the proposed 12-sectors, the harmonic distortion in stator current is considerably reduced.

From the simulation results it can be observed that the proposed algorithm gives better performance than in conventional vector control algorithm. As the proposed algorithm eliminates the reference frame transformation and PWM procedure, the complexity involved in proposed algorithm is less. The steady state ripple in current is slightly more than that of conventional vector control algorithm. Thus, the proposed algorithm is simple and gives good performance.

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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