VECTOR CONTROL OF INDUCTION MOTOR DRIVE BY USING THE CONSTANT SWITCHING FREQUENCY CURRENT CONTROLLER FOR REDUCED RIPPLE

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ABSTRACT

This paper presents a novel and simple vector control algorithm for induction motor drives. The classical vector control and direct torque control algorithms give the decoupled control. But, the classical vector control algorithm uses reference frame transformation, which increases the complexity of the algorithm for implementation. Whereas the direct torque control is simple for the implementation by using the lookup tables approach, but, it gives large steady state ripple in torque, flux and current. Hence, to overcome the drawbacks of both vector control and direct torque control, the proposed method combines the principles of both vector control and direct torque control. In the proposed algorithm, the d- and q-axes reference currents are generated as per the principles of vector control algorithm and vector based hysteresis comparators integrated with look-up tables are used as per the principle of direct torque control. Moreover, to reduce the torque ripple, a novel constant switching frequency current controller is proposed. To validate the proposed method numerical simulations have been carried out and compared with the existing algorithms. The simulation results show the effectiveness of the proposed technique.

Keywords: *Direct Torque Control, Induction motor, switching table, vector control*

1. INTRODUCTION

Nowadays in many industrial applications DC drives are replaced by induction motor drives due to their numerous advantages like low maintenance and low weight volume ratio. But, DC drives have advantages like high starting torque and decoupled control of torque and flux. To achieve characteristics of DC motors in induction motor drives both torque and flux are to be controlled independently. This independent control or decoupled control can be achieved in induction motors by using field oriented control. With the advent of vector control or field oriented control (FOC) technique, the induction motors became popular in variable speed drives applications [1]. The invention of the FOC brought a renaissance in the high performance speed control of induction motor drives. To improve the performance of vector control strategy, many techniques have been proposed in [2]-[4].

Though vector control algorithm achieves a decoupled control with good transient response, the complexity involved in the technique is more due to the several transformations. To achieve the decoupled control with reduced complexity, later the direct torque control (DTC) has been developed by Takahashi [5]. The DTC directly controls the both torque and flux without transformation by using the hysteresis controllers and lookup table. Moreover, the sensitivity to the parameter variations is also less when compared with the FOC. The detailed comparison between FOC and DTC has been discussed in [6]. Though, the DTC gives good dynamic response, it gives large steady state ripple in torque, flux and current. Whereas, the FOC gives less steady state ripples when compared with the DTC.

The classical current control algorithms use the hysteresis controllers for the generation of switching pulses. To reduce the complexity involved in the implementation of current controllers, a novel and simple approach has been presented in [7] by using the lookup table approach. Moreover, to achieve the constant switching frequency, a constant current controller is presented in [8]-[9] in which, the current error signal will be compared with the triangular carrier signal.

Hence, to overcome the drawbacks of FOC and DTC, this paper presents a new field oriented control or vector control scheme, which combines the principles of both vector control and DTC. To reduce the torque ripple further and to maintain a constant switching frequency, a simple current controller is introduced to replace the conventional hysteresis comparator. By proper selection of the current controller parameters, the reverse voltage vector selection is avoided during torque reduction. The proposed algorithm uses sophisticated lookup tables to generate the PWM signals to the inverter. Moreover, the proposed method does not require reference frame transformations and gives good steady state and transient performance.

2. CONVENTIONAL VECTOR CONTROL

In the FOC, the decoupled control can be achieved by transferring all the quantities to synchronous reference frame and resolving the stator current vector as torque producing current component i_{qs}^* and flux producing current component i_{ds}^*. The electromagnetic torque expression for an induction motor is given as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \tag{1}$$

To achieve decoupled control, i_{ds}^* is oriented along the rotor flux linkage vector, and the i_{qs}^* is perpendicular to the rotor flux vector. Thus, the entire rotor flux is aligned along d-axis and hence the q-axis flux component will become zero. Hence, the torque expression can be expressed as given in (2).

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

Hence, the total rotor flux can be given as in (3).

$$\psi_r = \psi_{dr} = L_m i_{ds} \tag{3}$$

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. Based on calculation of rotor flux position angle the vector control algorithm can be classified as direct and indirect vector control algorithms. In many industrial applications, the indirect vector control algorithm is popular. In indirect vector control the slip frequency and rotor flux linkage position angle can be evaluated from (4) and (5).

$$\omega_{sl} = \frac{L_m R_r}{L_r \lambda_r} i_{qs}^* \tag{4}$$

$$\theta_s = \theta_r + \theta_{sl} = \int\left(\omega_r + \omega_{sl}\right)dt = \int \omega_s dt \tag{5}$$

3. PROPOSED VECTOR CONTROL

In the proposed indirect vector control algorithm the electromagnetic torque equation given in (2) can be modified as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left|\bar{\lambda}_r\right|\left|\bar{i}_s\right|\sin\delta \tag{6}$$

where δ is the angle between stator current and rotor flux linkage vectors. From (6), it can be observed that the torque can be varied by varying the δ. Hence, fast torque control can be achieved by changing δ in the required direction. For a short time interval, the rotor flux linkage vector is almost unchanged in space due to rotor inertia. Hence, the rapid changes of electromagnetic torque can be produced by rotating the stator current vector in the required direction according to the reference torque.

By ignoring the stator resistance drop, the stator voltage can be expressed as given in (7).

$$\bar{v}_s = \frac{d\bar{\psi}_s}{dt} \tag{7}$$

The stator and rotor flux linkage space vectors of an induction motor can be expressed as given in (8) and (9).

$$\bar{\psi}_s = L_s \bar{i}_s + L_m \bar{i}_r \tag{8}$$

$$\bar{\psi}_r = L_r \bar{i}_r + L_m \bar{i}_s \tag{9}$$

From (9), the expression for rotor current can be calculated as

$$\bar{i}_r = \frac{\bar{\psi}_r - L_m \bar{i}_s}{L_r} \tag{10}$$

By putting (10) in (8), the stator flux linkage vector expression can be obtained as in (11).

$$\bar{\psi}_s = L_s \bar{i}_s + \frac{L_m}{L_r}\bar{\psi}_r - \frac{L_m^2}{L_r}\bar{i}_s \tag{11}$$

For short time durations, by assuming the rotor flux linkage vector as constant, the voltage expression can be simplified as follows.

$$\bar{v}_s = \frac{d\bar{\psi}_s}{dt} = \left(L_s - \frac{L_m^2}{L_r}\right)\frac{d\bar{i}_s}{dt} = \sigma L_s \frac{d\bar{i}_s}{dt} \tag{12}$$

where σ is the leakage coefficient of induction motor. From (12), for a short time interval of Δt, the stator current vector can be obtained as

$$\Delta \bar{i}_s = \frac{1}{\sigma L_s}\bar{v}_s \Delta t \tag{13}$$

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. By selecting a suitable voltage vector it is then possible to change the stator current in the required direction. Decoupled control can be achieved by acting on the $\bar{i}_{ds}$ and $\bar{i}_{qs}$ components of the stator current vector. 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 an active voltage vector is applied in forward direction then it causes rapid movement of $\bar{i}_s$ and torque increases with δ. On the other hand, when a zero voltage vector is used, $\bar{i}_s$ becomes stationary and the electromagnetic torque will decrease, since rotor flux continues to move in the forward direction slowly and the angle δ decreases. Thus, the speed of the stator current vector can be regulated by using the different voltage vectors in each sampling time period as shown in Fig. 1. This is the basic principle of operation of the proposed vector control algorithm.

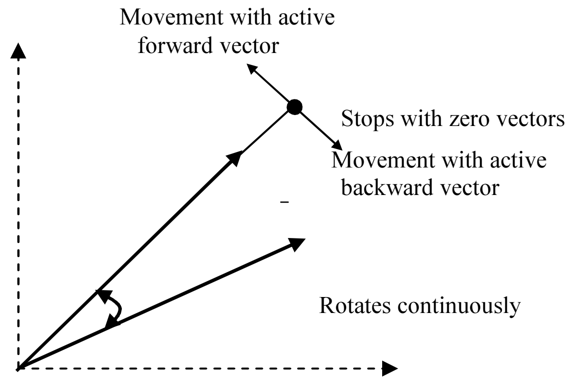

Fig. 1 Movement of stator current vector under the influence of voltage vectors

The selection of the voltage vectors can be done by using the concept of direct torque control (DTC). In the classical DTC, for the selection of suitable voltage vector, a three-level hysteresis controller for torque loop and a two-level hysteresis controller for flux loop are considered. Same as DTC, in the proposed vector control also, a 3-level and 2-level hysteresis controllers can be considered for torque component and flux component current controllers. But, a three-level torque component current hysteresis controller will give variable switching frequency operation, which will cause more ripples in the steady state torque. Hence, to overcome this drawback, in this paper a constant switching frequency based current controller is proposed. The structure of the proposed torque component current controller is as shown in Fig. 2.

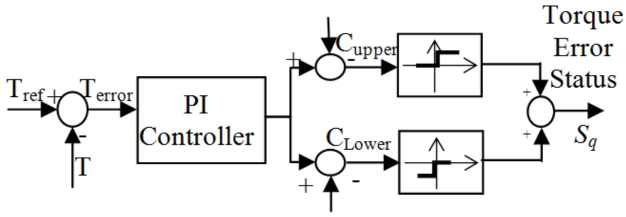

Fig. 2 Block diagram of the proposed current controller

The proposed torque component current controller consists of two triangular carrier signals, which are 180° out of phase each other, two comparators and one proportional integral (PI) controller. The absolute values of the dc offsets for the triangular waveforms are set to half of their peak to peak values. Because of the two opposite carrier signals (upper and lower), the output of the proposed current controller is similar to that of a three-level hysteresis comparator. Hence, the output values of the proposed current controller are 1, 0 or -1. This means that similar voltage vectors and look-up tables, as in the conventional DTC drive, can be used. The value of the instantaneous output of the torque component current controller (S_q) is given by (14).

$$S_q = \begin{cases} 1, & for T_c \geq C_{upper} \\ 0, & for C_{lower} < T_c < C_{upper} \\ 1, & for T_c \leq C_{upper} \end{cases} \tag{14}$$

The block diagram of the proposed vector control algorithm is as shown in Fig. 3.

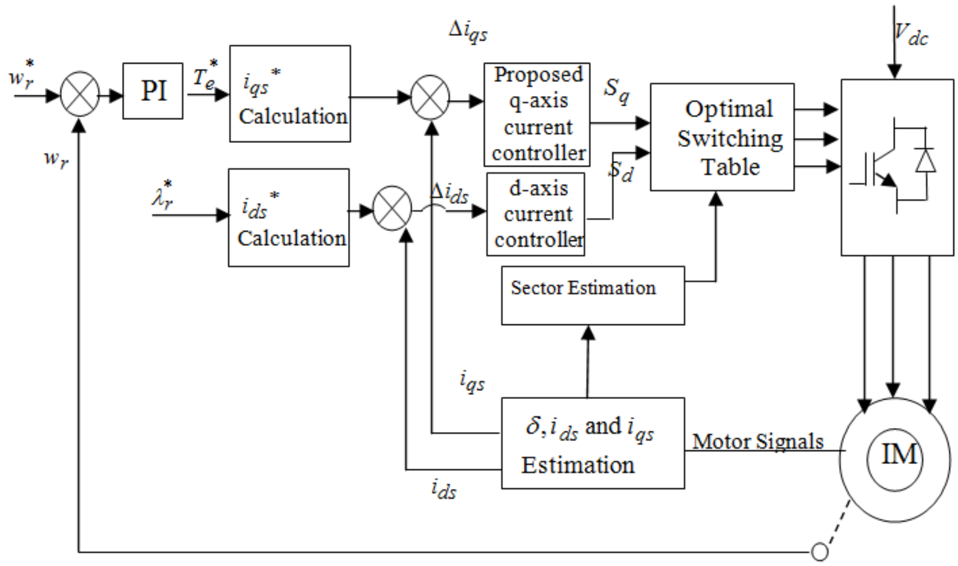

Fig. 3 Block diagram of the proposed vector controlled induction motor drive

As in conventional vector control, the torque current component (i_{qs}^*) and flux current component (i_{ds}^*) of stator currents, are at synchronously rotating reference frame. The error signals of d-axis and q-axis stator currents will be given to respective current controllers. The d-axis current controller consists of two-level hysteresis controller. The digitized outputs of d-axis current controllers can be obtained as if $\bar{i}_{ds} \leq \bar{i}_{ds}^* - \Delta\bar{i}_s$ then S_d=1 and if $\bar{i}_{ds} \geq \bar{i}_{ds}^* + \Delta\bar{i}_s$ then S_d=0. The digitized output values of the proposed q-axis current controller can be obtained from (14). Then, the digitized output values of the d- and q-axes current controllers and rotor flux angle will be given to the lookup tables as inputs. Based on these three inputs, the suitable voltage vector can be selected from the lookup table. The lookup table for the proposed vector control algorithm is given in Table. 1. The selected voltage vector will be applied to the VSI fed induction motor drive in order to keep the current errors within limits.

Table. 1 Optimum voltage vector switching table

S_d	Sector / S_q	I	II	III	IV	V	VI
1	1	$\bar{V}_2$	$\bar{V}_3$	$\bar{V}_4$	$\bar{V}_5$	$\bar{V}_6$	$\bar{V}_1$
	0	$\bar{V}_7$	$\bar{V}_0$	$\bar{V}_7$	$\bar{V}_0$	$\bar{V}_7$	$\bar{V}_0$
	-1	$\bar{V}_6$	$\bar{V}_1$	$\bar{V}_2$	$\bar{V}_3$	$\bar{V}_4$	$\bar{V}_5$
0	1	$\bar{V}_3$	$\bar{V}_4$	$\bar{V}_5$	$\bar{V}_6$	$\bar{V}_1$	$\bar{V}_2$
	0	$\bar{V}_0$	$\bar{V}_7$	$\bar{V}_0$	$\bar{V}_7$	$\bar{V}_0$	$\bar{V}_7$
	-1	$\bar{V}_5$	$\bar{V}_6$	$\bar{V}_1$	$\bar{V}_2$	$\bar{V}_3$	$\bar{V}_4$

4. SIMULATION RESULTS AND DISCUSSION

To validate the proposed vector control algorithm numerical simulation studies have been carried out in Matlab-simulink environment. For the simulation studies the motor parameters are taken as R_s =1.57Ω, R_r=1.21 Ω, L_m=0.165H, L_s=0.17H, L_r=0.17H and J=0.089Kg-m^2. Moreover, for the simulation results equal band widths have been considered for the hysteresis bands in the proposed and existing current controlled vector controlled drives. The simulation results of classical vector control algorithm are shown in from Fig.4 to Fig.9. The simulation results of proposed vector control algorithm are shown in from Fig.10 to Fig.15.

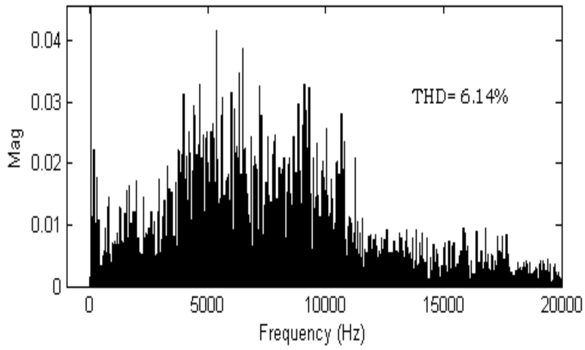

Fig. 6 Harmonic spectra of stator current in classical vector control algorithm

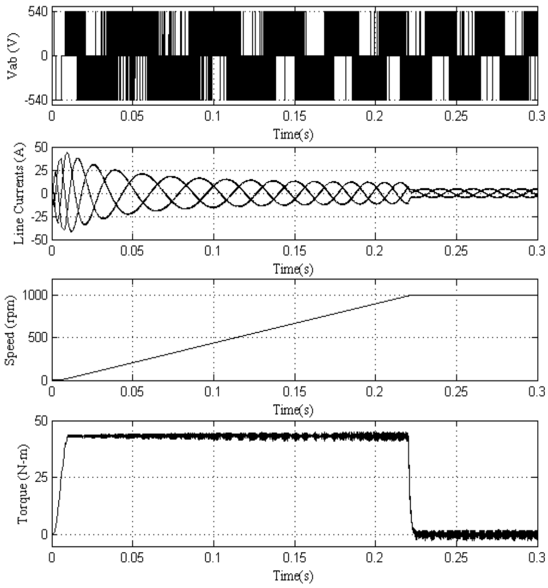

Fig. 4 Starting transients of classical vector control algorithm based induction motor drive

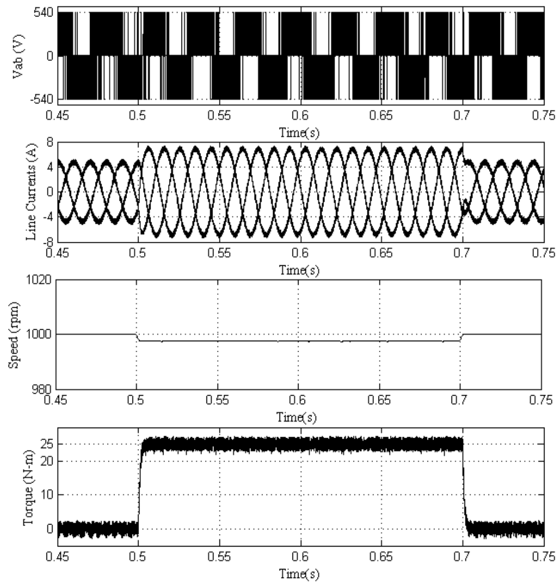

Fig. 7 Transients during the step change in load (a 25 N-m load is applied at 0.5 sec and removed at 0.7 sec) for classical vector control algorithm based induction motor drive

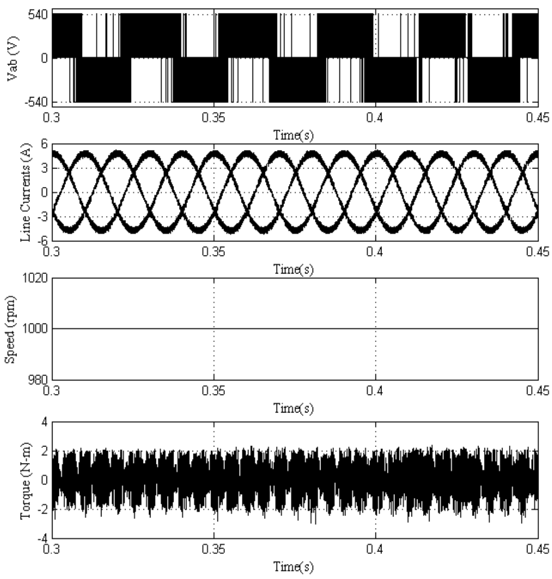

Fig. 5 Steady state plots of classical vector control algorithm based induction motor drive

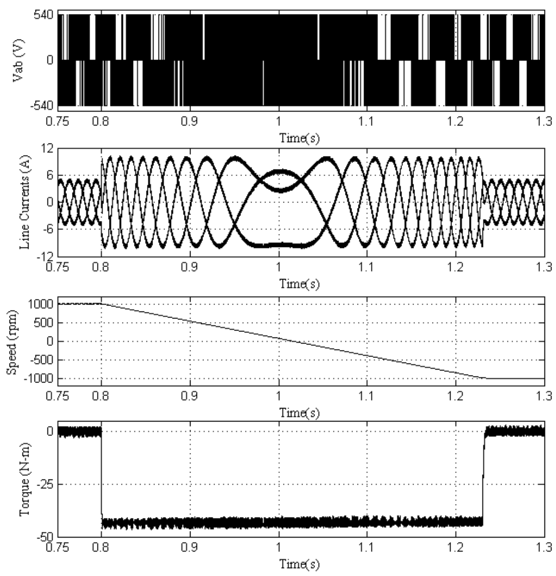

Fig. 8 Transients during the speed reversal (from +1000 rpm to -1000 rpm) for classical vector control algorithm based induction motor drive

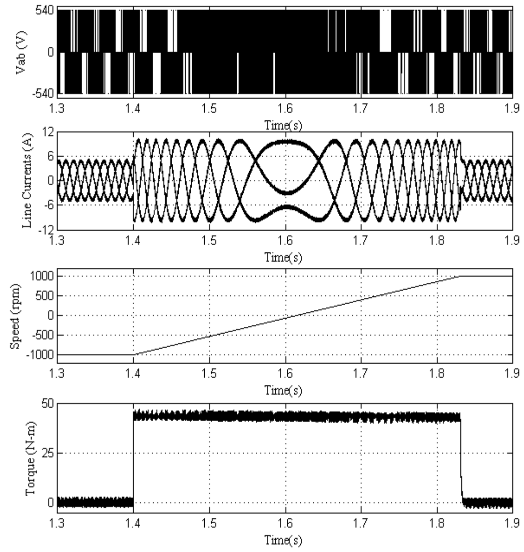

Fig. 9 Transients during the speed reversal (from -1000 rpm to +1000 rpm) for classical vector control algorithm based induction motor drive

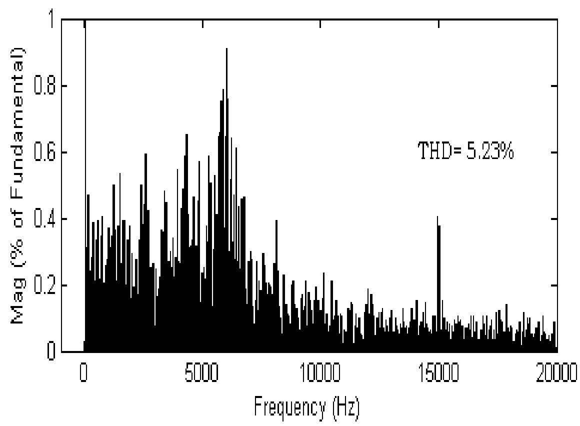

Fig. 12 Harmonic spectra of stator current in proposed vector control algorithm

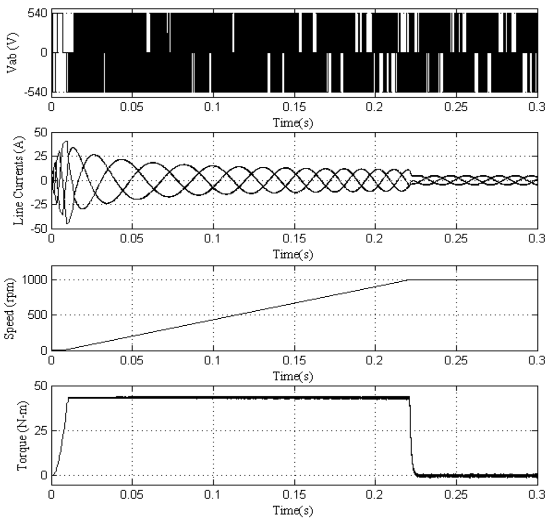

Fig. 10 Starting transients of proposed vector control algorithm based induction motor drive

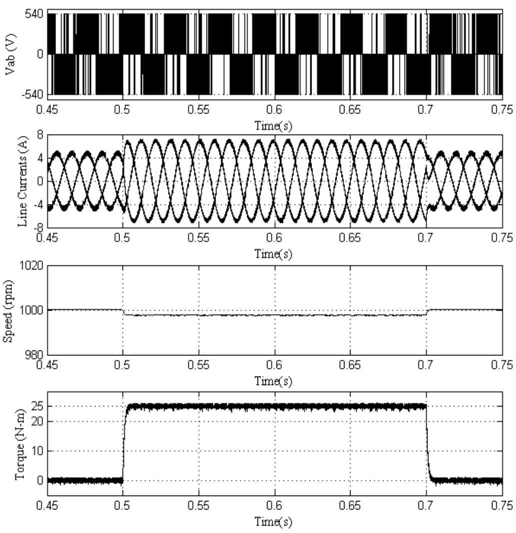

Fig. 13 Transients during the step change in load (a 25 N-m load is applied at 0.5 sec and removed at 0.7 sec) for proposed vector control algorithm based induction motor drive

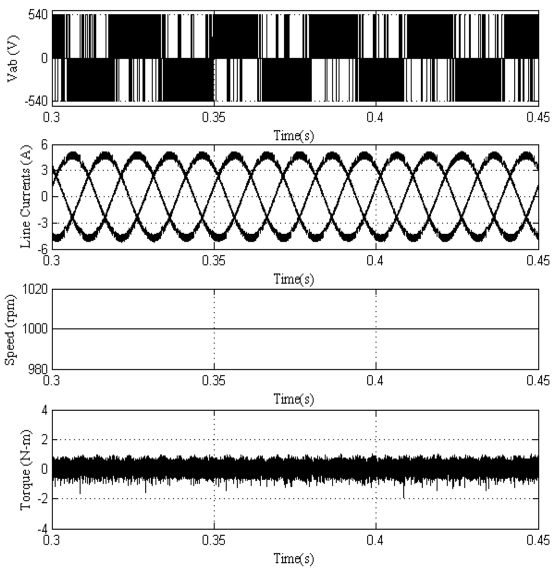

Fig. 11 Steady state plots of proposed vector control algorithm based induction motor drive

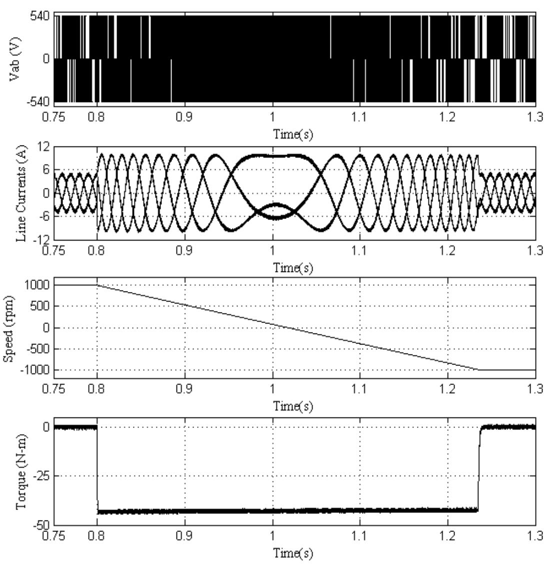

Fig. 14 Transients during the speed reversal for proposed vector control algorithm based induction motor drive

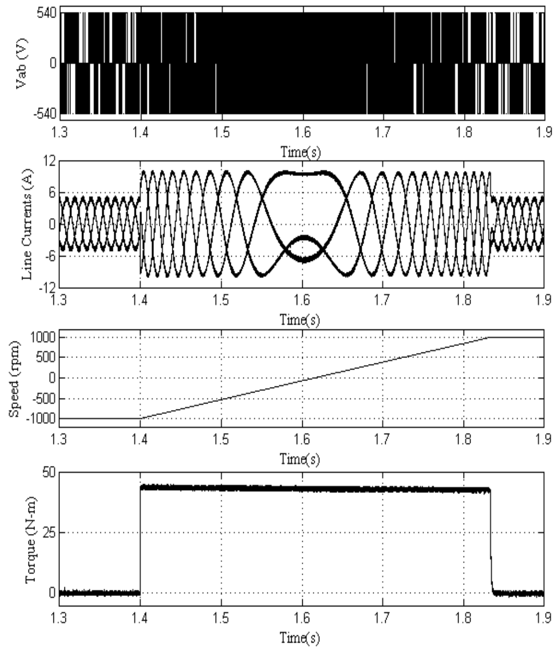

Fig. 15 Transients during the speed reversal for classical vector control algorithm based induction motor drive

From the simulation results, it can be observed that the proposed vector control algorithm gives good transient response similar to the classical vector control algorithm. Moreover, from the steady state simulation results, it can be observed that the proposed algorithm gives reduced steady state torque ripple and current ripple. Also, from the harmonic spectra of line currents, it can be observed that the proposed algorithm gives reduced harmonic distortion when compared with the classical vector control algorithm.

5. CONCLUSIONS

The decoupled control strategy for induction motor drives gives fast transient response. The conventional vector control technique gives better dynamic performance but the complexity involved is more due to the reference frame transformations and PWM procedure. Hence, to reduce the complexity, a new vector control algorithm is proposed by combining the principles of both vector control and direct torque control. The proposed vector control technique uses lookup tables and eliminates the use of reference frame transformations and PWM procedure. Moreover, to reduce the torque ripple in steady state a novel constant switching frequency based current controller has been proposed. From the simulation results it can be observed that the proposed algorithm gives good transient performance similar to the classical vector control algorithm and gives better performance in steady state when compared with the classical vector control in terms of torque and current ripple during steady state operation.

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