The International Journal Of Engineering And Science (IJES)
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805
Pages || 06-14 || 2014 ||

Direct Torque Controlled Four-Quadrant Induction Motor Drive

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--ABSTRACT---

In this paper, Conventional Direct Torque Control (CDTC), torque and flux are controlled independently by selecting the optimum voltage space vector for entire switching period and the errors are monitored within the hysteresis band. For less torque and flux error, frequency of operation of pulse width modulation (PWM) inverter should be very high. The switching frequency always varies according to the width of hysteresis bands. CDTC has high dynamic performance, accurate speed response. The DTC based voltage source inverter fed induction motor drive is capable of offering four quadrants in the torque-speed plane of operation like, forward motoring, forward generating, reverse generating and reverse motoring. To validate the proposed algorithms numerical simulations has been carried out in Matlab/Simulink environment using Runge-Kutta solver. Variation in stator currents, speed, electromagnetic torque developed and stator flux during different operating conditions of the drive like starting, steady state, step change in external load and reference torque reversal are presented.

KEYWORDS: *Direct torque control (DTC), Induction motor (IM), Inverter.*

I. INTRODUCTION

The per-phase equivalent circuit of the induction machine is valid only for steady state analysis only. But in the case of adjustable speed drive, the machine normally constitutes an element with feedback loop, and therefore its transient behaviour has to be taken in to consideration. Besides a high performance drive control, such as FOC, DTC are based on the dynamic d-q model [1] of the machine. The development of high performance control strategies for AC drives driven by industry requirements has followed a rapid evolution during the last two decades. Among the FOC and DTC high performance control strategies for induction motor drives, DTC scheme has been considered as the next generation motor control method. Though the operating principles are different, the objectives of the two control techniques are same. The main aim of both the control schemes is to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any other external disturbances. DTC was first introduced by Takahashi in 1986. The principle is based on limit cycle control and it enables both quick torque response and efficiency operation. DTC controls the torque and speed of the motor, which is directly based on the electromagnetic state of the motor. It has many advantages compare to FOC, such as less machine parameter dependence, simpler implementation and quicker dynamic torque response. It only needs to know the stator resistance and terminal quantities (voltage and current) in order to perform the stator flux and torque estimations. The configuration of DTC is simpler than the FOC system due to the absence of frame transformer, current controlled inverter and position encoder, which introduces delays and requires mechanical transducer. Takahashi had proved the feasibility of DTC compared to FOC.

The DTC scheme is known to produce a quick and robust response in AC drives due to the low motor parameter sensitivity of the stator voltage equation in estimating stator flux. However during steady state, pulsations of torque, flux and current may occur. The DTC based voltage source inverter fed induction motor drive is capable of offering four quadrants in the torque-speed plane of operation like, forward motoring, forward generating, reverse generating and reverse motoring. The simulated results are presented for four quadrants.

II. DIRECT TORQUE CONTROL

High performance instantaneous torque or speed controlled induction motor drives have been used for more than 20 years. With the pioneering works of Hasse [2], Blaschke [3], and Leonhard [4-5], vector-controlled drives have become increasingly popular, and have become the standard in the drives industry. DTC induction motor drives were developed more than 20 years ago by Takahasi [6-7] and Depenbrock [8-9] in late 80’s. Today many experts claimed that DTC is the latest AC motor control method with the features of precise and quick torque response, reduced complexity compared with FOC algorithms.

2.1. Principle of DTC VSI-fed Induction Motor : DTC induction motor drive, fed from a VSI, it is possible to control both the stator flux linkages and electromagnetic torque directly, by selecting an optimum inverter switching modes. The selection limits the flux and torque errors to be within the respective hysteresis bands, so that fast torque response, low switching frequency and low harmonic losses are attained. The electromagnetic torque developed in an induction motor is given by equation

$$T_e = \frac{3}{2}\frac{P}{2}(\overline{\lambda_s} \text{ x } \overline{i_s}) \tag{1}$$

Where $\overline{\lambda_s}$ is the stator flux, $\overline{i_s}$ is the stator current and P is the no. of poles of an induction motor.

The equations for stator and rotor fluxes are given by equations (2) and (3).

$$\overline{\lambda_s} = L_s\overline{i_s} + L_m\overline{i_r} \tag{2}$$

$$\overline{\lambda_r} = L_s\overline{i_r} + L_m\overline{i_s} \tag{3}$$

$$\overline{i_s} = \frac{L_r}{L_sL_r - L_m{}^2}\overline{\lambda_s} - \frac{L_m}{L_sL_r - L_m{}^2}\overline{\lambda_r} \tag{4}$$

Substituting equation (4) in equation (1)

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\xi L_sL_r}(\overline{\lambda_r} \text{ x } \overline{\lambda_s}) \tag{5}$$

DTC is based on the space vector approach. In a symmetrical 3-phase induction machine, the instantaneous electromagnetic torque is proportional to the cross product of the stator flux linkage space vector, $\overline{\lambda_s}$ and rotor flux linkage space vector, $\overline{\lambda_r}$, and so given by (6). γ is the angle between the stator flux linkage space vector and rotor flux linkage space vector, as shown in fig.2 and ξ is the leakage coefficient given by (7).

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\xi L_sL_r}|\lambda_r||\lambda_s|\sin(\gamma) \tag{6}$$

$$\text{Where } \xi = 1 - \left(\frac{L_m^2}{L_sL_r}\right) \tag{7}$$

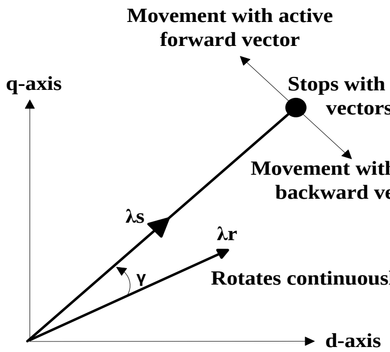


Fig.2 Movement of $\overline{\lambda_s}$ relative to $\overline{\lambda_r}$ under the influence of voltage vectors

The expression given in (6) is applicable for both the steady state and transient state conditions. In steady state both the stator flux and rotor flux moves with the same angular velocity. The rotor flux lags the stator flux by torque angle. But during transients these two vectors do not the same velocity. From (6), it is clear that the motor torque can be varied by varying the rotor or stator flux linkage vectors as shown in fig.2. The magnitude of the stator flux is normally kept constant.

2.2. Conventional Direct Torque Controlled Induction Motor Drive : The block diagram of CDTC motor drive as shown in fig.3 employing a VSI inverter. DTC involves the separate control of the stator flux and torque through the selection of optimum inverter switching modes.

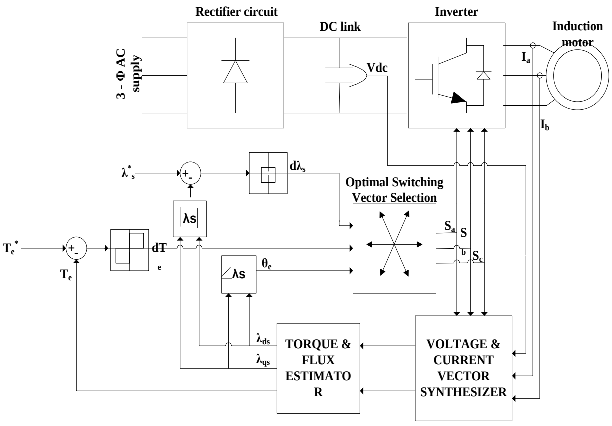


Fig.3 Block diagram of CDTC of induction motor drive

The stator flux-linkage components can be obtained by integrating appropriate monitored terminal voltages reduced by the ohmic losses, as shown in (9), (10), (11) and (12). The sector number can be estimated using (13):

$$\lambda_s = \int (V_s - R_s i_s) dt \tag{9}$$

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds}) dt \tag{10}$$

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs}) dt \tag{11}$$

$$|\lambda_s| = \sqrt{\lambda_{ds}{}^2 + \lambda_{qs}{}^2} \tag{12}$$

$$\theta_e = \mathrm{Tan}^{-1}\left[\frac{\lambda_{qs}}{\lambda_{ds}}\right] rad \tag{13}$$

The electromagnetic torque of the induction motor in stator reference frame is given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{14}$$

The electromagnetic dynamic equation describing the mechanical model of the induction motor is,

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_l \tag{15}$$

2.3. Optimum Switching Vector selection : Based on the theoretical analysis done in section 2, optimum switching vector selection is tabulated which is shown in the table 1.

Table 1 Optimum voltage switching vector look-up table

$d\lambda$	dT_e	S-I	S-II	S-III	S-IV	S-V	S-VI
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	$\overline{V_5}$	$\overline{V_6}$	$\overline{V_1}$	$\overline{V_2}$	$\overline{V_3}$	$\overline{V_4}$

This gives the optimum selection of the switching vectors for all the possible stator flux linkage space vector positions (six positions corresponding to six vectors).In 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. If a stator flux increase is required then $d\lambda = 1$; if a stator flux decrease is required then $d\lambda = 0$; The notation corresponds to the fact that the digital output signals of a two-level flux hysteresis comparator is $d\lambda$, where

$$d\lambda = 1 \quad if\left|\overline{\lambda_s}\right| \leq \left|\overline{\lambda_s^*}\right| - |\Delta\lambda_s|$$

$$d\lambda = 0 \quad if\left|\bar{\lambda}_s\right| \geq \left|\bar{\lambda}_s^*\right| + |\Delta\lambda_s|$$

If a torque increase is required then dT_e=1, if a torque decrease is required then dT_e=-1, and if no longer change in torque is required then dT_e=0. The notation corresponds to the fact that the digital output signal of the three-level hysteresis comparator is $dT_{e.}$ For anticlockwise rotation or forward rotation,

$$dT_e = 1 \quad if\ |T_e| \leq |T_e^*| - |\Delta T_e|$$

$$dT_e = 0 \quad if\ |T_e| \geq |T_e^*|$$

And for clockwise rotation or backward rotation

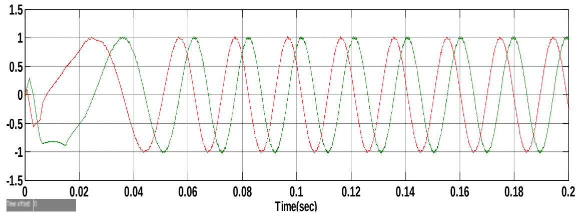
$$dT_e = -1 \quad if\ |T_e| \geq |T_e^*| + |\Delta T_e|$$

$$dT_e = 0 \quad if\ |T_e| \leq |T_e^*|$$

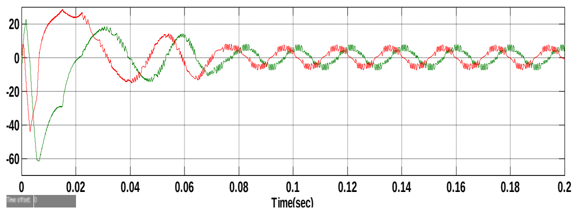
The selection of the width of the hysteresis bands has important effects; a too small value may have the effect of losing the control.

III. SIMULATION RESULTS

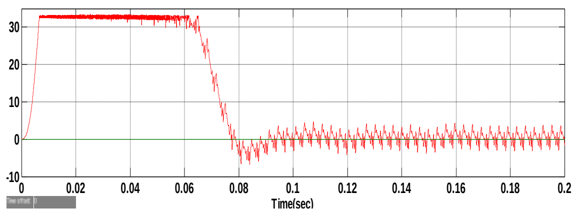
3.1. I-quadrant operation under no-load



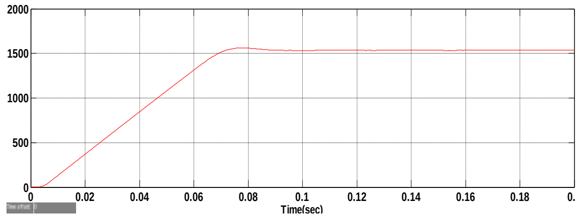
(a) Fluxes_q_d



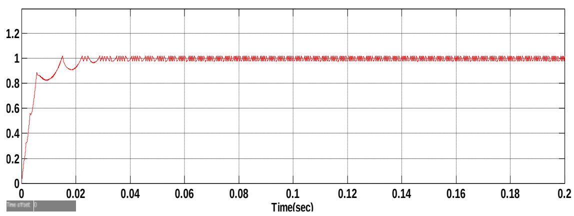
(b) Currents_q_d



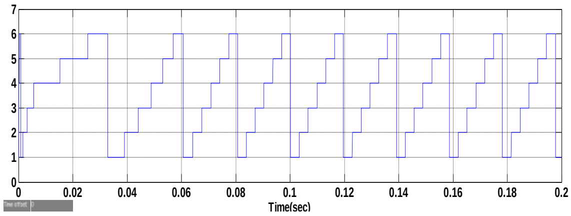
(c) Generated Torque



(d) Speed



(e) Flux

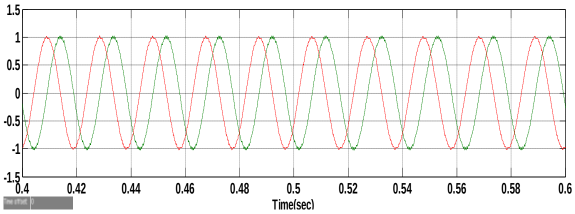


(f) Sectors

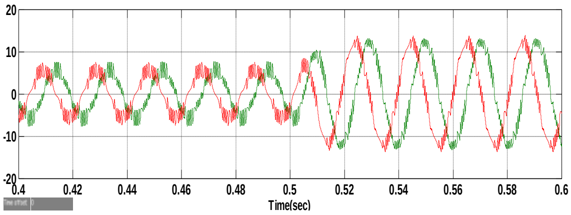
Fig.4 starting transients during no load operation of induction motor drive

The simulation parameters and specifications of induction motor used in this paper are given in Appendix. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 150% of the rated torque, 33 N-m.

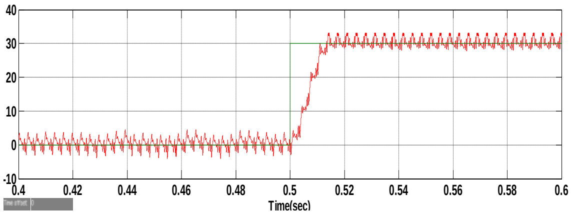
3.2. I-quadrant operation under at load



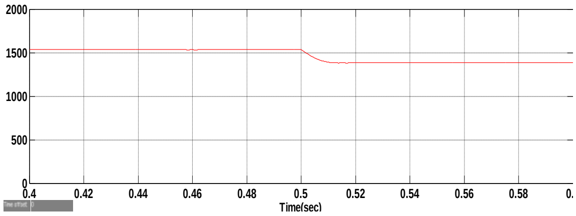
(a) Fluxes_q_d



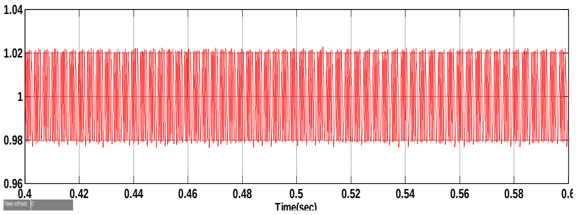
(b) Currents_q_d



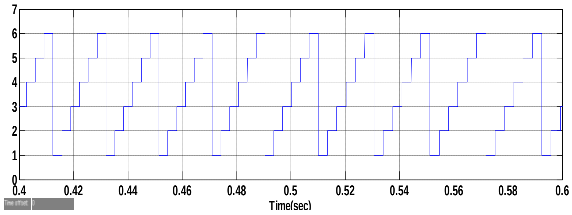
(c) Generated Torque



(d) Speed



(e) Flux

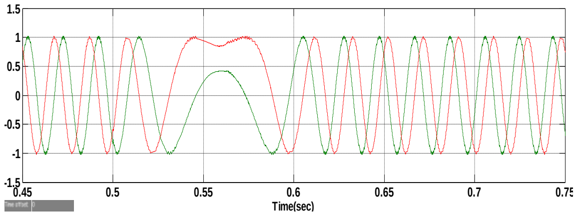


(f) Sectors

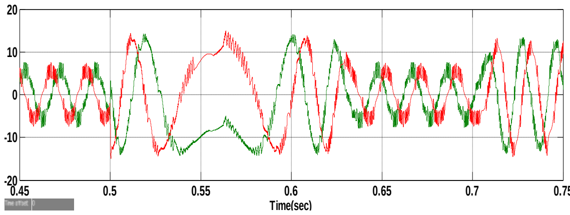
Fig.5 Transients during step change in load 30 N-m is applied at 0.5sec

Up to 0.5 sec the drive is operating under no load condition, at 0.5 sec an external load of 30 N-m is applied. Due to this step change in load, the drive generates torque very quickly to trace the load torque 30 N-m. Speed of the motor is decreased due to the applied load on the motor and rotates constant speed under constant stator flux linkage.

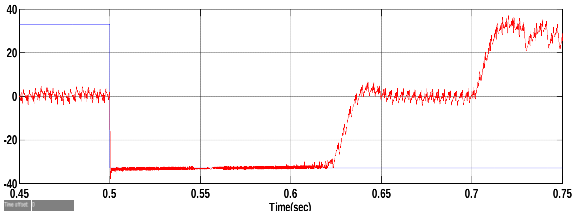
3.3. II-quadrant operation under at load



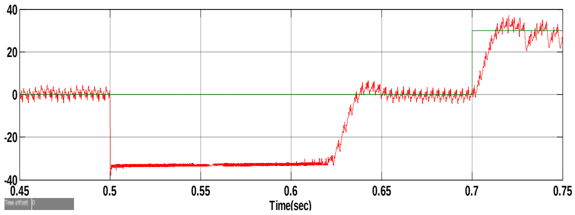
(a) Fluxes_q_d



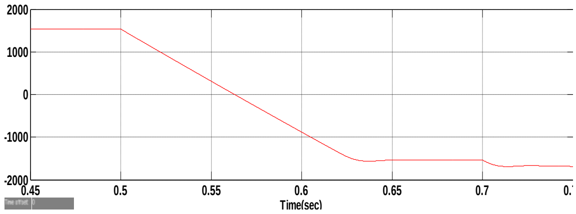
(b) Currents_q_d



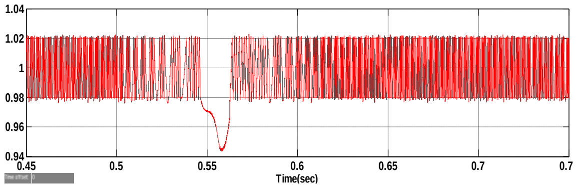
(c) Ref.Torque & Gen.Torque



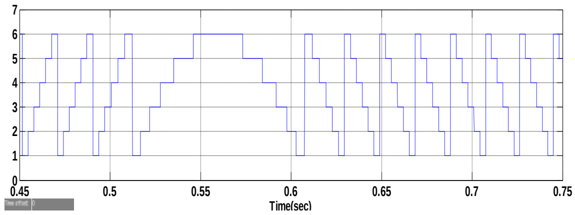
(d) Gen.Torque & Load Torque



(e) Speed



(f) Flux

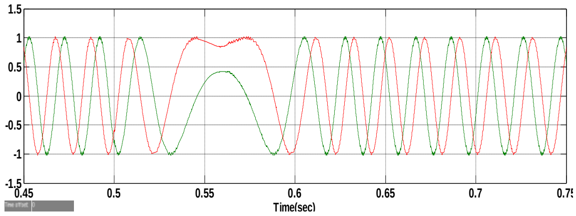


(g) Sectors

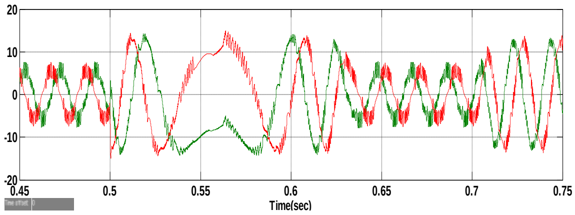
Fig.6 Transients during torque reversal with load 30 N-m at 0.7sec, Ref.Torque is changed from 33 N-m to -33 N-m at 0.5sec

The drive tries to stop motor in forward direction and rotating in reverse direction without changing any two stator terminals. The generated torque is positive and opposite of the rotor rotation. Speed is negative means rotor rotated in reverse direction, the speed of the motor is increased.

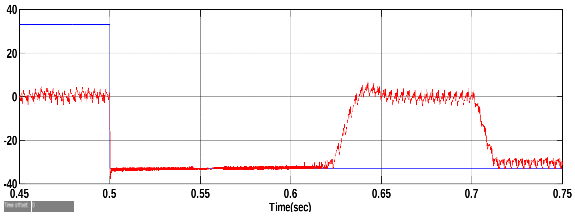
3.4. III-Quadrant operation under at load



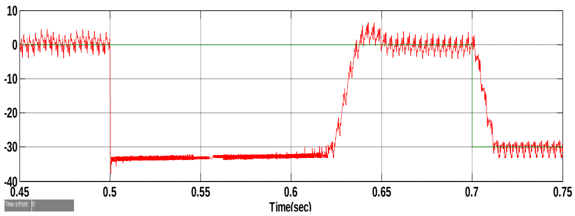
(a) Fluxes_q_d



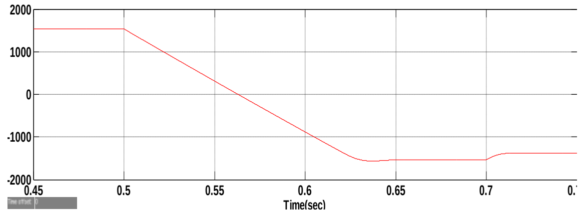
(b) Currents_q_d



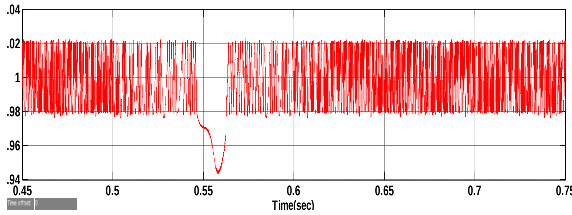
(c) Ref.Torque & Gen.Torque



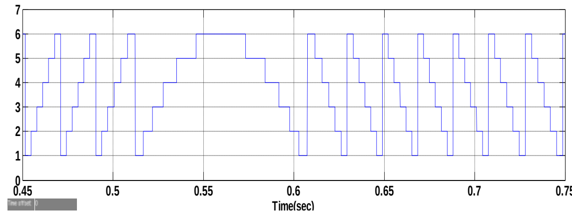
(d) Gen.Torque & Load Torque



(e) Speed



(f) Flux

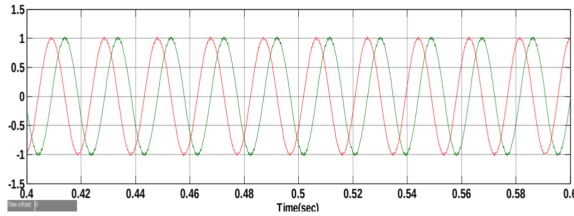


(g) Sectors

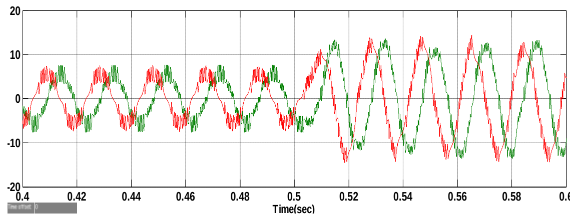
Fig.7 Transients during torque reversal with load -30 N-m at 0.7sec. Ref.Torque is changed from 33 N-m to -33 N-m at 0.5sec

The generated torque is same direction of the rotor rotation at negative load torque is applied. The generated torque and speed of the motor are opposite to the forward motoring operation. When the load is applied in this operation the speed of the motor is decreased.

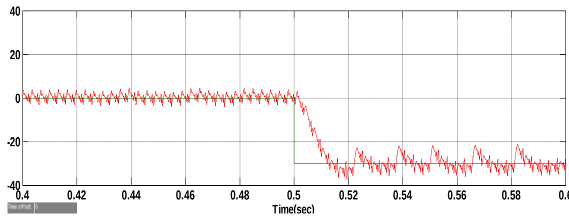
3.5. IV-Quadrant operation under at load



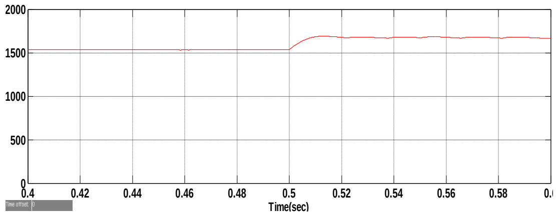
(a) Fluxes_q_d



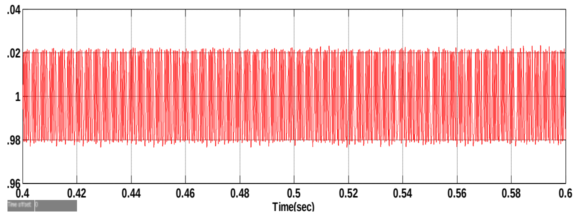
(b) Currents_q_d



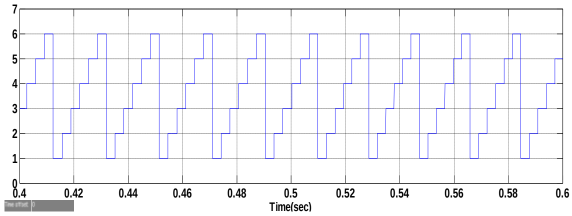
(c) Torque



(d) Speed



(e) Flux



(f) Sectors

Fig.8 Transients during load torque reversal -30 N-m at 0.5sec.

During this operation the motor is rotating in the same direction as rotated in the forward motoring. The generated torque is negative and the speed is positive. When the load is applied in this mode, the load torque adds to the generated torque, the speed of the motor is increased. In this mode the induction motor drive operates as a generator, it takes the reactive power from the supply to magnetise the stator and generate the active power to the supply mains. This mode of operation is known as forward generating.

IV. CONCLUSION

DTC is simple and gives fast dynamic torque, speed response. The results presented have demonstrated that the step change in load, the generated torque meets the load torque very quickly and speed reaches to nominal speed with less amount of time. Also, the reversal of reference torque changes direction of rotation of the drive with load and without load very satisfactorily. Hence, the dc motor drive in all industries will be replaced with induction motor drive.

Appendix : The parameters of the three-phase Induction Motor employed for simulation purpose, in SI units are

R_s =1.405, R_{rp} =1.395, L_{ls} = 5.839e-3, L_{lrp},= 5.839e-3,L_m =172e-3, P=4, J =0.0131, B= 0.002985

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