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Direct Torque Control Algorithm for Induction Motor Drives for the Mitigation of Common Mode Voltage

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Abstract

This paper presents a novel direct torque control (DTC) algorithm for induction motor drives for the reduction of common mode voltage. In the Proposed DTC algorithm-I the space vector plane is divided into six sectors same as that of Conventional DTC algorithm. In the proposed algorithm-II, the space vector plane is divided into twelve sectors instead of six sectors as in conventional DTC algorithm and Proposed DTC algorithm-I. Moreover, the proposed algorithm does not use the zero voltage vectors. To validate the proposed algorithm, numerical simulations have been carried out using MATLAB-Simulink and results are presented and compared. From the simulation results it can be observed the proposed algorithm reduces the common mode voltage variations compared to conventional DTC algorithm with slightly increased ripples in current, torque and flux.

Keywords: Common mode voltage, direct torque control, induction motor drives, look-up table, voltage vectors

1. Introduction

Nowadays the induction motors are popular in the industry because of their advantages. The high performance control algorithms that are used for induction motor drives are field oriented control (FOC) or vector control and direct torque control (DTC) or direct self control (DSC) (2002). F. Blaschke (1972) propsed FOC which permits independent control of the torque and flux by decoupling stator current into two orthogonal components. In contrast, Werner Leonard (2003), Isao Takahashi and Toshihiko Noguchi(1986) and M. Depenbrock (1988) proposed DTC which is simple, robust to parameter variations; do not require any co-ordinate transformations . James N. Nash (1997) proposed DTC that abandons the stator current control philosophy and achieves bang-bang torque and flux control by directly modifying the stator voltage in accordance with the torque and flux errors. The basic concept of DTC is to control both electromagnetic torque and stator flux simultaneously by proper selection of optimum inverter switching states in accordance with the torque and flux errors.

In spite of its simplicity, DTC generates high level common mode voltage variations. To avoid the problems of common mode voltage variations a new DTC algorithm has developed by Maurizio Cirrincione, Marcello Pucci, Gianpaolo Vitale and Giansalvo Cirrincione (2006) by using only even or only odd voltage vectors in every sector. However, this method gives torque ambiguity. To overcome the torque ambiguity, modified DTC algorithm and 12-sector based DTC algorithms have been proposed by Y.V.Siva Reddy, M.Vijayakumar and T. Brahmananda Reddy (2007). This paper presents a novel direct torque control algorithms for reduced common mode voltage variations. In the proposed DTC two algorithms are considered. In the proposed algorithm-I, a six sector based DTC is considered same as in CDTC without using zero voltage vectors. In proposed algorithm-II, 12-sector based DTC algorithm is considered where the first sector zone is from 0^0 to 30^0.

1.1 ***Principle of Conventional DTC***

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

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

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. This shows the torque produced is dependent on λ_s, λ_r and the phase angle between the stator and rotor flux vectors.

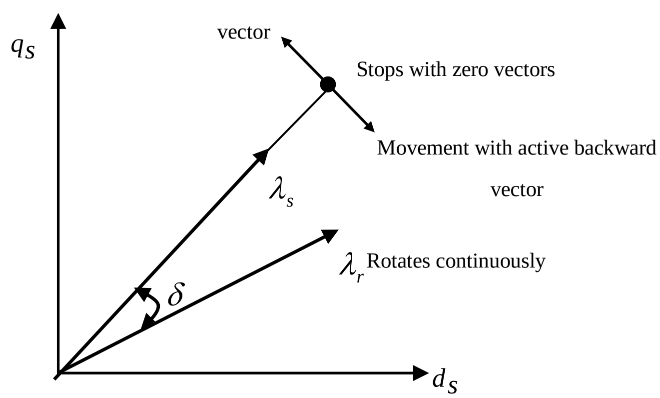

Figure 1: Relative movement of stator flux vector with respect to rotor flux vector

During steady state as both stator and rotor fluxes move with same angular velocity, the angle determines the electromagnetic torque developed. But during transient state both fluxes do not move with same velocity. As the rotor time constant of an induction motor is large, rotor flux change slowly with respect to stator flux. Therefore, any change in torque can be produced by rotating stator flux in the required direction. Stator flux linkage space vector can be changed with stator voltages. Neglecting the rotor resistance drop, for a short time interval Δt, when the voltage vector is applied, $\Delta\vec{\lambda}_s = \overline{V}_s \Delta t$. Thus, the stator flux linkage space vector moves by $\Delta\vec{\lambda}_s$ in the direction of the stator voltage space vector at a speed proportional to magnitude of voltage space vector. By selecting step-by-step the appropriate stator voltage vector, it is then possible to change the stator flux in the required direction. If a forward active voltage vector is applied then it causes rapid movement of stator flux and torque increases with angle. If a zero vector is used stator flux becomes 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.

1.1.1 **Conventional DTC**

The block diagram of conventional DTC is shown in Fig 2. The torque and flux comparators compare the torque reference with actual torque and the flux reference with actual flux. Actual torque and flux values are calculated by the adaptive motor model. In conventional DTC (CDTC), the stator flux linkage and torque errors are restricted within their respective hysteresis bands, which are $2\Delta\lambda_s$ and $2\Delta T_e$ wide respectively. The flux controller is a two-level comparator in which, if a stator flux increase is required then b_λ=1; if a stator flux decrease is required then b_λ=0. The digitized output signals of the two level flux hysteresis controller are defined as,

If $\lambda_s \le \lambda_s^* - \Delta\lambda_s$ then $b_\lambda=1$

If $\lambda_s \le \lambda_s^* + \Delta\lambda_s$ then $b_\lambda=0$. (2)

If a torque increase is required then b_T=1, if a torque decrease is require then b_T= -1, and if no change in the torque is required then b_T =0. The digitized output signals of the three level torque hysteresis controller for the anticlockwise rotation or forward rotation can be defined as,

If $T_e - T_e^* \ge \Delta T$ then $b_T=1$

If $T_e \ge T_e^*$ then $b_T=0$ (3)

And for clockwise rotation or backward rotation

If $T_e^* - T_e \le -\Delta T_e$ then $b_T=-1$,

If $T_e \le T_e^*$ then $b_T=0$ (4)

Depending upon the b_T, b_λ, and the position of the stator flux vector, the switching state is determined from the lookup table. This switching table selects the suitable voltage vector to limit torque and flux errors with in the hysteresis band, which results in direct control. The selection of voltage vector is explained in Fig 3.

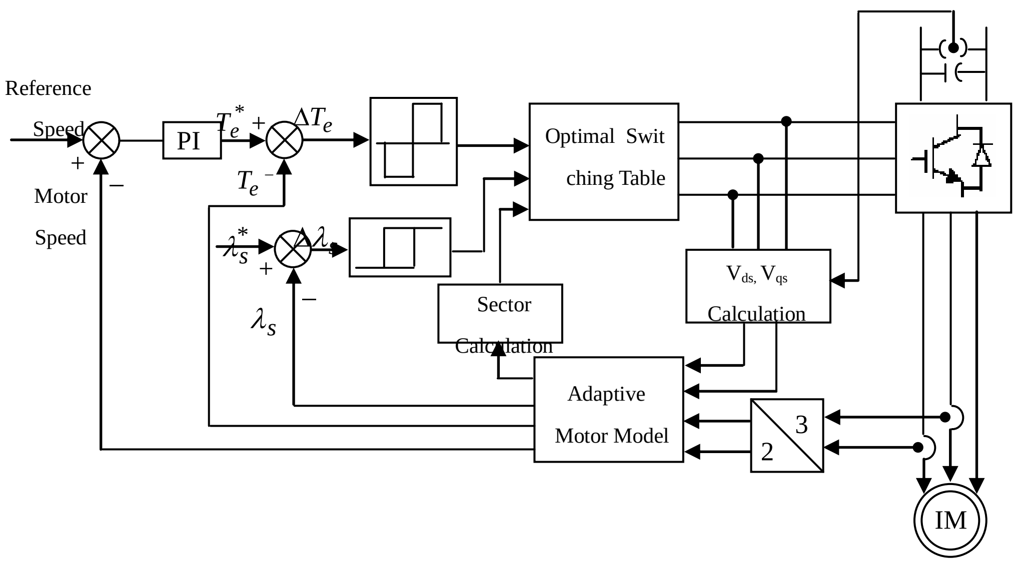

Figure2: Block diagram of Conventional DTC

The position of stator flux is divided into six different sectors , the zone of first sector is from -30^0 to 30^0 .If the stator flux vector is in the first sector then any one of the voltage vectors V_2, V_3, V_5, V_6 are applied. If voltage vector V_2 is applied it causes an increase in flux amplitude and increase in torque, if voltage vector V_3 is applied it causes a decrease in flux amplitude, increase in torque, if voltage vector V_6 is applied it causes an increase in flux amplitude, a slight decrease in torque. If voltage vector V_5 is applied it causes a decrease in flux amplitude and decrease in torque. Voltage vectors V_1 and V_4 are not used in first sector because they can increase or decrease the torque at the same sector depending on the position if the voltage vector is in its first 30^0 or in its second ones. Voltage vectors V_1 and V_4 causes torque ambiguity. If the stator flux vector is in the second sector then any one of the voltage vectors V_3, V_1, V_4, V_6 are applied. If voltage vector $V_{1,}$ is applied it causes an increase in flux amplitude, a slight decrease in torque, if voltage vector V_3 is applied it causes an increase in flux amplitude, increase in torque and if voltage vector V_4 is applied it causes a decrease in flux amplitude and increase in torque, if voltage vector V_6 is applied it causes an decrease in flux amplitude and decrease in torque. Voltage vectors V_2 and V_5 are not used in second sector because they can increase or decrease the torque at the same sector. The lookup table for all sectors is given in Table-1.

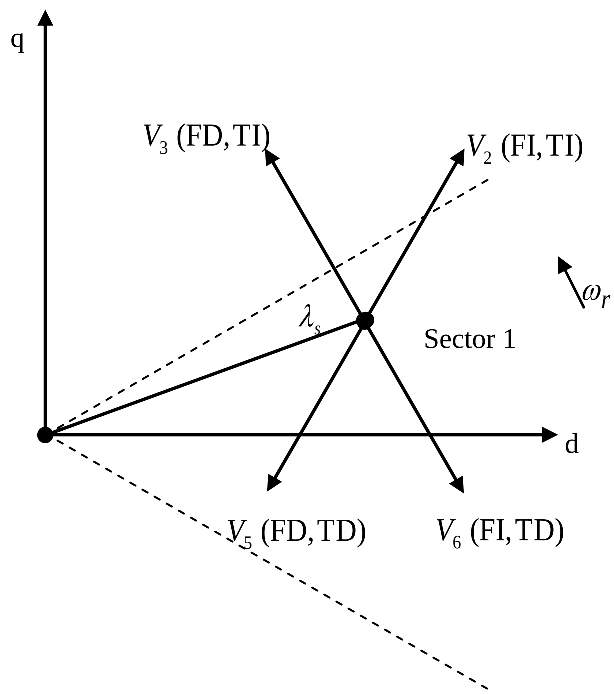

Figure 3: Selection of voltage vector in first sector

Table 1: Lookup table for Conventional DTC Algorithm

b_λ	b_T	R_1	R_2	R_3	R_4	R_5	R_6
1	1	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$
	0	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$
	-1	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$	$\overline{V}_5$
0	1	$\overline{V}_3$	$\overline{V}_4$	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$
	0	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$	$\overline{V}_0$	$\overline{V}_7$
	-1	$\overline{V}_5$	$\overline{V}_6$	$\overline{V}_1$	$\overline{V}_2$	$\overline{V}_3$	$\overline{V}_4$

1.1.2 ***Common mode voltage (CMV)***

For the most common two-level voltage source inverter there are three switching variables a, b, c one per phase of the inverter. Fig 4 shows a voltage source inverter(VSI) connected to a motor.

Every terminal of the induction motor will be connected to the pole of one of the inverter legs, and thereby, either to the positive dc bus or the negative dc bus. There are eight out put voltage vectors in which six are active voltage vectors and remaining two vectors are zero voltage vectors with totally eight possible switching states of the inverter. The CMV is the potential of the star point of the load with respect to the centre of the dc bus of the VSI.

The CMV generated by a star connected three phase electric machine is given by

$$V_{com} = \frac{(V_{ao} + V_{bo} + V_{co})}{3} \qquad (5)$$

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

If the drive is fed by balanced three phase supply, the CMV is zero. But, when the drive is inevitably fed from an inverter, CMV changes instantaneously. DC-link voltage (V_{dc}) and the switching states of the inverter decide the common mode voltages, regardless of the ac machine impedance.

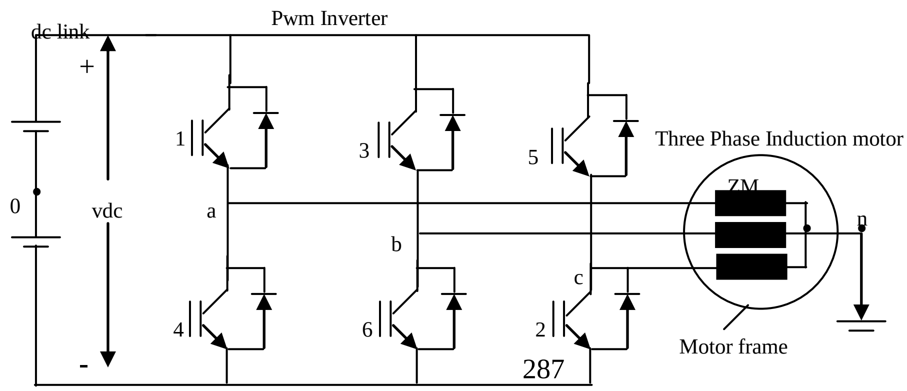

Figure 4: Three phase voltage source Inverter (VSI)

From Table -2 it can be observed that the CMV changes from one switching state of the inverter to the other, if only even or only odd vectors are used there will be no change in v_{com}, if a transition from an even voltage vector to an odd voltage vector occurs, a v_{com} variation of $V_{dc}/3$ is generated, if a transition from an odd(even) voltage vector to the zero voltage vector occurs a v_{com} of $2*V_{dc}/3$ is generated which is a worst case. So, in order to avoid common mode variations neglect the zero voltage vector. Hence, the proposed algorithm uses only active voltage vectors in all sectors in order to reduce the CMV variations.

TABLE 2: Common Mode Voltages for Different Inverter Switching States

Voltage vector	V_{ao}	V_{bo}	V_{co}	V_{com}
V_o	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$
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	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$

2 Proposed DTC Algorithm

The block diagram of proposed DTC algorithm-I is same as that of CDTC except that a two-level torque hysterisis controller is used instead of three level controller. The lookup table for all sectors is given in Table-3 for proposed algorithm-I. Though algorithm-I reduces the common mode voltage variations but it has high total harmonic distortion (THD). In order to reduce THD as well as common mode voltage variations algorithm –II is proposed.

TABLE 3: Look-up Table for the Proposed DTC Algorithm –I

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_3	V_4	V_5	V_6	V_1	V_2
	-1	V_5	V_6	V_1	V_2	V_3	V_4

The block diagram of proposed DTC algorithm-II is shown in Fig.5. The simplest way to overcome this difficulty is to avoid the adoption of the zero-voltage vector and therefore to use a four-level hysteresis torque controller and a two-level flux controller which commands only active voltage vectors. To utilize all six active states per sector, the stator flux locus is divided into twelve sectors.

A 4-level torque controller is used so as to measure the small and large variations of torque. This is traded off with an increase of the harmonic content of all electrical signals (stator voltages and currents) and of the torque and flux ripples. This DTC strategy, without the zero-voltage vector, will be simply called "Proposed DTC. The selection of voltage vector is explained in Fig. 6. First sector is from 0^0 to 30^0.

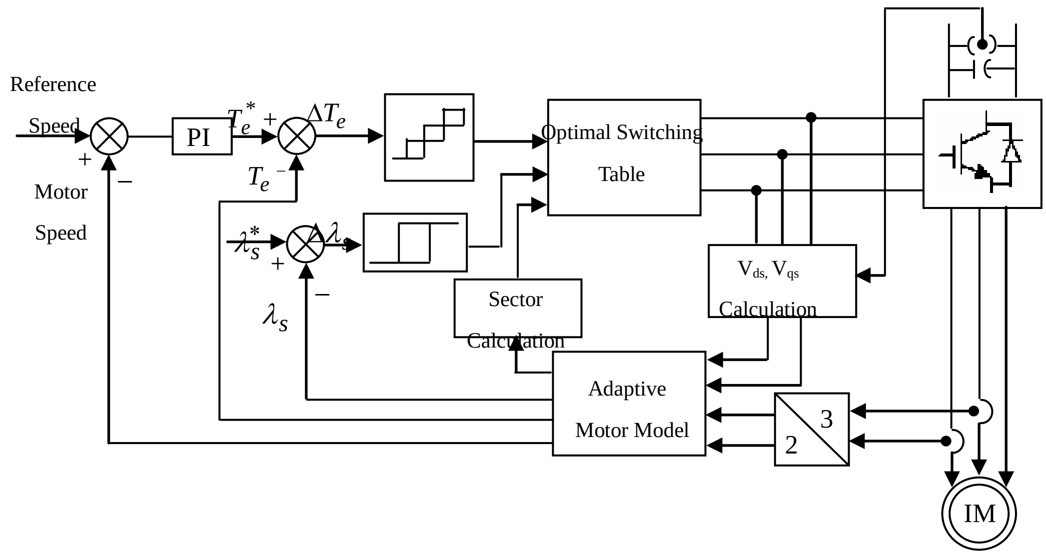

Figure. 5 Block diagram of proposed DTC Algorithm-II

Suppose assume the initial stator flux vector and rotor flux are in the first sector as shown in Fig.6. If voltage vector V_6 is applied it causes an increase in flux amplitude, a large decrease in torque. If voltage vector V_1 is applied it causes an increase in flux amplitude, a small decrease in torque. If voltage vector V_2 is applied it causes an increase in flux amplitude, a large increase in torque. If voltage vector V_3 is applied it causes a decrease in flux amplitude, a large increase in torque. If voltage vector V_4 is applied it causes an decrease in flux amplitude, a small increase in torque. If voltage vector V_5 is applied it causes a decrease in flux amplitude, a large decrease in torque. The lookup table for all sectors is given in Table-4. From the lookup table, where b_T=1 indicates large increase in torque, b_T=2 indicates small increase in torque, b_T=3 indicates small decrease in torque, b_T=4 indicates large decrease in torque. Thus, as shown in Fig. 6, the proposed algorithm uses only active voltage vectors in each and every sector. Hence, the proposed algorithm gives less CMV variations. Moreover, the proposed DTC can overcome the problems of torque ambiguity and flux ambiguity.

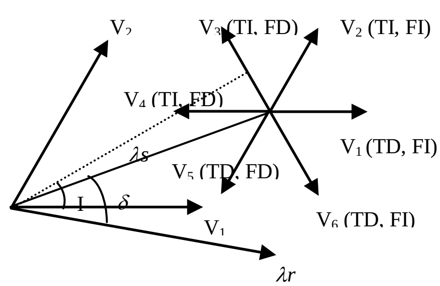

Figure. 6 Selection of voltage vector in first and second sectors

TABLE 4: Look-up Table for the Proposed DTC Algorithm-II

b_λ	b_T	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}
1	1	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
	2	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1

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	3	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6
	4	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
0	**1**	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3
	2	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3
	3	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4
	4	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5

3. Results and Discussion

To validate the proposed method, a numerical simulation has been carried out by using Matlab/Simulink. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 45 N-m. For the simulation studies, a 3-phase, 400V, 4 kW, 4-pole, 50 Hz, 1470 rpm Squirrel cage induction motor has considered. The parameters of the given induction motor are as follows: R_s=1.57ohm, R_r=1.21ohm, L_m= 0.165H, L_s= 0.17H, L_r= 0.17 H and J= 0.089 Kg - m^2. For the simulation, PI in proposed diagram algorithm was designed based on trail and error method.

Various conditions such as starting, steady state and speed reversal are simulated. But, in this paper only steady state and load change results are presented. The results for conventional direct torque controlled induction motor drive are shown in Fig 7 - Fig 11. The results for proposed algorithm-I of direct torque controlled induction motor drive without zero voltage vectors are shown in Fig 12 - Fig 16 and the results for proposed algorithm-II are shown in Fig 17 - Fig 21 along with their total harmonic distortion (THD) and CMV variations. From Fig. 7, Fig. 12 and Fig. 17 it can be observed that the steady state plots of proposed algorithms along with CDTC. From Fig. 8, Fig. 13 and Fig. 18 it can be observed that, the CMV changes from $+V_{dc}/6$ or $-V_{dc}/6$ in proposed DTC based algorithm instead of $+V_{dc}/2$ or $-V_{dc}/2$ as in conventional DTC algorithm due to elimination of zero voltage vectors. From Fig. 9, Fig. 14 and Fig. 15 it can be observed that the THD of proposed algorithm-II is reduced compared to CDTC as well as proposed algorithm-I . From the simulation results, it can be observed that the proposed algorithms reduce the CMV variations of direct torque controlled induction motor drive compared to conventional DTC.

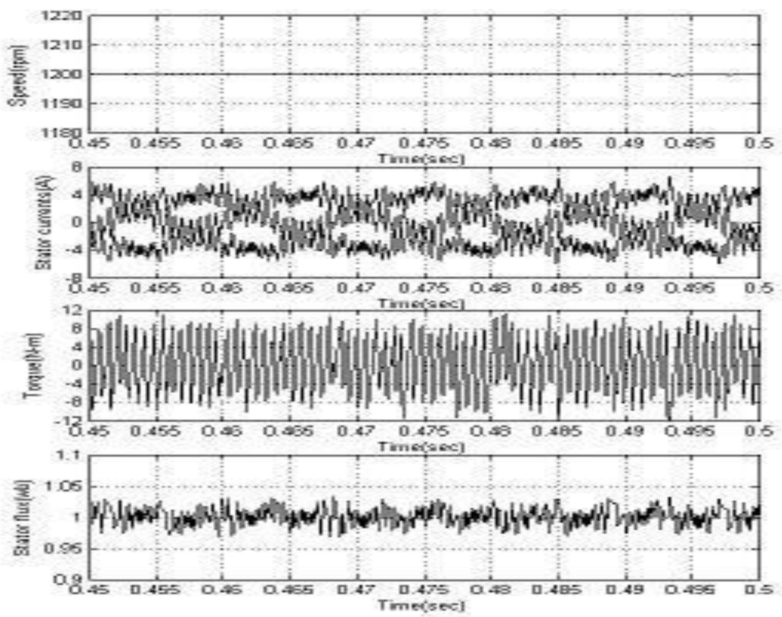

Figure. 7 Steady state plots with conventional DTC algorithm

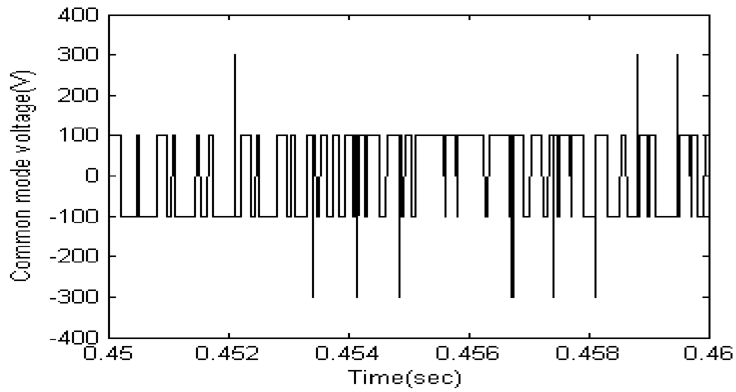

Figure. 8 common mode voltage variations in conventional DTC algorithm

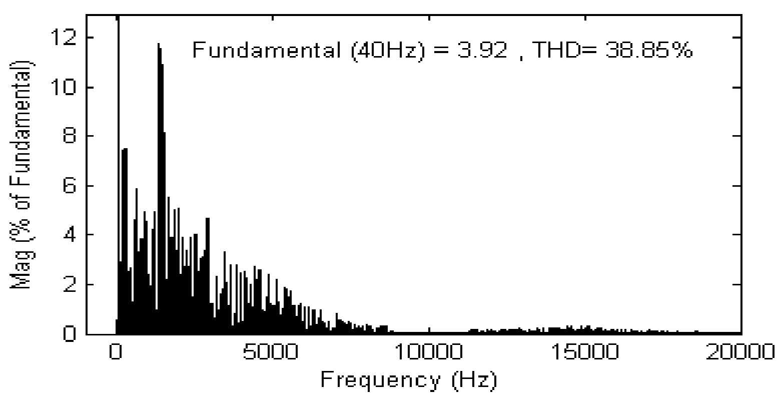

Figure 9 Harmonic spectra of stator current in conventional DTC algorithm

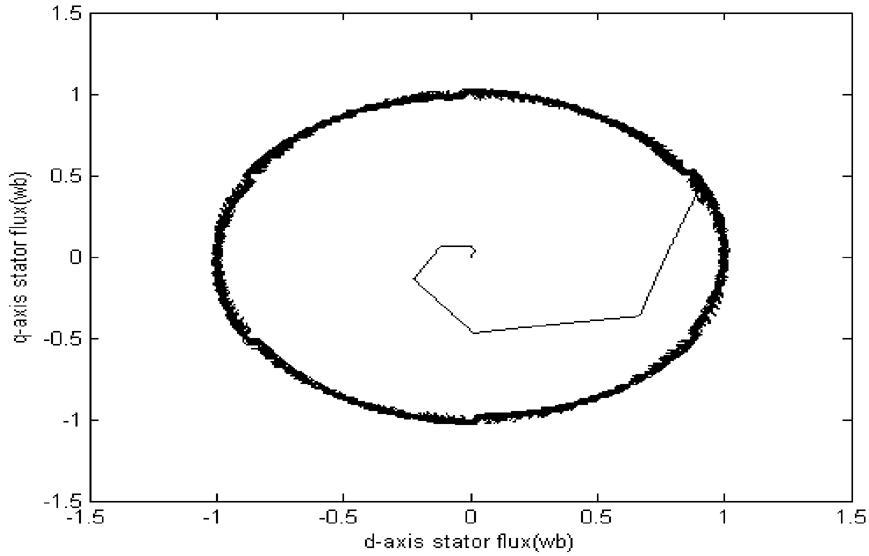

Figure.10 Locus in conventional DTC algorithm

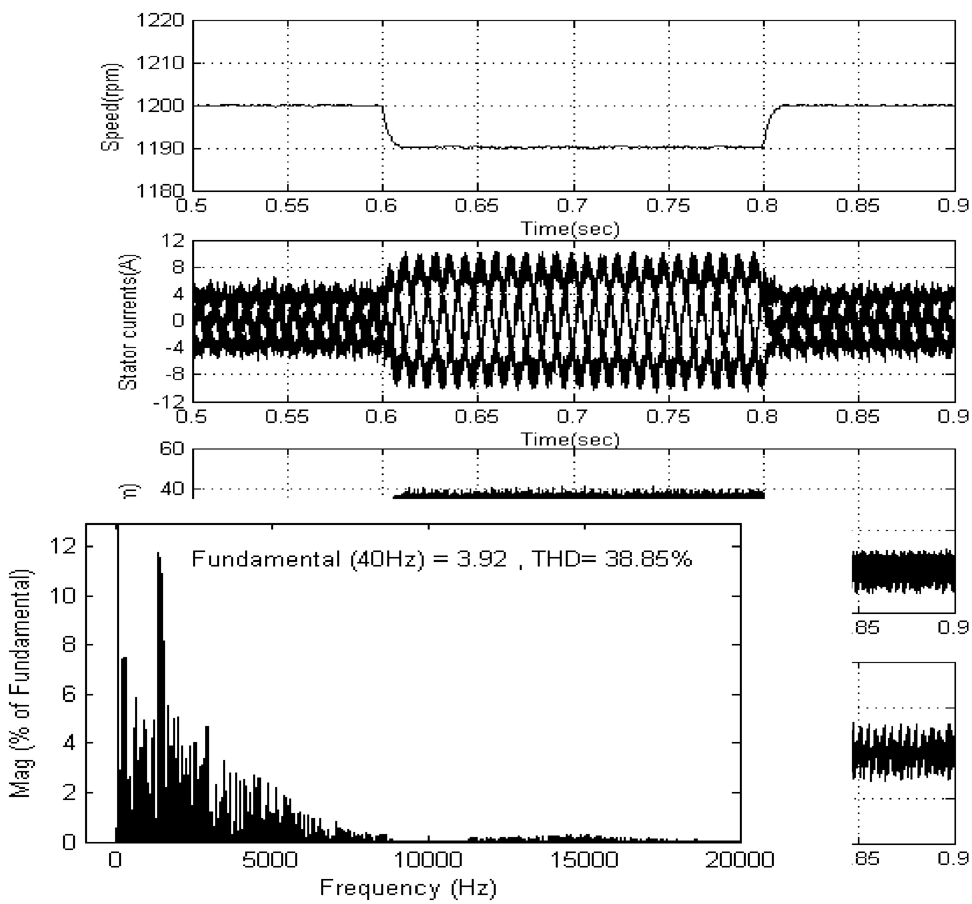

Figure.11 Load change in current in conventional DTC algorithm

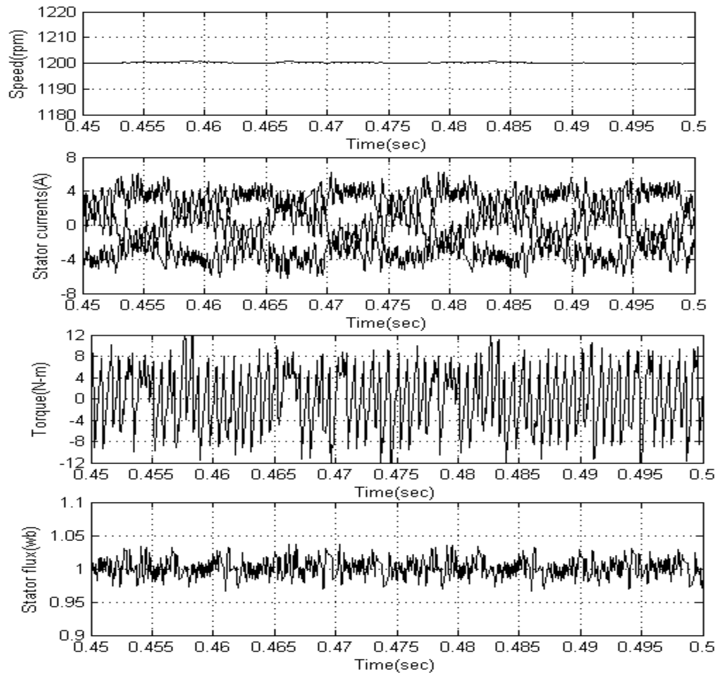

Figure 12 Steady state plots in proposed algorithm-I

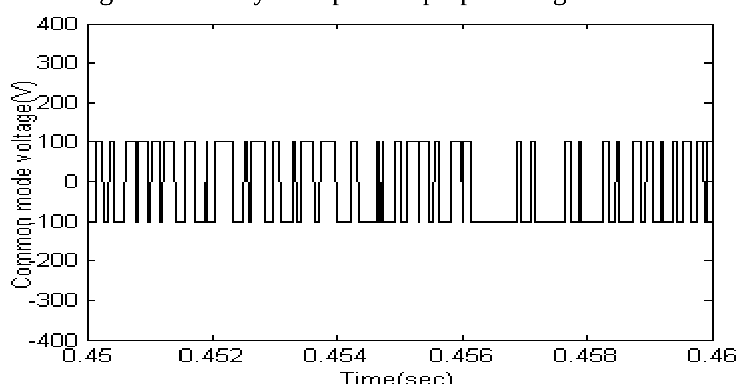

Figure 13 Common mode voltage variations in proposed algorithm-I

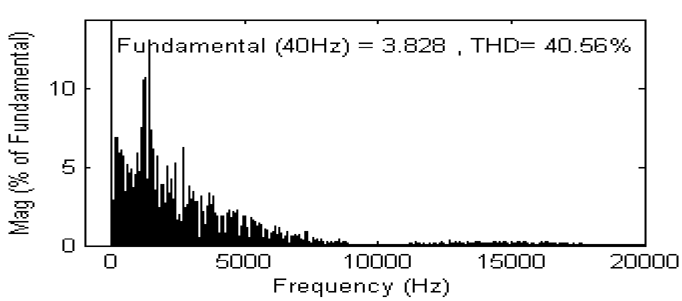

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Figure 14 Harmonic spectra of stator current in Proposed DTC algorithm-I

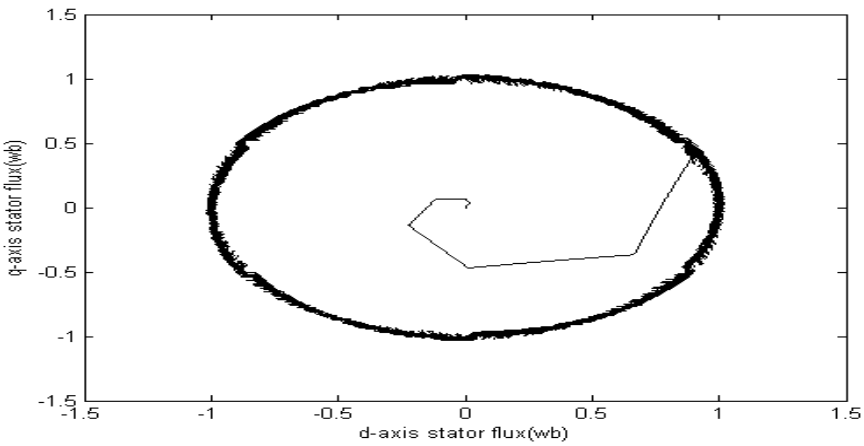

Figure.15 Locus in Proposed DTC algorithm-I

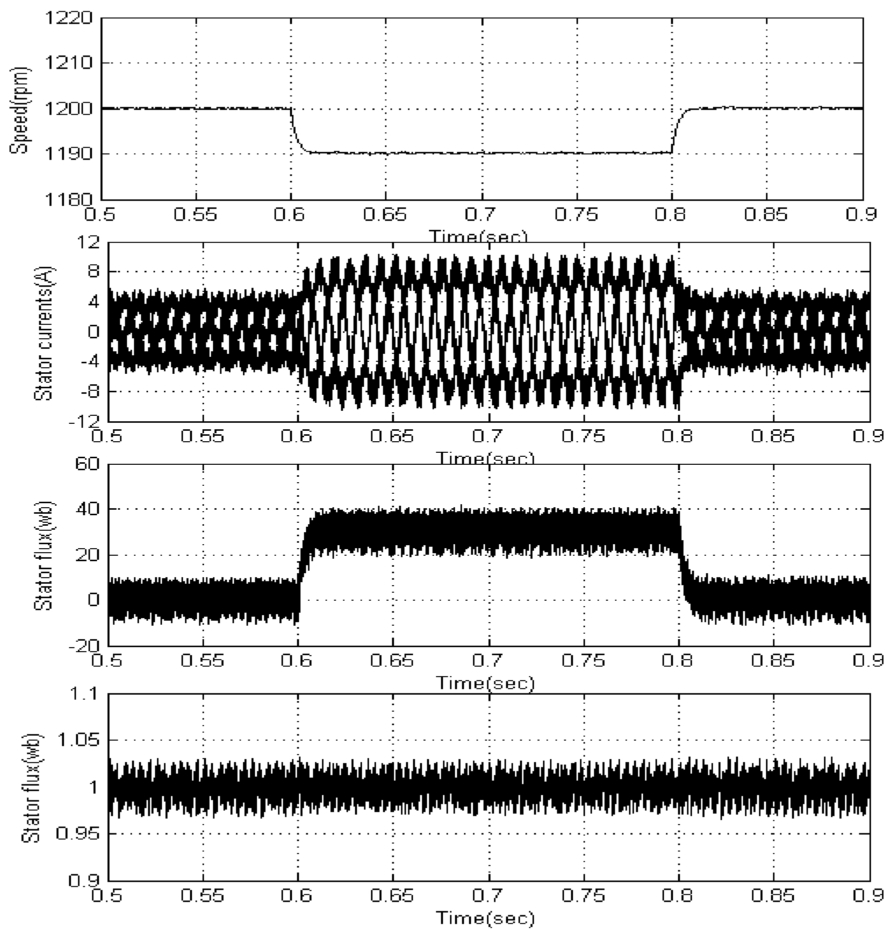

Figure 16 Load change in Proposed DTC algorithm-I

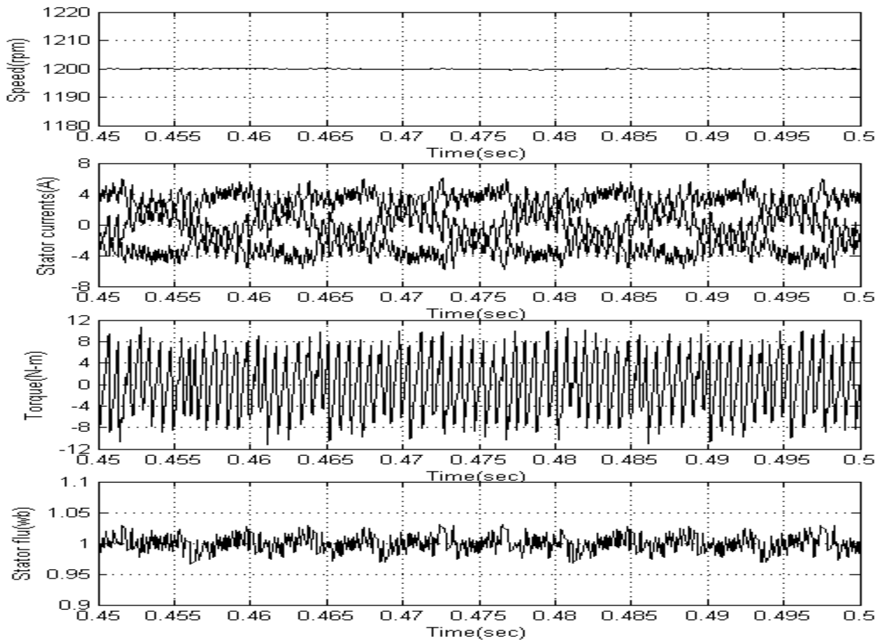

Figure 17 Steady state plots in proposed algorithm-II

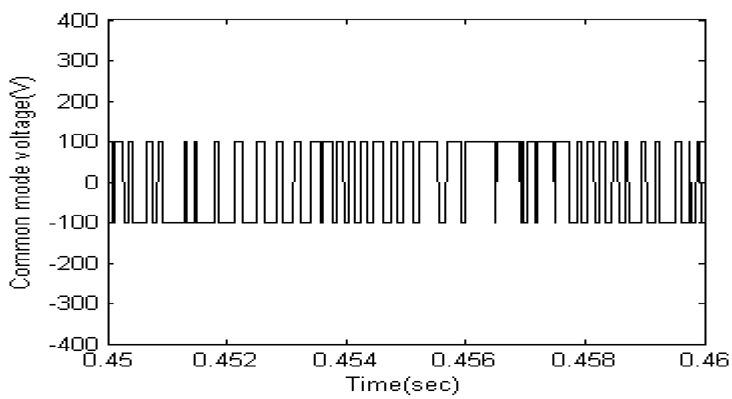

Figure 18 Common mode voltage variations in proposed algorithm-II

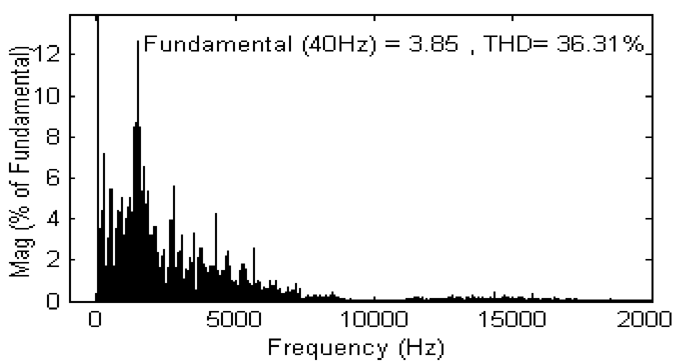

Figure 19 Harmonic spectra of stator current in Proposed DTC algorithm-II

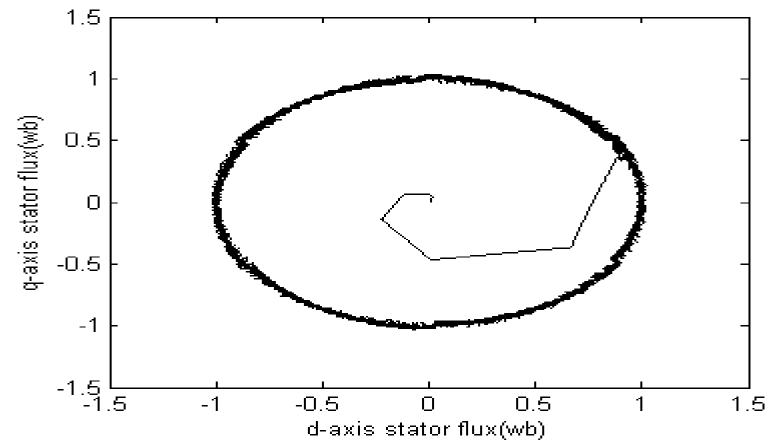

Figure.20 Locus in Proposed DTC algorithm-II

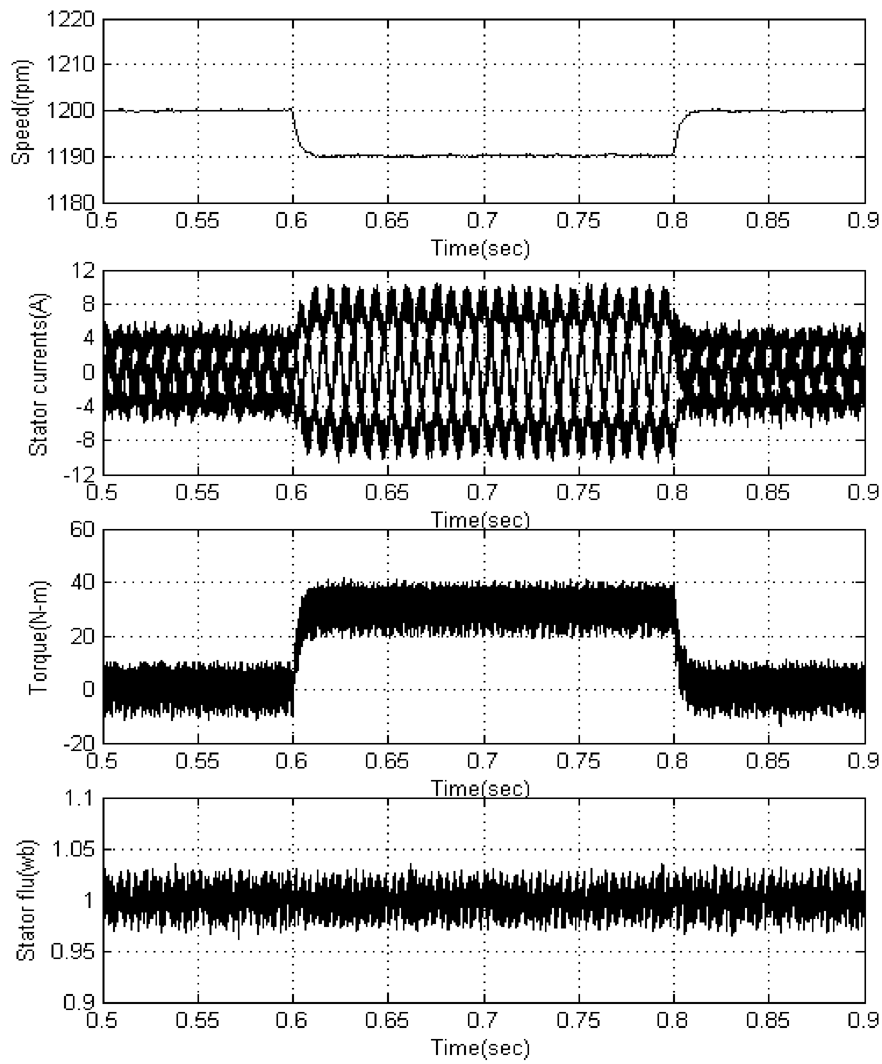

Figure.21 Load change in Proposed DTC algorithm-I

4. Conclusion

In conventional DTC CMV variations are very high because of zero voltage vectors. To reduce the CMV variations, a novel DTC algorithm has proposed in this paper. Proposed DTC algorithm-I is same as that of CDTC except that usage of zero voltage vectors are avoided. Though the Proposed DTC algorithm-I reduces the CMV variations its THD is high compared with CDTC. So, in order to reduce THD as well as CMV variations algorithm-II is proposed for DTC. In the proposed algorithm-II, all the six active voltage vectors are used in each sector. Thus, by eliminating the zero voltage vectors, the CMV variations are reduced and also the total THD of stator current is reduced compared with CDTC and proposed algorithm-I. From the simulation results, it can be observed that the CMV is very less in the proposed algorithm compared to conventional DTC algorithm.

5. References

C. Domenico Casadei, Francesco Profumo, Giovanni Serra, and Angelo Tani,(2002), "FOC and DTC: Two Viable Schemes for Induction Motors Torque Control",*IEEE Trans. Power Electron.*, vol. 17, no.5, pp. 779-787.

F. Blaschke(1972), "The principle of field orientation as applied to the new transvector closed loop control system for rotating-field machines," *Siemens Re view*, pp 217-220.

Werner Leonard (2003), "Control of electrical drives" Springer-Verlag, Third Edition.

Isao Takahashi and Toshihiko Noguchi (1986), "A new quick-response and high- efficiency control strategy of an induction motor," *IEEE Trans.Ind. Applicat.*, vol. IA-22, no.5, pp. 820-827.

M. Depenbrock(1988), "Direct-self control (DSC) of inverter-fed induction machine," *IEEE Trans. Power Electron*., vol. 3, no. 4, pp. 420-429.

James N. Nash (1997), "Direct Torque Control, Induction Motor Vector Control with out an Encoder" *IEEE Trans. Ind. Applicat.*, vol. 33, no. 2, Mar/Apr 1997, pp.333-34a,

Maurizio Cirrincione, Marcello Pucci, Gianpaolo Vitale and Giansalvo Cirrincione(2006), "A new direct torque control strategy for the minimization of com mon-mode emissions" *IEEE Trans. Ind. Appl.*,vol.4, no.2.

Y.V.Siva Reddy, M.Vijayakumar and T. Brahmananda Reddy (2007), "Direct Torque Control of Induction Motor Using Sophisticated Lookup Tables Based on Neural Networks AIML Journal, Volume (7), Issue (1).