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Direct Torque Control Algorithm for the Reduction of Common Mode Voltage Using Look-up Tables

V. Anantha Lakshmi[1], T. Brahmananda Reddy[1], G. Naresh Kumar Reddy[1], M.Surya Kalavathi[2] and V.C.Veera Reddy[3]
1E.E.E Department, G. Pulla Reddy Engineering College, Kurnool, Andhra Pradesh, India
Email: v.al@rediffmail.com
[2]E.E.E Department, J.N.T. University, Hyderabad, Andhra Pradesh, India
Email: munagala12@yahoo.co.in
[3]E.E.E Department, S.V. University, Tirupati, Andhra Pradesh, India
Email:veera reddyj1@rediffmail.com

Abstract—**This paper has described the application of the newly developed direct torque control (DTC) scheme for the reduction of common mode voltage of an induction motor drive. This DTC scheme for the reduction of common mode voltage does not use any zero voltage vectors. To validate the proposed algorithm, numerical simulation has been carried out using MATLAB-Simulink and results are presented and compared. From the simulation results, it can be concluded that common mode voltage variations are reduced with a slight increase of torque and flux ripples when compared with conventional DTC.**

Index Terms—**Common mode voltage, direct torque control, induction motor drive, modified direct torque control**

I. INTRODUCTION

The innovative studies of M. Depenbrock and I. Takahashi replaced decoupling control with bang-bang control commonly referred as DTC [1]. It is recognized as an alternative method to field oriented control (FOC) [2]. Industrial drives with DTC are present in the market today [3]. DTC is proposed to control electromagnetic torque and stator flux by directly modifying the stator voltage in accordance with the torque and flux errors [4-6].

Though DTC is simple and gave fast transient response, it generated high level common mode voltage variations. To avoid the problems of common mode voltage variations a new DTC algorithm was developed [7], in which, only odd or only even voltage vectors will be applied in each sector in which stator flux lies without using any zero voltage vectors. However, this method gave torque ambiguity. To overcome the torque ambiguity, modified DTC algorithm has been proposed [8].

This paper has presented a novel direct torque control algorithms for reduced common mode voltage variations. In the proposed DTC two cases were considered. In first case, both even and odd active voltage vectors are applied in each sector. Whereas in the second case, only even voltage vectors were applied for odd sectors and only odd voltage vectors were applied for even sectors.

II. PRINCIPLE OF CONVENTIONAL DTC

The torque produced by the induction motor can be expressed as given in (1).

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\lambda_r||\lambda_s|\sin\delta \quad (1)$$

where δ is the angle between the stator flux linkage space vector (λ_s) and rotor flux linkage space vector (λ_r) as shown in Fig 1.

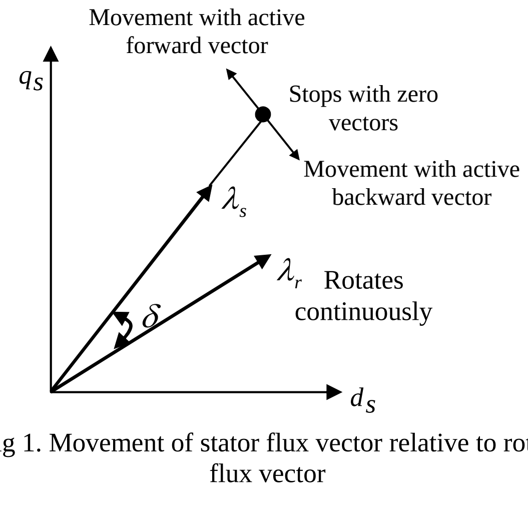

Fig 1. Movement of stator flux vector relative to rotor flux vector

As the rotor time constant of an induction motor is larger than the stator, rotor flux changes slowly with respect to stator flux. Neglecting the stator ohmic drop, the stator flux can be expressed as. $\Delta\lambda_s = V_s * \Delta t$. Thus, torque can be controlled by quickly varying the stator flux position by means of the stator voltage applied to the motor. There is a possibility of changing the stator flux in the required direction by selecting step-by-step the appropriate stator voltage vector. Application of a forward active voltage vector causes rapid movement of stator flux away from rotor flux and thus increases the torque with angle. Application of a zero vector causes stator flux to become stationary and torque decreases.

The torque and flux can be controlled by switching the appropriate voltage vector based on location of stator flux space vector.

III. Proposed DTC algorithms

The common mode voltage generated by a three phase electric machine is given by

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

where V_{ao}, V_{bo} and V_{co} are the pole voltages.

Hence, if the drive is fed by balanced three phase supply, the common mode voltage is zero. But, when the drive is fed from an inverter common mode voltage changes instantaneously. DC-link voltage (V_{dc}) and the switching states decide the common mode voltages and these are given in Table -1 for different voltage vectors. The block diagram of proposed DTC is shown in Fig.2. Actual torque and flux values are calculated by the adaptive motor model. The torque and flux comparators compare the torque reference with actual torque and the flux reference with actual flux. On the basis of the torque and flux errors, the voltage source inverter state is determined so as to rapidly reduce these errors and to maintain them within prefixed limits. Block diagram for both the cases remain the same. First sector is from 0^0 to 60^0 for both the cases.

Table 1: Common mode voltages for different inverter switching state:

States	V_{ao}	V_{bo}	V_{co}	V_{com}
V_0	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$
V_1	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
V_2	$V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/6$
V_3	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
V_4	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
V_5	$-V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/6$
V_6	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
V_7	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$

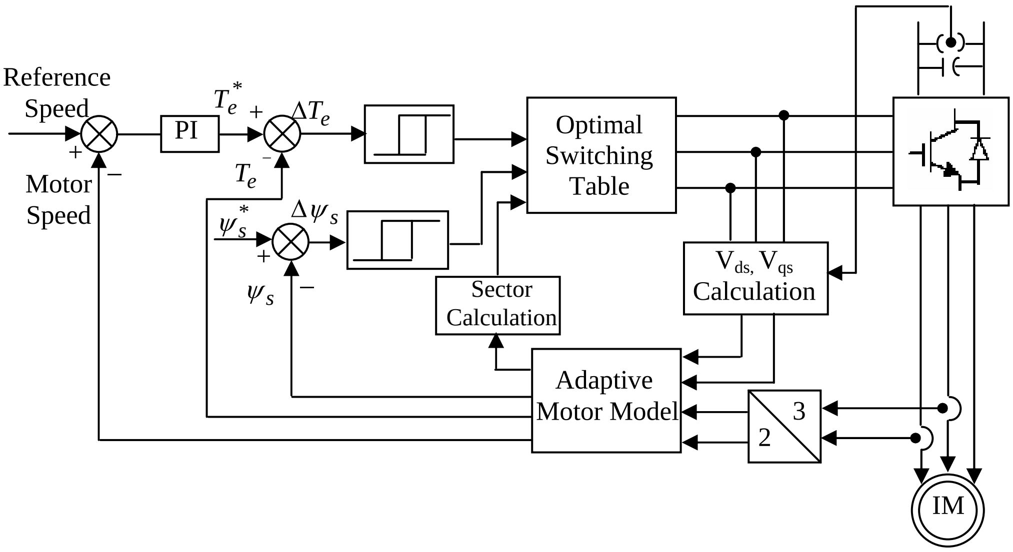

Fig. 2 Block diagram of proposed DTC

A. *Case - I*

The selection of voltage vector is explained in Fig. 3.

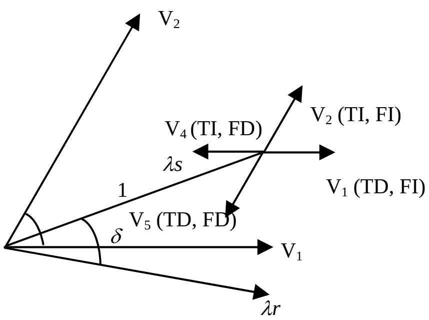

Fig. 3 Selection of voltage vectors for proposed algorithm (case – I)

Assume that the initial stator flux vector and rotor flux are in the first sector as shown in Fig.3. Application of voltage vectors V_2 and V_1 can increase the stator flux and V_4 and V_5 can decrease the stator flux. Similarly V_2 and V_4 can increase the torque and V_1 and V_5 decrease the torque. Similarly, the suitable voltage vectors can be selected for other sectors. Because of flux ambiguity voltage vectors V_3 and V_6 are not used in this first sector, V_1 and V_4 for second sector and so on. The lookup table for all sectors is given in Table. 2.

Table-2: Switching vector table for proposed DTC

b_λ	b_T	R_1	R_2	R_3	R_4	R_5	R_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_1	V_2	V_3	V_4	V_5	V_6
0	1	V_4	V_5	V_6	V_1	V_2	V_3
	-1	V_5	V_6	V_1	V_2	V_3	V_4

The common mode voltage of proposed DTC is reduced when compared with Conventional DTC when the zero voltage vectors is neglected. But within the sector itself common mode voltage varies from $V_{dc}/6$ to $-V_{dc}/6$ due to the application of even and odd voltage vectors simultaneously. So to overcome that variation and to maintain constant value within a sector second method is proposed in which only even voltage vectors are applied for odd sectors and odd voltage vectors are applied for even sectors.

B. Case - II

Assume that the initial stator flux vector and rotor flux are in the first sector as shown in Fig. 4.

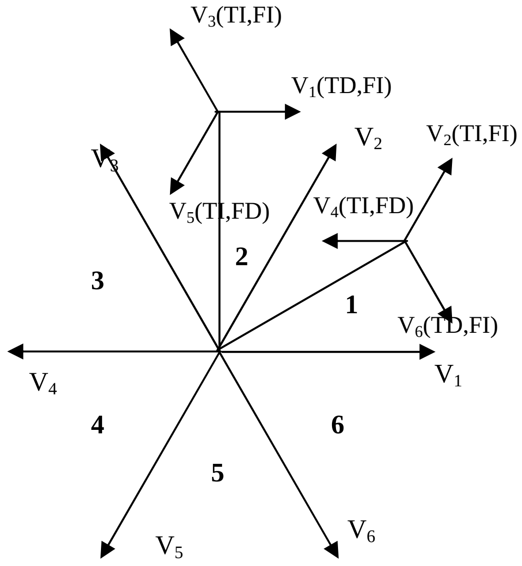

Fig. 4 Selection of voltage vectors in proposed algorithm (case – II)

Application of voltage vector V_2 and V_4 causes an increase in torque and V_6 decrease in torque Application of voltage vectors V_4 and V_6 causes a decrease in flux amplitude and V_2 and V_6 causes an increase in flux amplitude The common mode voltage of voltage vectors V_2, V_4, V_6 is $V_{dc}/6$. If the stator flux vector is in the second sector then any one of the odd voltage vectors is applied. Application of voltage vectors V_1 and V_3 causes an increase in flux amplitude and V_1 and V_5 causes a decrease in flux amplitude. Application of voltage vector V_5 and V_3 causes an increase in torque and V_1 decrease in torque. The common mode voltage of odd voltage vectors is-$V_{dc}/6$.

Thus, only even voltage vectors will be selected for odd sectors and only odd voltage vectors will be selected for even sectors. The lookup table for all sectors is given in Table. 3. Table-3: Switching vector table for proposed DTC

b_λ	b_T	R_1	R_2	R_3	R_4	R_5	R_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_4	V_5	V_6	V_1	V_2	V_3
	-1	V_6	V_1	V_2	V_3	V_4	V_5

As long as stator flux vector lies in even or odd sector, there will be no variation in common mode voltage. Variation in common mode voltage occurs, when stator flux vector goes from one sector to another, therefore at each sector crossing variation of common mode voltage should be minimum.

IV. Simulation Results and Discussions

To validate the proposed method, a numerical simulation has been carried out by using Matlab/ Simulink. For the simulation studies, the reference flux is taken as 1wb and starting torque is limited to 45 N-m. Various conditions such as starting, steady state, load change and speed reversal are simulated. The results for conventional direct torque controlled induction motor drive are shown in Fig 5 - Fig 7 and the results for proposed methods are shown in Fig 8 - Fig 15.

From the simulation results, it can be observed that with the proposed algorithms, the common mode voltage variations of direct torque controlled induction motor drive system can be decreased compared to conventional DTC with slight increase in torque, stator current and stator flux ripples.

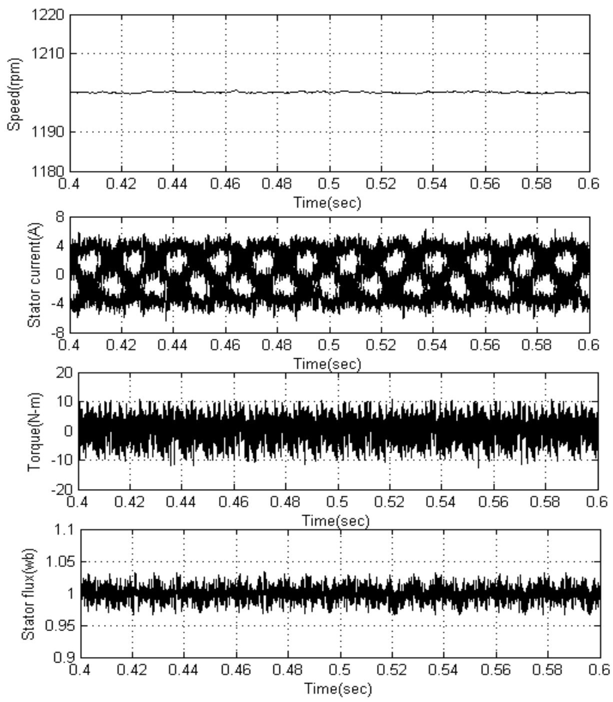

Fig. 5 Steady state plots of conventional DTC

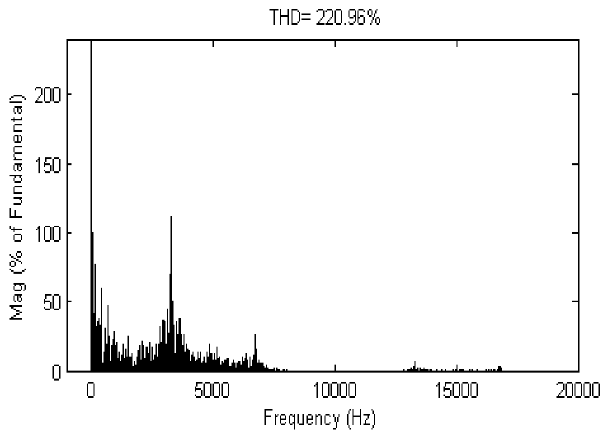

Fig. 6 Harmonic spectra of stator current in conventional DTC

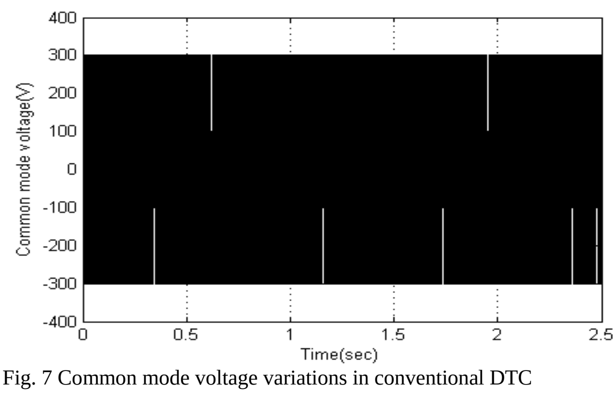

Fig. 7 Common mode voltage variations in conventional DTC

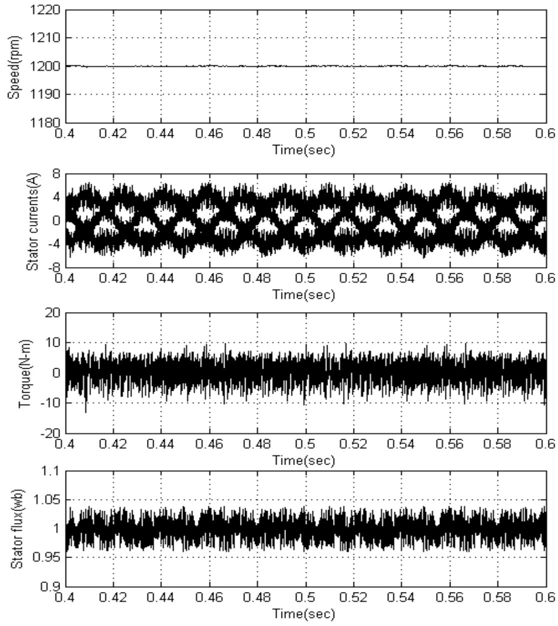

Fig. 8 Steady state plots in proposed DTC algorithm (Case-I)

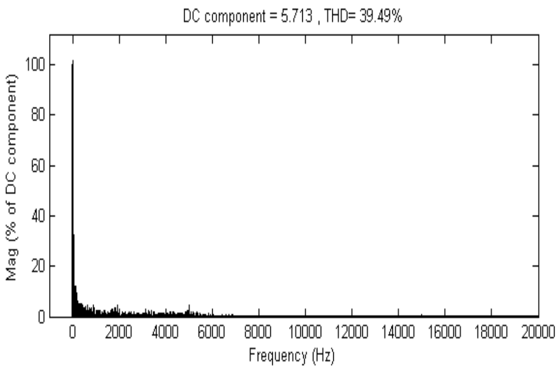

Fig. 9 Harmonic spectra of stator current in proposed DTC (Case-I)

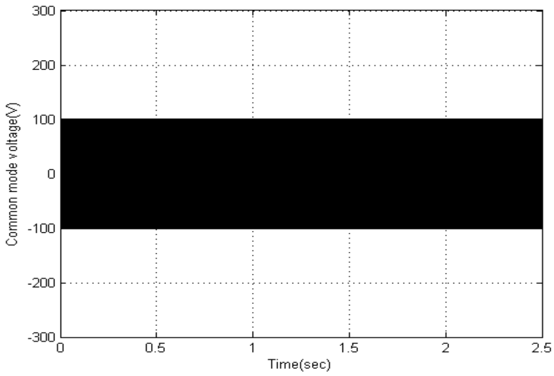

Fig. 10 Common mode voltage variations in proposed DTC (case-I)

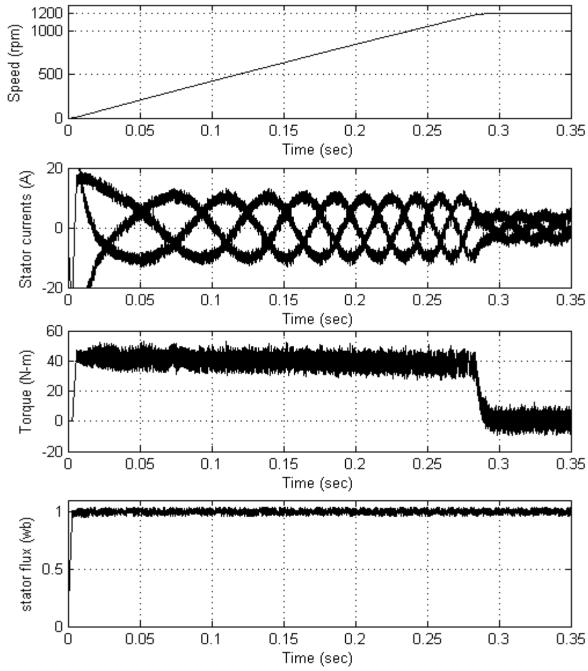

Fig. 11Starting transients in proposed DTC (case-II)

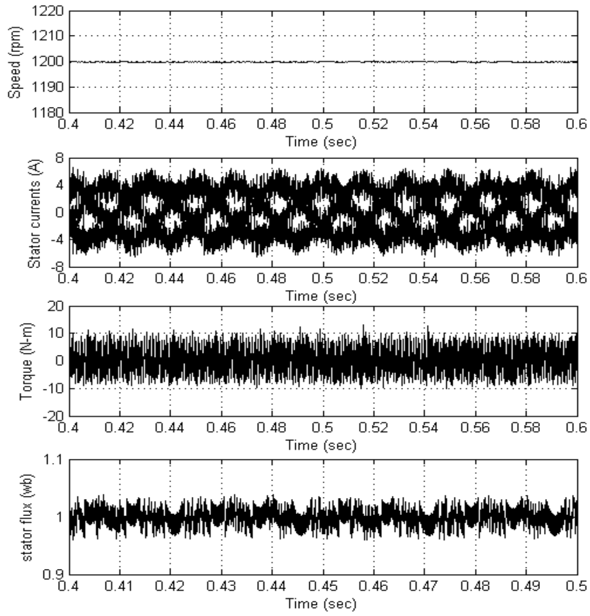

Fig. 12 Steady state plots in proposed DTC (case-II)

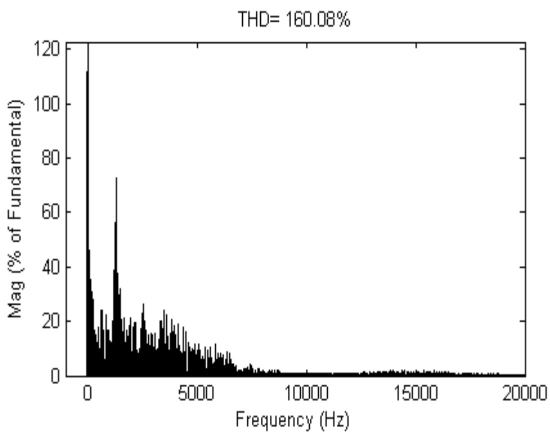

Fig. 13 Harmonic spectra of stator current in proposed DTC (case-II)

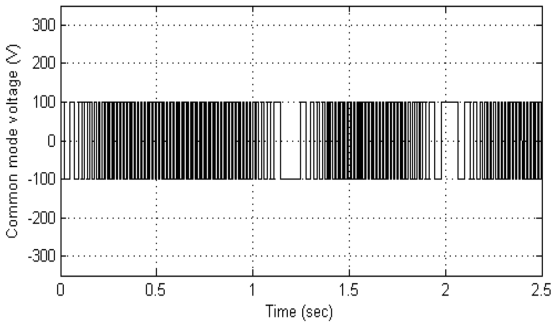

Fig. 14 Common mode voltage variations in proposed DTC (case-II)

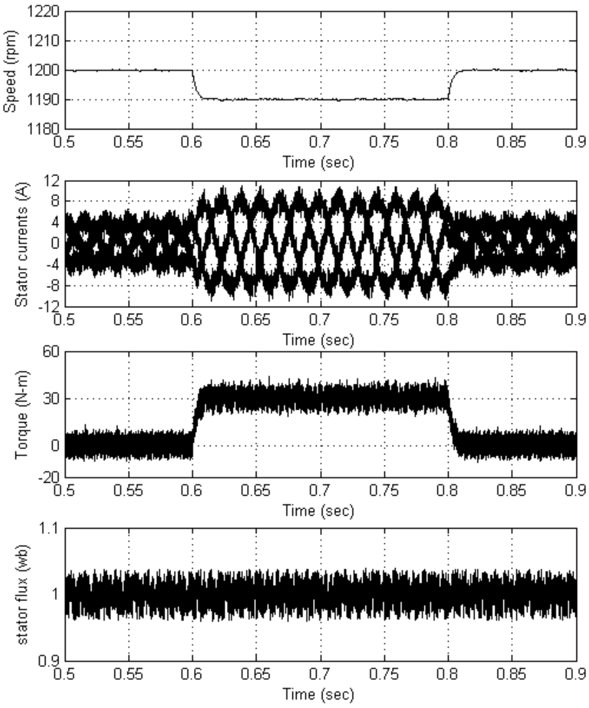

Fig. 15 Transients during step change in load in proposed DTC (case-II)

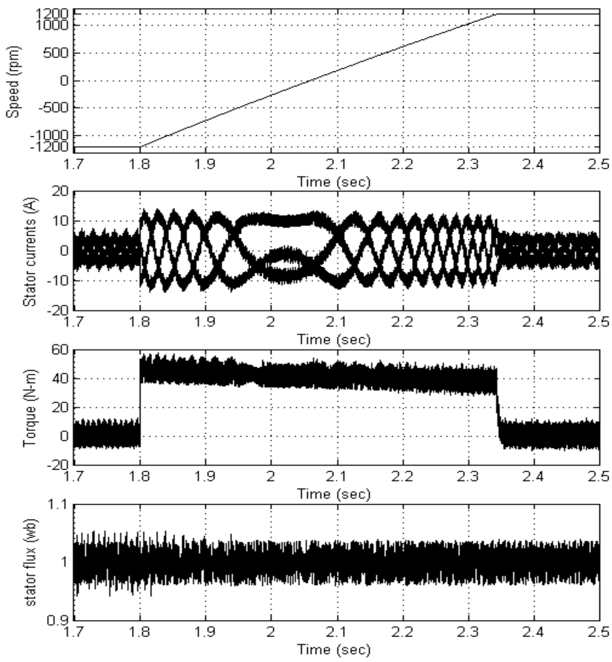

Fig. 16 transients during speed reversal in proposed DTC (case-II)

V. CONCLUSIONS

In conventional DTC common mode voltage variations are very high because of zero voltage vectors. To reduce the common mode voltage variations, a novel algorithm has been proposed for DTC. In the proposed algorithm, only even voltage vectors will be selected for odd sectors and only odd voltage vectors will be selected for even sectors. When the zero voltage vectors are eliminated, the common mode voltage variations are reduced. From the simulation results, it can be observed that the common mode voltage is very less in the proposed algorithm compared to CDTC. But, there is slight increase in the steady state torque, current and flux ripples.

APPENDIX A: INDUCTION MOTOR PARAMETERS

400 V, 4-pole, 1470 rpm, 50 Hz, 3-phase induction motor has the following parameters:

Stator resistance	R_s: 1.57 ohm
Rotor resistance	R_r: 1.21 ohm
Stator inductance	L_s: 0.17 H
Rotor inductance	L_r: 0.17 H
Mutual inductance	L_m: 0.165 H
Moment of Inertia	J; 0.089 kg-m^2

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