An Effective Voltage Switching State Algorithm for Direct Torque Controlled Five-Phase Induction Motor Drive to Reduce Torque Ripple

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Abstract—**In this paper, an improved DTC scheme for five phase inverter fed induction motor is presented. The work present here aims to the development of conventional DTC to reduce the torque ripple. For this, a multi-band torque hysteresis controller is implemented as a modification in a conventional DTC mathematical model of 5 phase induction machine based on reference frame theory is also discussed in detail. Modification in hysteresis controller gives the optimum utilization of thirty two voltage vectors in five phase inverter which results in reduction in torque ripple at various speed operations. Simulation results are developed in MATLAB/Simulink software.**

Keywords— Five-phase inverter, five-phase induction motor, direct torque control, speed control, torque ripple.

I. INTRODUCTION

With the advancements in power electronics, the popularity of multiphase induction machine has been on the rise and has become the major driving factors in the development of high performance control strategy [1]. The multiphase drives, originated in the 1960's, are developed in order to overcome the problem in three-phase six-step inverter fed machines which are low frequency torque ripple. Multi-phase drive has many advantages over conventional three-phase induction machine [4]. Those advantages are increased frequency and reduced amplitude of torque pulsation, reduced current per phase, reduced rotor harmonic current, without increase in voltage per phase and lower dc link current harmonics with increased reliability [5].

There are many proposed control strategies available, among which Field-Oriented Control (FOC) and Direct Torque Control (DTC) are the most researched. These two control strategies have different operating principles but their objectives are similar. The objective is to control the torque and flux of the rotary machine regardless of load condition and other external disturbances. Conventional DTC method gives high dynamic performance along with an ease to control the torque and flux separately by choosing proper voltage switching states of inverter compared to Field-Oriented Control method [2], [5].

In this paper, a modified DTC is implemented for five-phase induction machine. It can be shown that by increasing the number of switching states, dynamic performance of machine can be improved since it gives more degrees of freedom to select the most optimal voltage vector. It is also shown that with increase in sublevels in a hysteresis comparator gives a less torque ripples. The mathematical model is given along with a detailed explanation of torque performance, minimization of torque ripples with constant switching frequency. In this paper, the fundamental concept of conventional DTC is examined in order to emphasize the effects created by a specified voltage space vectors on torque variations. The aim of this technique is to reduce the torque ripple in five phase induction motor drive, especially at low speed operating conditions. The torque variations are predicted analytically for the existing and proposed schemes. From the simulation results, torque ripples are effectively reduced by proposed method when compared with conventional DTC technique. The paper is organized as follows. First, the d-q model of five phase induction motor model is discussed. Second, proposed DTC based on five phase induction motor drive is introduced. Third, selection of optimum voltage switching states is tabulated. Finally, simulation results of the existing and proposed schemes are presented.

II. PROPOSED METHOD

A. d-q model of 5- phase Induction Machine:

In a mathematical transformation of a physical five-phase induction machine, the number of variables before and after the transformation remains the same. Therefore it will have five new stator voltage (current, flux) components after the transformation with a spatial displacement of $\alpha = 2\pi/5$ between any two consecutive stator phases. The co-ordinate transformation is used in the power invariant form. The following Transformation matrix is applied to the stator 5 phase winding by assuming sinusoidal distribution of flux around the air gap.

The presence of x-y components makes five-phase induction machine model different from the three-phase model. The equations of x-y components are decoupled from all the other components. These components do not contribute to torque production. A zero sequence component is neglected as rotor winding are short circuited. Since stator to rotor coupling occurs only in d-q equations, the rotational transformations are applied to d-q pairs of equations [6], [8]. Assuming transformation is occurring in arbitrary reference

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frame rotating at angular speed ω_e . The model of five-phase equation is given as follows:

Stator circuit Equations:

$$V_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d\psi_{ds}}{dt} \tag{1}$$

$$V_{qs} = R_s i_{qs} + \omega_e \psi_{ds} + \frac{d\psi_{qs}}{dt} \tag{2}$$

Rotor circuit Equations:

$$V_{dr} = R_r i_{dr} - (\omega_e - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \tag{3}$$

$$V_{qr} = R_r i_{qr} + (\omega_e - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt} \tag{4}$$

Flux Linkage Equations in terms of current:

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\psi_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\psi_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\psi_{qr} = L_r i_{qr} + L_m i_{qs}$$
$$\psi_{xs} = L_s i_{xs}$$
$$\psi_{xr} = L_r i_{xr}$$
$$\psi_{ys} = L_s i_{ys}$$
$$\psi_{ys} = L_s i_{ys}$$
$$\psi_{0s} = L_s i_{0s}$$
$$\psi_{0r} = L_r i_{0r} \tag{5}$$

Where L_m is stator to rotor mutual inductance in phase variable model.

Torque Equation:

$$T_e = \left(\frac{5P}{4}\right)\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{6}$$

Speed Equation:

$$\omega_r = \int_0^t \frac{P}{2J}\left(T_e - T_L\right)dt \tag{7}$$

B. *Modelling of 5- phase Inverter*

A five-phase inverter has a front-side converter structure similar to that of a three-phase voltage source inverter. The fixed voltage and fixed frequency grid supply voltage is converted to DC by using either a controlled (thyristor based or power transistor based) or uncontrolled rectifier (diode based). The output of the rectifier (AC-DC converter) is filtered to remove the ripple in the output voltage signal. The rectified and filtered DC voltage is fed to the inverter (DC-AC) block. The inverter block outputs five-phase variable voltage and variable frequency supply to feed motor drives or other applications as desired.

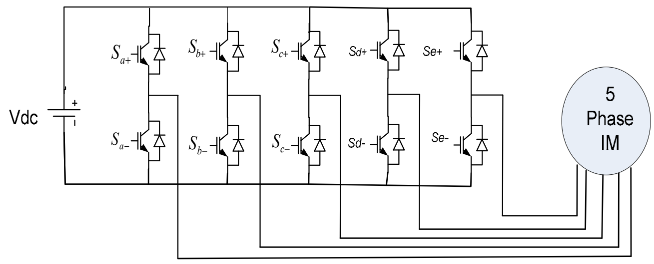

Figure 1: 5- phase inverter–fed induction motor drive.

The basic operating principles of the five-phase VSI (voltage source inverter) are developed as follows, assuming ideal commutation and zero forward voltage drop. The upper and lower power switches of the same leg are complimentary in operation, i.e. if the upper switch is 'ON,' the lower must be 'OFF,' and vice-versa. This is done to avoid shorting the DC supply. The line-to-neutral voltage can be expressed by [1], [3]:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} = \frac{1}{5}\begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \\ V_{dg} \\ V_{eg} \end{bmatrix} \tag{8}$$

C. *Conventional DTC for 5- phase Induction Machine:*

The basic idea of DTC is that the existing errors in torque and flux can be used directly to drive the inverter without any intermediate current control loops or any co-ordinate transformation. Flux and Torque controllers are of hysteresis types and their outputs are used to determine which of the possible inverter states should be applied to machine terminals so that the errors in flux and torque remain within the prescribed hysteresis band. The Stator flux can be obtained from the stator voltage equation as follows [7]:

$$\psi_s = \int_0^t \left(V_s - i_s R_s\right)dt \tag{9}$$

Since Rs is very small, it is clear that Stator flux is directly dependent on voltage and sampling time period. Thus, by selecting thirty two voltage vectors Vs properly, it is possible to control the stator flux. By controlling theradial and tangential components of stator flux space vector, an independent control of stator flux and torque can be achieved.

In a five-phase VSI there are thirty two voltage vectors, out of which two are null vectors. These voltage vectors have three different amplitudes in the ratio of 0.618:1:1.618. The switching plane is divided into 10 sectors. The resultant voltage space vectors can be expressed as [2]:

$$V_s(t) = \left(\frac{2}{5}\right)V_{dc}\begin{pmatrix} S_a + S_b \exp(j2\pi/5) + \\ S_c \exp(j4\pi/5)\ S_d \exp(-j4\pi/5) + \\ S_e \exp(-j2\pi/5) \end{pmatrix} \tag{10}$$

where Vdc is the dc link voltage, Sa, Sb, Sc, Sd and Se are inverter switching states and Vs(t) is the voltage space vector which will occupy any of the thirty two positions as shown [22]. Using these thirty two voltage vectors or switching states, torque and flux can be controlled independently and directly.

D. Proposed DTC scheme

The proposed DTC scheme has a modification in torque hysteresis controller for reducing torque ripples and avoiding infeasible states in control operation with more number of sublevels into a comparator level (+2,+1,0,-1,-2).As a result output of hysteresis controller will give different error levels and optimal voltage vector will get selected under the consideration of speed level. The block diagram Fig. 2 shows the modification in hysteresis controller and in this paper only torque hysteresis controller is improved because of influence of torque ripples in DTC.

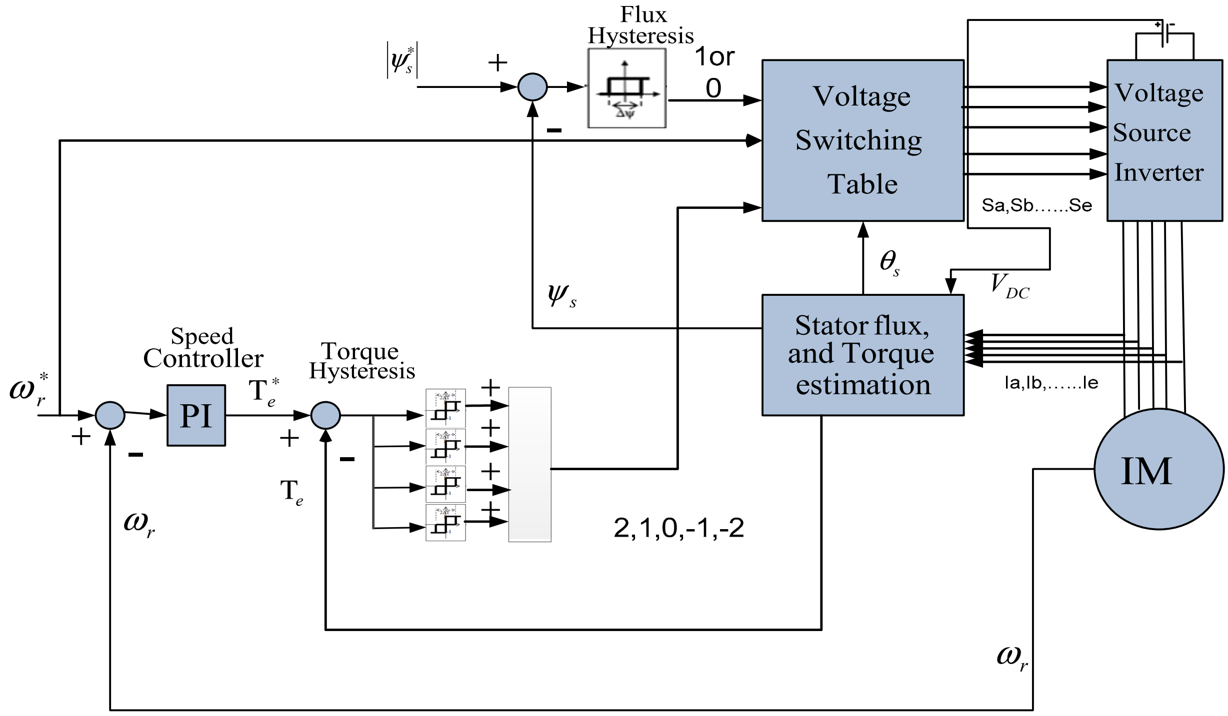

Figure 2: Proposed DTC block diagram

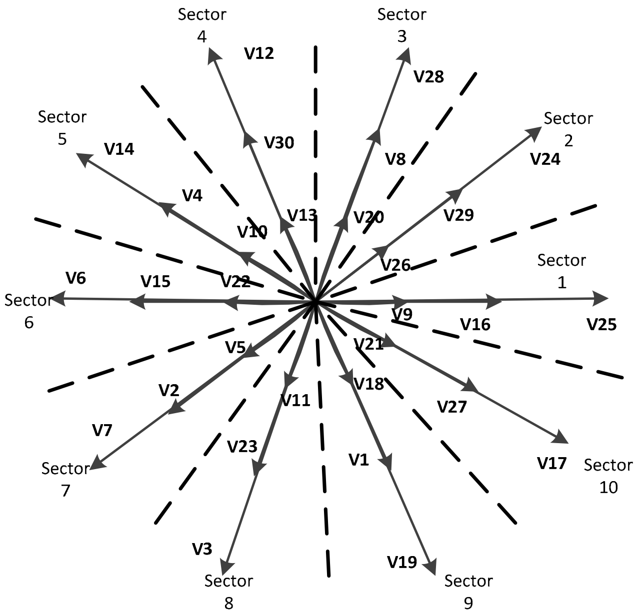

Figure 3: Space Voltage vector for inverter fed five phase drive system

i. Selection of voltage vectors

The thirty two voltage vectors are divided into 3 groups as per their amplitudes as shown in Fig (3). The larger the amplitude of voltage vector, higher will be the influence on the flux and torque Te. Consider that the motor runs in counter clockwise direction. Initially, the space voltage vector V25, in the largest amplitude group, is employed to start the motor and build the stator flux within a short period of time. To increase stator flux and torque, voltage vector V24 is selected. Similarly a decrement in stator flux and torque can be done by selecting V7 voltage vector. When flux needs to be increased and torque needs to be decreased, voltage vector V19 is selected. Similarly, selection of V12 will lead to a decrement in flux and increment in torque. A similar selection of voltage vectors can be done on second and third groups as well.

Table-1: Voltage switching table

For high speed:

Torque error	Flux error	Sectors									
		1	2	3	4	5	6	7	8	9	10
2 or 1	1	V24	V28	V12	V14	V6	V7	V3	V19	V17	V25
	0	V14	V6	V7	V3	V19	V17	V25	V24	V28	V12
0	1	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
	0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31
-2 or -1	1	V17	V25	V24	V28	V12	V14	V6	V7	V3	V19
	0	V3	V19	V17	V25	V24	V28	V12	V14	V6	V3

For medium speed:

Torque error	Flux error	Sectors									
		1	2	3	4	5	6	7	8	9	10
2 or 1	1	V29	V8	V30	V4	V15	V2	V23	V1	V27	V16
	0	V4	V15	V2	V23	V1	V27	V16	V29	V8	V4
0	1	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
	0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31
-2 or -1	1	V27	V16	V29	V8	V30	V4	V15	V2	V23	V1
	0	V23	V1	V27	V16	V29	V8	V30	V4	V15	V2

For low speed:

Torque error	Flux error	Sectors									
		1	2	3	4	5	6	7	8	9	10
2 or 1	1	V26	V20	V13	V10	V22	V5	V11	V18	V21	V9
	0	V10	V22	V5	V11	V18	V21	V9	V26	V20	V13
0	1	V31	V0	V31	V0	V31	V0	V31	V0	V31	V0
	0	V0	V31	V0	V31	V0	V31	V0	V31	V0	V31
-2 or -1	1	V21	V9	V26	V20	V13	V10	V22	V5	V11	V18
	0	V11	V18	V21	V9	V26	V20	V13	V10	V22	V5

III. SIMULATION RESULTS

After analyzing the mathematical model and DTC for five-phase induction machine, simulations are conducted using MATLAB/SIMULINK. Comparison of DTC performances for different applications of voltage vectors of different amplitudes is done. A load torque of 20N-m is applied at 0.5 sec and removed at 1.0 sec and this load torque is applied for every application of amplitude vector. The results for torque, flux, speed are shown in Fig.4, Fig.5 and Fig. 6 for different amplitudes.

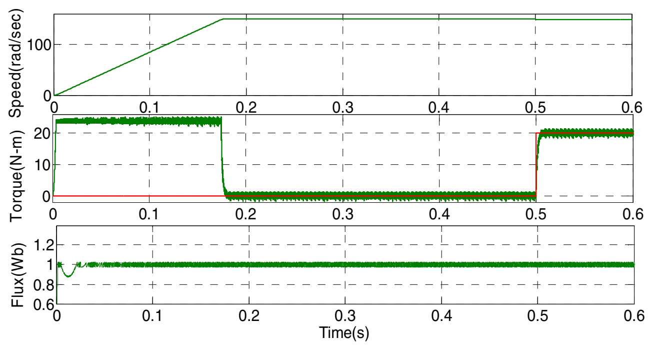

Figure.4: Simulation result of DTC (longest amplitude voltage vector selected) (a) variation of speed from 0 to 150 rad/sec . (b)20 N-m load torque is applied at 0.5 sec and removed at 1.0 sec. (c) stator flux.

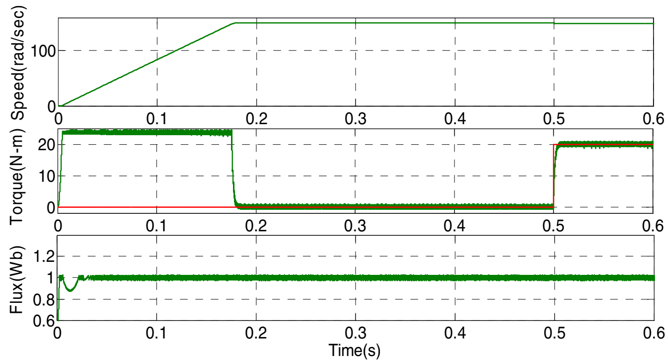

Figure.5: Simulation result of DTC (Medium amplitude voltage vector selected) (a) variation of speed from 0 to 150 rad/sec . (b)20 N-m load torque is applied at 0.5 sec and removed at 1.0 sec. (c) stator flux.

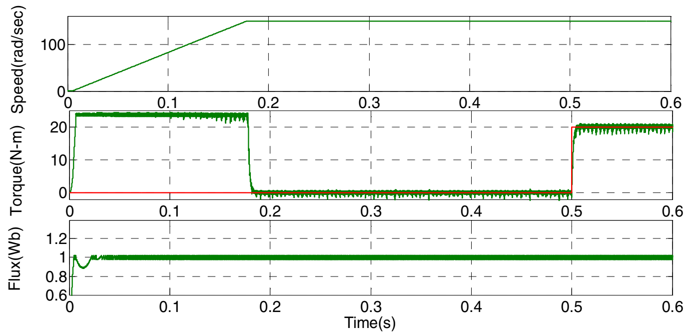

Figure.6: Simulation result of DTC (Smallest amplitude voltage vector selected) (a)variation of speed from 0 to 150 rad/sec . (b)20 N-m load torque is applied at 0.5 sec and removed at 1.0 sec. (c) stator flux.

From the results obtained, it can infer that torque ripples are less in case of the smallest voltage vector. But for high speed operation, DTC performance deteriorates when the smallest voltage vector is applied. So, for higher speed operation, torque regulation is excellent when the largest amplitude voltage vector is used.

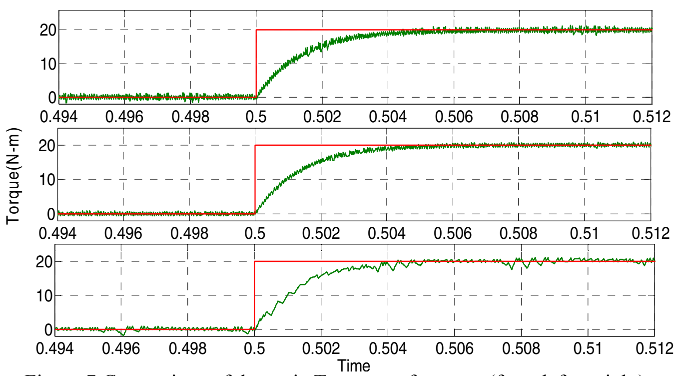

Figure.7:Comparison of dynamic Torque performance(from left to right) (a)longest amplitude (b)medium amplitude (c)smallest amplitude.

It can conclude from the Fig. 7 that fastest dynamic Torque performance can be achieved by implementing longest voltage vector. It can also be inferred that, for middle speed operations voltage vector of medium amplitude gives better torque regulation.

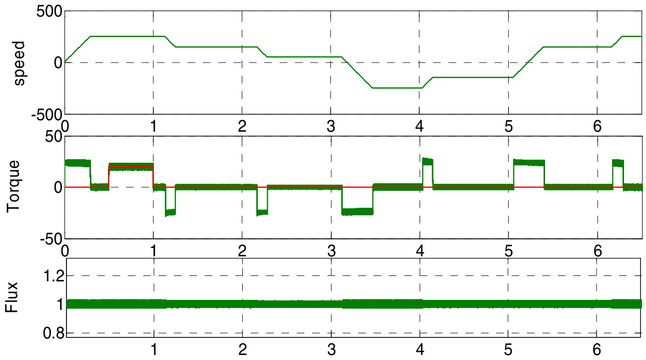

Figure 8:Various speed operation(a)speed varied from 250 rad/sec to -250 rad/sec (b)Torque response when a load torque of 20 N-m is applied at 0.5 sec. and removed at 1.0 sec. (c)Flux(Wb)

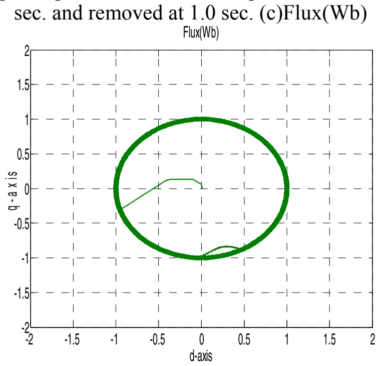

Figure 9: Flux Trajectories of proposed DTC (radius 1.02 wb)

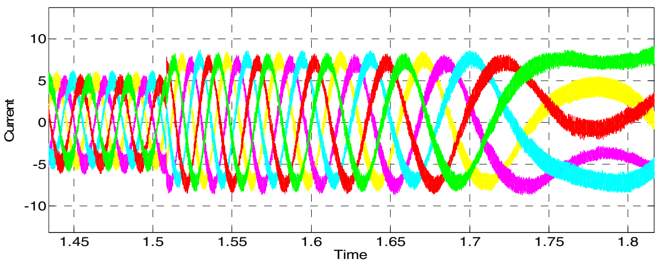

Figure 10:Stator current (Amps)

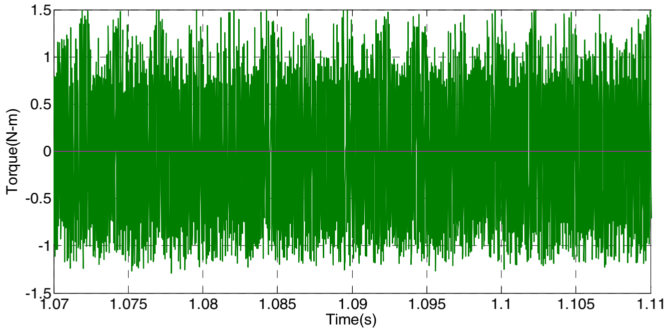

Figure 11: Torque ripples in conventional DTC at speed 250 rad/sec.

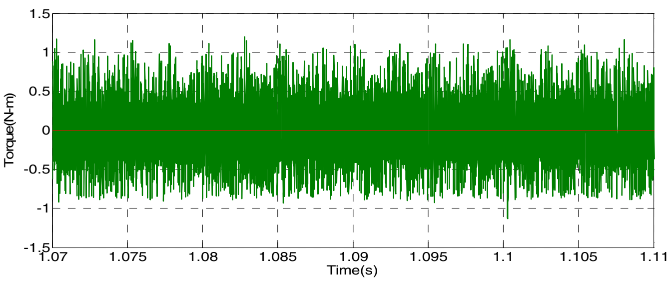

Figure 12:Torque ripples in Proposed DTC at speed 250 rad/sec.

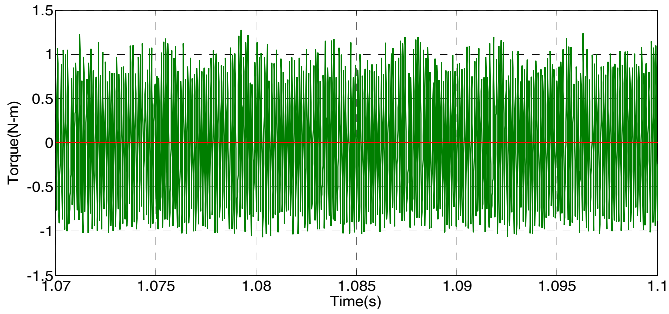

Figure 13: Torque ripples in Conventional DTC at speed 150 rad/sec.

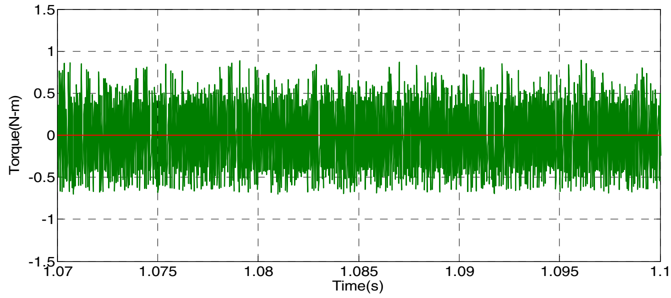

Figure 14: Torque ripples in proposed DTC at speed 150 rad/sec.

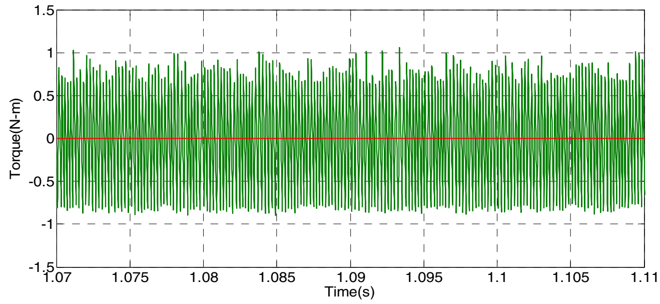

Figure 15:Torque ripples in Conventional DTC at 50 rad/sec.

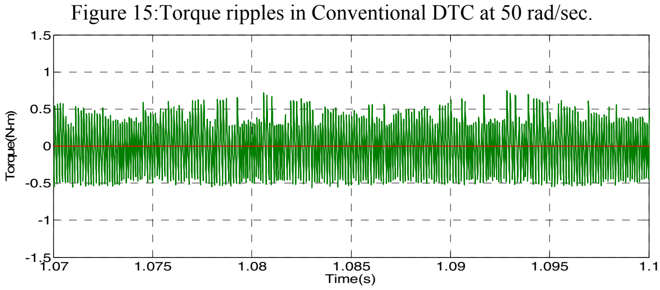

Figure 16: Torque ripples in proposed DTC at 50 rad/sec.

DTC induction motor drives gives better dynamic performance but has undesired torque ripples which occur due to internal computational drawback in control action such as switching frequency ,bands of hysteresis controller and voltage vector selection. One way to reduce torque ripple is by increasing the switching frequency, but it leads to an extremely high switching losses. By introducing sub levels in hysteresis comparator it selects higher level for higher speed operations and lower level for lower speed operations keeping the switching frequency constant. The ripple in torque obtained with the proposed DTC scheme is lower than those obtained with the conventional DTC.

It is observed that (Fig. 11 and Fig.12) that torque ripples are reduced due to modification in torque hysteresis controller at speed 250 rad/sec. Similarly, torque ripple are reduced at middle speed i.e 150 rad/sec (Fig. 13 and Fig.14) and low speed i.e. 50 rad/sec (Fig. 15 and Fig. 16). The summary of simulations results are presented in Fig. 17.

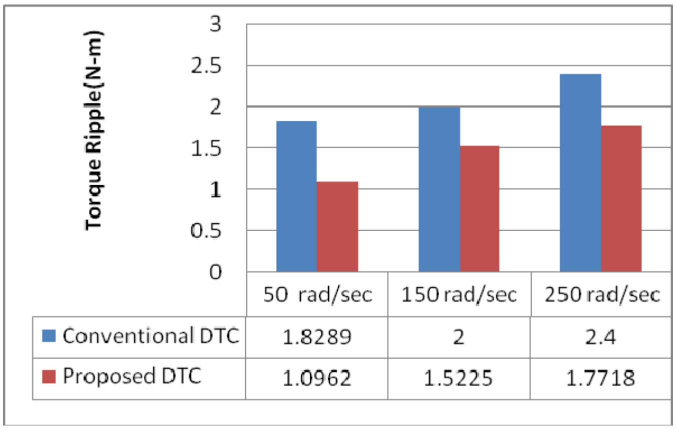

Figure 17: Torque Ripple for Conventional and Proposed DTC.

IV. CONCLUSION

This paper proposed a new DTC technique for inverter fed 5 phase induction drive. The optimal switching strategy is obtained by using three lookup tables of different voltage vectors of different amplitude. It is shown that for a particular range of speed, torque ripple of DTC can be reduced by selecting the optimal voltage vector. Five-phase voltage source inverter and motor modelling is also discussed. The proposed scheme gives the optimal usage of voltage vectors. The purpose of research is to encourage the use of five-phase DTC system as it offers more options like more number of switching vectors to achieve better performance like high power relevance at a particular speed operation.

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