A New Space Vector Pulsewidth Modulation for Reduction of Common Mode Voltage in Direct Torque Controlled Induction Motor Drive

Y. V. Siva Reddy, M. Vijaya Kumar, and T. Brahmananda Reddy

***Abstract*—This paper presents a new space vector pulsewidth modulation (SVPWM) algorithm for reduction of common mode voltage in direct torque controlled induction motor drives. The proposed PWM algorithm does not use any zero voltage vectors for inverter control; hence it can restrict common mode voltage better than conventional SVPWM algorithm. The main advantage of the proposed algorithm is that the number of commutations required in one sector and from one sector to the next sector remains the same as in conventional SVPWM technique. To validate the proposed method, the simulation results are presented and compared to those obtained with conventional SVPWM based direct torque control algorithm.**

***Index Terms*—Common mode voltage, direct torque control, SVPWM.**

NOMENCLATURE

v_{qs}, v_{ds}	d and q axis stator voltages, V
v_{dr}, v_{qr}	d and q axis rotor voltages, V
i_{ds}, i_{qs}	d and q axis stator currents, A
i_{dr}, i_{qr}	d and q axis rotor currents, A
ω_r	Electrical rotor speed, rad/sec
T_e	Electromagnetic torque, N-m
$\lambda_{ds}, \lambda_{qs}$	Stator flux linkages in d and q axes, V-sec
$\lambda_{dr}, \lambda_{qr}$	Rotor flux linkages in d and q axes, V-sec
V_{com} or V_{sn}	Common mode voltage
V_{an}, V_{bn}, V_{cn}	Pole voltages
Y_1, Y_2, Y	Random variables

I. INTRODUCTION

In the recent years, direct torque control (DTC) [1]-[2] has proven to be a powerful method for controlling induction motors. Despite being simple, DTC is able to produce very fast torque and flux control and also robust to parameter variations. However its inherent fast switching frequency generates high level common mode voltage variations, thus causing the drive itself to be less reliable. Also the common mode voltage results in undesired electromagnetic interference [3], fault actuation of detection circuits [4] and damage to motor bearings [5]. To mitigate the problems of common mode voltage, a new DTC algorithm is presented in [6], which is based on the application of only odd or only even voltage vectors in each sector in which the stator flux lies. Though, it reduces the common mode voltage variations, but it does not overcome the problems like variable switching frequency. To reduce the common mode voltage two space vector based PWM algorithms, asymmetrical and symmetrical have been proposed in [7]. In case of asymmetrical PWM technique the switching pattern is not symmetrical as in conventional method and hence increases current disturbance. In case of symmetrical space vector based PWM algorithm the switching pattern is symmetrical and number of commutations within a sampling period is the same as that for conventional SVPWM. But the number of commutations increases when transition takes place from one sector to the next sector and hence switching losses increases.

In this paper, a novel SVPWM technique has been proposed which reduces the common mode voltage. In the proposed SVPWM technique instead of zero voltage vectors, non-zero nonadjacent vectors are used in composing the reference voltage vector. Also the proposed technique preserves the best of conventional SVPWM in two ways 1) The vector times associated with the proposed technique are same as that of conventional SVPWM technique and 2) The number of commutations in a sector and from one sector to the next remains the same as in conventional SVPWM technique.

II. MACHINE MODELING

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

$$\begin{aligned} v_{ds} &= R_s i_{ds} + p\lambda_{ds} \\ v_{qs} &= R_s i_{qs} + p\lambda_{qs} \\ 0 &= R_r i_{dr} + \omega_r \lambda_{qr} + p\lambda_{dr} \\ 0 &= R_r i_{qr} - \omega_r \lambda_{dr} + p\lambda_{qr} \end{aligned} \qquad (1)$$

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 by

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Y. V. Siva Reddy and T. Brahmananda Reddy are with the Department of Electrical and Electronics Engineering, G. Pulla Reddy Engineering College, Kurnool, AP, India (e-mails: siva@rediffmail.com, tbnr@rediffmail.com).

M. Vijaya Kumar is with the Department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University, Anantapur, AP, India (e-mail: mvk_2004@rediffmail.com).
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Fig. 1. Three phase voltage source inverter.

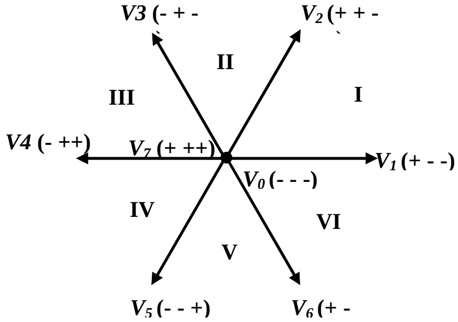


Fig. 2. Voltage space vectors of a three-phase voltage source inverter.

$$\begin{aligned}\lambda_{ds} &= L_s i_{ds} + L_m i_{dr}\\ \lambda_{qs} &= L_s i_{qs} + L_m i_{qr}\\ \lambda_{dr} &= L_r i_{dr} + L_m i_{ds}\\ \lambda_{qr} &= L_r i_{qr} + L_m i_{qs}\end{aligned} \tag{2}$$

The electromagnetic torque in the stationary reference frame is given as

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{3}$$

III. COMMON MODE VOLTAGE

The common mode voltage generated by a Voltage source inverter controlled drive as shown in Fig. 1 is given by

$$V_{com} = \frac{1}{3}(V_{an} + V_{bn} + V_{cn}) \tag{4}$$

where V_{an}, V_{bn}, V_{cn} are inverter output phase voltages if the drive is fed by balanced three phase supply, the common mode voltage is zero. But, the common mode voltage exists inevitably when the drive is fed from an inverter employing PWM technique. It can be shown that the switching state and DC bus voltage decides the common mode voltage. There are eight available output voltage vectors in accordance with the eight different switching states of the inverter as depicted in Fig. 2.

According to the switching states of the inverter the common mode voltage can be expressed as

$$V_{com} = \frac{V_{dc}}{6}(S_a + S_b + S_c) \tag{5}$$

where S_a, S_b, S_c denotes the inverter switching states in which $S_i = 1$ ($i = a,b,c$), if the upper leg switch is on and $S_i =$ -1 ($i = a,b,c$), if the upper leg switch is off

The motor pole voltages can be derived as

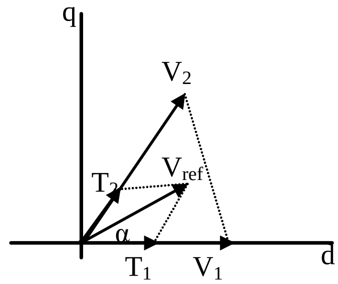


Fig. 3. Vector composition of reference vector for conventional SVPWM technique in first sector.

TABLE I
COMMON MODE VOLTAGE AND OUTPUT VOLTAGE GENERATED BY A SWITCHING STATE

Switching state	Inverter output voltage V_{an}	V_{bn}	V_{cn}	V_{com}
(-1, -1, -1)	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$
(1, -1, -1)	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
(1, 1,-1)	$V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/6$
(-1, 1,- 1)	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
(-1, 1, 1)	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
(-1, -1, 1)	$-V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/6$
(1, -1, 1)	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
(1, 1, 1)	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$

$$\begin{aligned}V_{an} &= \frac{V_{dc}}{6}(2S_a - S_b - S_c)\\ V_{bn} &= \frac{V_{dc}}{6}(2S_b - S_c - S_a)\\ V_{cn} &= \frac{V_{dc}}{6}(2S_c - S_a - S_b)\end{aligned} \tag{6}$$

The common mode voltage changes by $V_{dc}/3$ for every switching state of the inverter and the variation of V_{com}, the common mode voltages according to output voltage vectors of the inverter are summarized in Table. I.

IV. CONVENTIONAL SVPWM TECHNIQUE

If a constant reference voltage vector V_{ref} at an angle α in any given sector is to be generated then it can be done by using two zero vectors V_0 and V_7 in combination with two adjacent non zero vectors V_n and V_{n+1}.

The vector composition of the reference vector in first sector is given in Fig. 3.

The times T_1, T_2 and T_0 for which V_n, V_{n+1} and V_0 or V_7 (the duration of zero vector) act respectively can be expressed as

$$\begin{aligned}T_1 &= T.M.\frac{\sin(60^o - \alpha)}{\sin 60^o}\\ T_2 &= T.M.\frac{\sin\alpha}{\sin 60^o}\\ T_0 &= T - T_1 - T_2\end{aligned} \tag{7}$$

where T = sampling period, T_1 = the duration of vector V_n, T_2 = the duration of vector V_{n+1} and T_0 = the duration of zero voltage vector V_0 or V_7 and M is the modulation index, given by $3V_{ref}/2V_{dc}$ .To reduce the ripple the zero vector time is equally distributed with in a sampling period

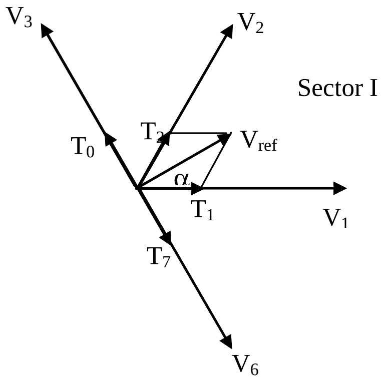
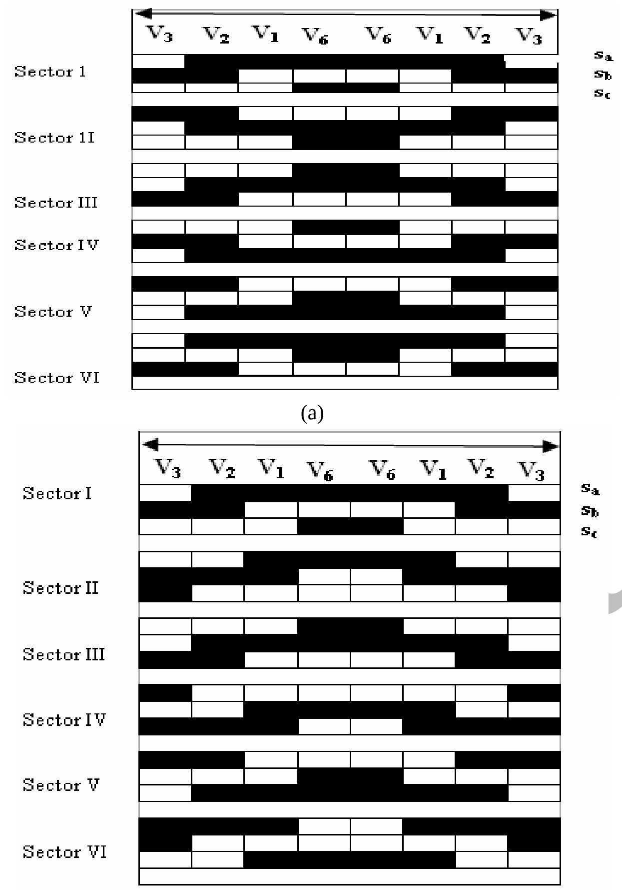


Fig. 4. Vector composition of the reference vector for the proposed method in first sector.



(a)

(b)

Fig. 5. Switching pattern for (a) SVPWM technique proposed in [7], and (b) Novel SVPWM technique.

and the switching sequence in Sector I becomes as 0127-7210.

V. Novel SVPWM Algorithm

In the proposed SVPWM technique for direct torque controlled induction motor drive there is no usage of zero vectors in the composition of reference vector. Instead of using zero vectors, non zero, non adjacent voltage vectors are used to compose the reference vector.

The vector composition of the reference vector V_{ref} in first sector is as shown in Fig. 4.The switching sequences in each sector for the novel SVPWM technique and the technique proposed in [7] are given in Fig. 5.

The switching pattern illustrates that for the methods the number of commutations in a particular sector remains the same as in conventional SVPWM technique. But the

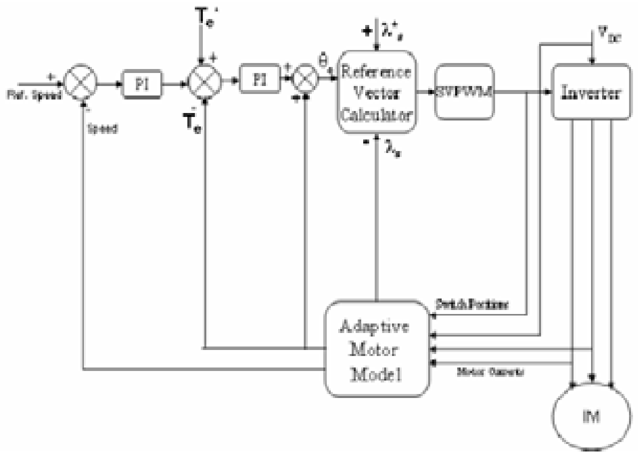


Fig. 6. Block diagram of the proposed SVPWM based DTC.

number of commutations during transition from one sector to the next decreases in the proposed method. Moreover the vector times associated with the given technique is the same as with conventional SVPWM technique. Hence the novel SVPWM method preserves the best of conventional SVPWM method in addition accomplishes the task of decreasing the common mode voltage.

The volt-second balance equation for the proposed method is given as

$$V_{ref}.T = V_1 T_1 + V_2 T_2 + \frac{V_3 T_0}{2} + \frac{V_6 T_0}{2} \quad (8)$$

VI. Proposed SVPWM Based DTC

Block diagram of Fig. 6 depicts the direct torque control of induction motor using the proposed SVPWM algorithm. In this approach the actual stator flux vector is determined by using the stator currents and voltage measurements. The calculated one is then compared with a reference and an error signal in flux is generated which when divided by the sampling time period gives a reference voltage vector used for direct control of torque and flux.

VII. Simulation Results and Discussion

To verify the proposed scheme, a numerical simulation has been carried out by using Matlab/Simulink. Sampling time of 125μs and ode 4 (Runge-Kutta) methods are used for a fixed step size of 10μs. For the simulation, reference stator flux is taken as 1wb and starting torque is limited to 40 N-m. The induction motor used in this case study is a 4 kW, 400 V, 30 N-m, 1470 rpm, 4-pole, 50 Hz, 3-phase induction motor having the following parameters: $R_s = 1.57\ \Omega$, $R_r = 1.21\ \Omega$, $L_s = 0.17$ H, $L_r = 0.17$ H, $L_m = 0.165$ H, $J = 0.089$ Kg.m$^{2.}$

Various conditions of the drive system such as starting, steady state, step change in load and speed reversal are simulated. The simulation results for conventional SVPWM are given in Figs. 7-10.

Fig. 11 gives the simulation results for common mode voltage with conventional SVPWM and with the proposed SVPWM technique. The simulation results for the DTC with proposed SVPWM algorithm are given in Figs. 12-15. From the simulation results it is observed that there is a

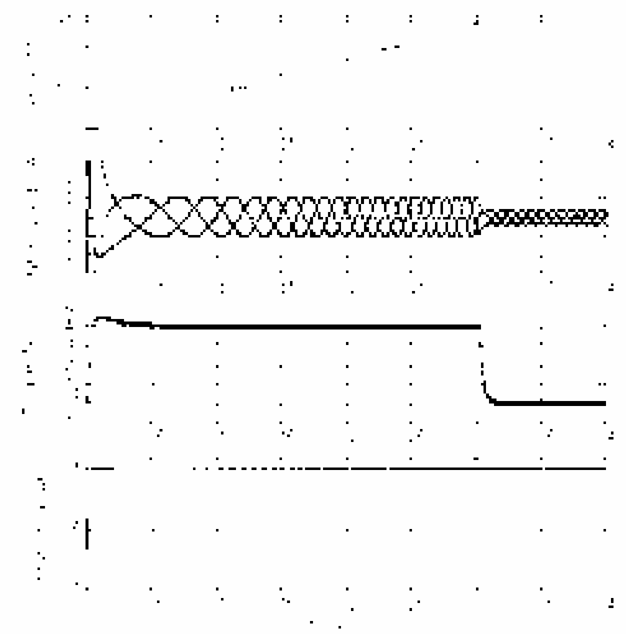


Fig. 7. Simulation results of conventional SVPWM based DTC: starting transients.

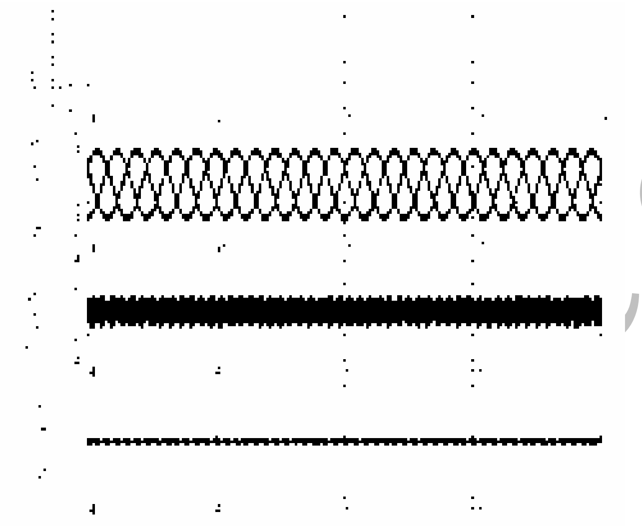


Fig. 8. Simulation results of conventional SVPWM based DTC: steady state plots at a speed of 1300 rpm.

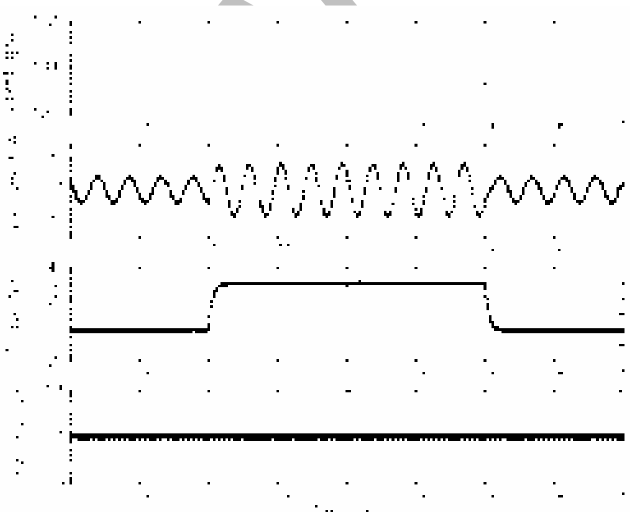


Fig. 9. Simulation results of SVPWM based DTC; a 30 N-m load is applied at 0.7 sec and removed at 0.9 sec.

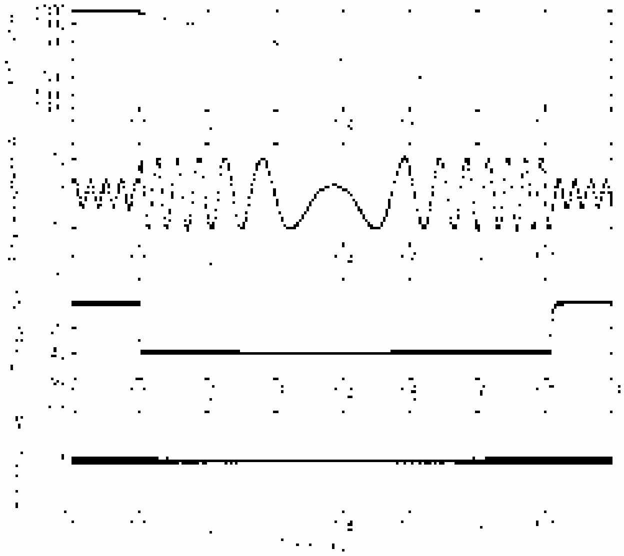


Fig. 10. Transient responses during speed reversal for SVPWM based DTC; Speed is changed from +1300 rpm to -1300 rpm.

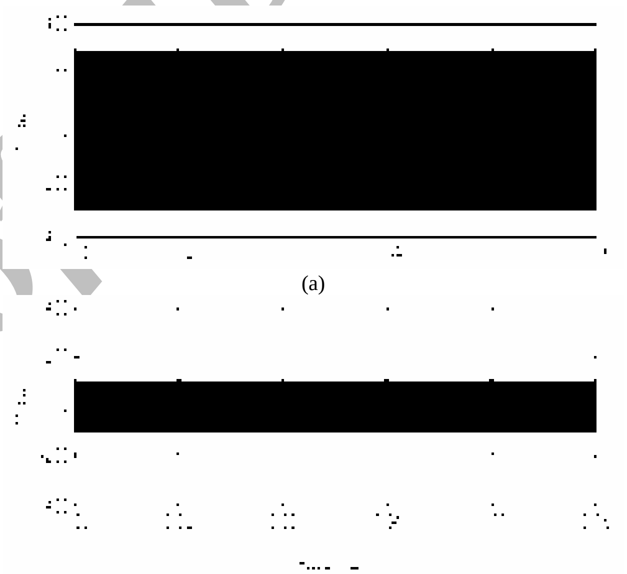


Fig. 11. Common mode voltages with (a) conventional SVPWM and (b) proposed SVPWM.

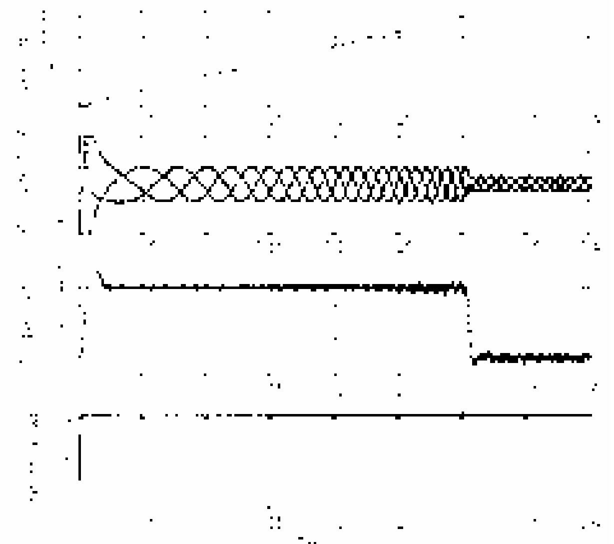


Fig. 12. Simulation results of proposed SVPWM based DTC: starting transients.

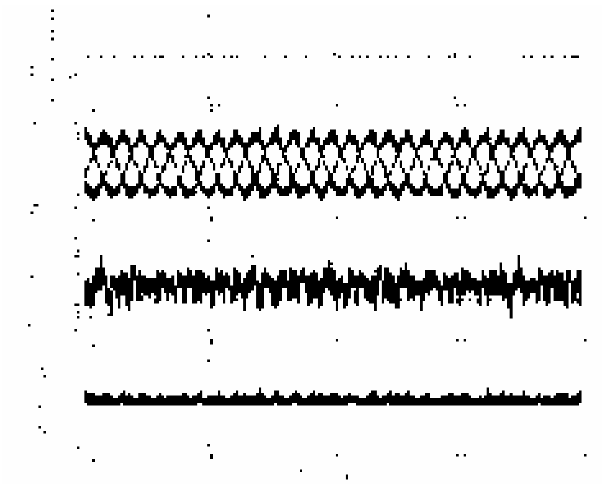


Fig. 13. Simulation results of proposed SVPWM based DTC: steady state plots at a speed of 1300rpm.

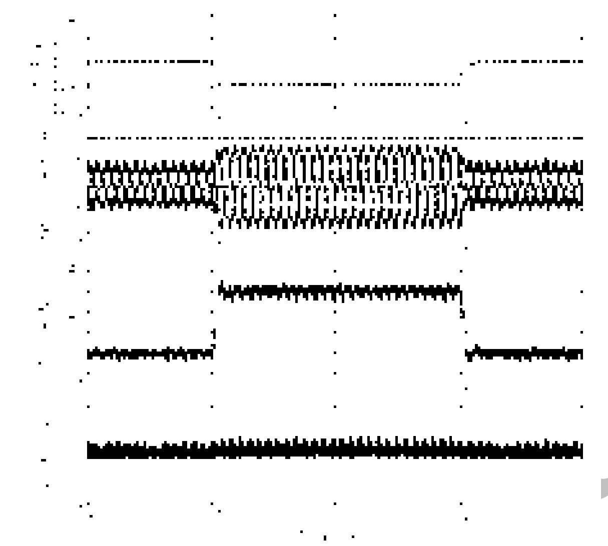


Fig. 14. Simulation results of proposed SVPWM based DTC: a 30N-m load is applied at 0.7 sec and removed at 0.9 sec.

reduction in common mode voltage at the expense of considerable increase of ripple in flux, current and torque.

VIII. Conclusion

In this paper a new SVPWM algorithm for direct torque controlled induction motor drives has been proposed, which reduces common mode emissions of the drive. In the proposed SVPWM technique instead of zero voltage vectors, non-zero nonadjacent vectors are used in composing the reference voltage vector.

It preserves the best of Conventional SVPWM technique in two ways 1) The vector times associated with the proposed technique are same as that of conventional SVPWM technique and 2) The number of commutations in a sector and from one sector to the next remains the same as in conventional SVPWM technique.

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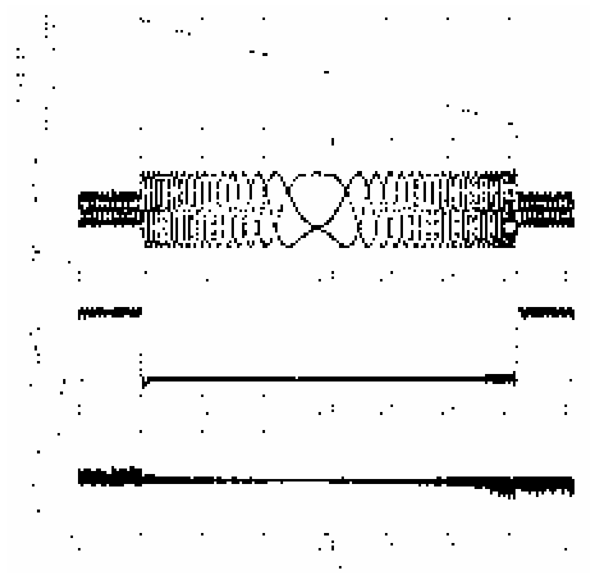

Fig. 15. Transient responses during speed reversal for proposed SVPWM based DTC; Speed is changed from +1300 rpm to -1300 rpm.

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Y. V. Siva Reddy received B.Tech and M.Tech degrees from JNT University, Anantapur in the year 1995 and 2000 respectively. He is currently pursuing Ph.D. at JNT University, Hyderabad. He is presently Associate Professor in the Electrical and Electronics Engineering Department, G. Pulla Reddy Engineering College, Kurnool. His research areas include Power systems and Electrical Drives.

T. Brahmananda Reddy graduated from Sri Krishna Devaraya University, Anantapur in the year 2001, M.E from Osmania University, Hyderabad in the year 2003. He is currently pursuing Ph.D. at J.N.T.University, Hyderabad. He is presently Assistant Professor in the Electrical and Electronics Engineering Department, G. Pulla Reddy Engineering College, Kurnool. His research areas include PWM techniques, and Electrical Drives.

M. Vijaya Kumar graduated from NBKR Institute of Science and Technology, Vidyanagar, A.P, India in 1988. He obtained M.Tech degree from Regional Engineering College, Warangal, India in 1990. He received Doctoral degree from JNT University, Hyderabad, India in 2000.

Currently he is working as Professor in Electrical and Electronics Engineering Department, JNT University, Anantapur, A.P, India. He is a member of Board of studies of S.V. University, Tirupathi and JNT University, Hyderabad, India. He has published over 40 research papers. He received two research awards from the Institution of Engineers (India). His areas of interests include Electrical Machines, Electrical Drives, Microprocessors and Instrumentation.