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A Novel Switching Table to Suppress Unreasonable Torque Ripple for the IM DTC Drives

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Abstract

Direct Torque Control of inverter-fed Induction Machine allows high dynamic performance by means of very simple control schemes. In this paper various direct torque control methodologies as conventional DTC (C_DTC), modified DTC (M_DTC) and New sector (N_DTC) have been analyzed and compared in order to evaluate the influence of the motor operating condition on steady state performances. A particular emphasis on stator flux trajectory, torque ripple and stator current distortion has been made. Simulation results show the effectiveness of the proposed methods.

Index Terms: Induction motor, Direct torque control, three phase inverter, look-up table.

Introduction
Modern techniques for control of electrical machines are in need of separate control of magnetic flux and torque; this was achieved using dc machines in the early days. When Field Oriented Control [1] was introduced a huge turn took place in the field of electrical drives as with this control the robust induction machine can be controlled with a high performance. Later in the eighties a new control method for induction machines was introduced. A simple implementation and fast dynamic response was characterized with the Direct Torque Control (DTC) method, in which the inverter is directly controlled by the algorithm, if the control is implemented on a digital system, the actual values of flux and torque could cross their boundaries too far [2] [3], which

is based on independent hysteresis control of flux and torque. The main advantages of DTC are absence of co-ordinates transformation and current regulator absence of separate voltage modulation block. The common disadvantage of conventional DTC are sluggish response in both starts up and changes in either flux or torque, large and small errors in flux and torque are not distinguished. In other words, the same vectors are used during start up and step changes and during steady state. In order to overcome the mentioned drawbacks, there are different solutions, which can be classified as follows modification of the switching table, so modified DTC (M_DTC) and New sector DTC (N_DTC). In this paper a comparison of various direct torque control methodologies (Conventional DTC, M-DTC, and N_DTC) have been presented with evaluation of the influence on the transient performances of induction motor.

Block Diagram of Direct Torque Control Scheme

Figure 1 shown represents the block diagram of DTC scheme, in which the stator flux and torque are calculated for stator variables by using closed loop calculator [1]and they can be controlled independently by properly selecting the inverter switching configuration.

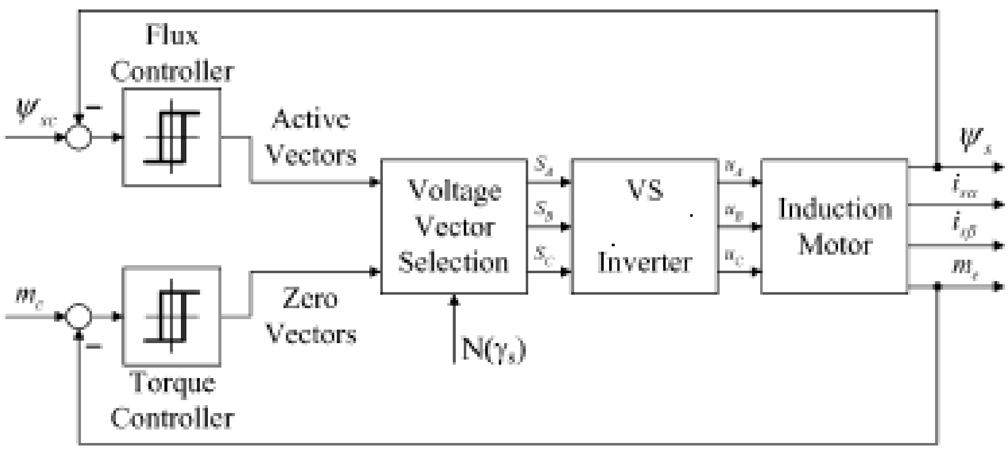

Figure 1: Basic Direct Torque Control scheme for AC motor drives.

Vector Model of Inverter Output Voltage

Figure 2 shown represent a three phase voltage inverter as there are three legs there will be eight different possible states, switching command of each leg is complimentary at any instant, only one switch in each leg will be on. Thus for each leg a logic state Ci (i =a,b,c) can be defined. Ci is 1 if the upper switch is commanded to be closed and 0 if the lower one in commanded to be close.

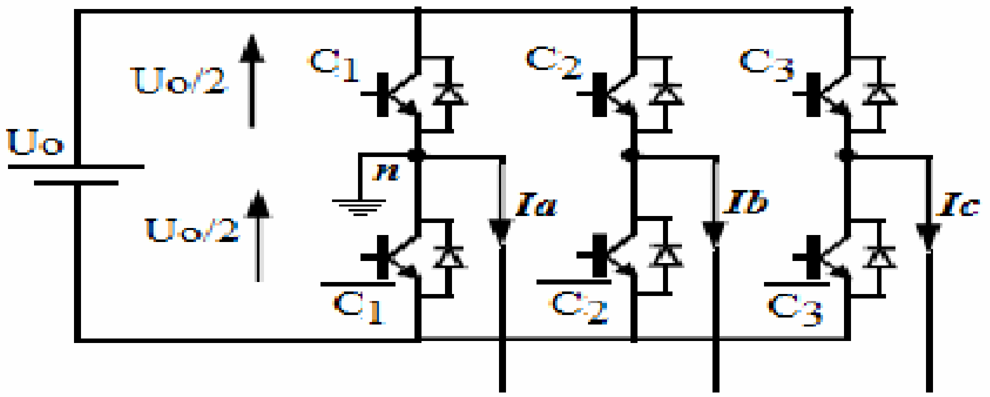

Figure 2: Three phase voltage inverter.

There are six non zero voltage vectors and two zero voltage vectors as shown by figure 3 [1] [3] Applying the vector transformation described as:

$$V_s = \sqrt{\frac{2}{3}} U_0 \left[C_1 + C_2 e^{j\frac{2\pi}{3}} + C_3 e^{j\frac{4\pi}{3}} \right] \tag{1}$$

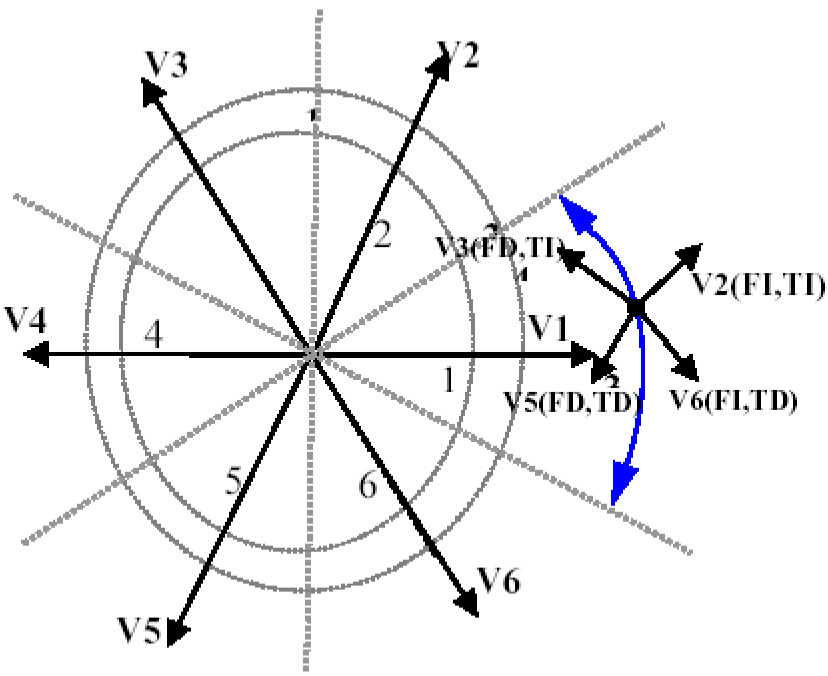

Figure 3: Partition of the d, q plane into six sectors.

Stator flux control

The direct axis and quadrature axis stator voltage components are perpendicular and are determined from measured values (Uo and Isabc). Boolean switching controls (C1,C2 ,C3,) by, [1][2]:

$$\begin{cases} V_{Sd} = \sqrt{\frac{2}{3}} U_0 \left(C_1 - \frac{1}{2}(C_2 + C_3) \right) \\ V_{Sq} = \frac{1}{\sqrt{2}} U_0 (C_2 - C_3) \end{cases} \quad (2)$$

And stator current components (Isd, Isq) :

$$\begin{cases} I_{Sd} = \sqrt{\frac{2}{3}} Isa \\ I_{Sq} = \frac{1}{\sqrt{2}} (Isb - Isc) \end{cases} \quad (3)$$

The stator flux is estimated by integrating the difference between the input voltage and the voltage drop across the stator resistance as given by equations (4):

$$\overline{\varphi}_S = \int_0^t (\overline{V}s - R_S \overline{I}s)dt \quad (4)$$

During the switching interval, each voltage vector is constant and (4) is then rewritten as in (5):

$$\varphi_S(t) \approx \varphi_{S0} + V_s T_e \quad (5)$$

In equation; ös0 stands for the initial stator flux condition. In fact, we have $sd\varphi_s/dt \approx Vs$. The following Figure.4 is established for the case Vs=V3.

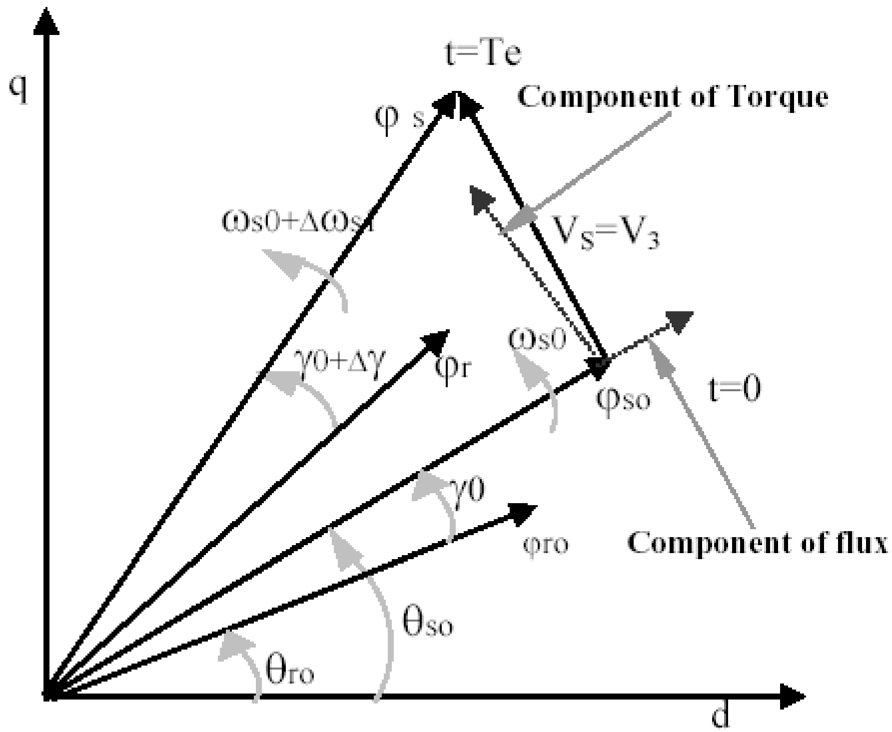

Figure 4: An example for flux deviation.

From the diagram it is clear tha the stator flux vector will move in the direction of the applied voltage vector when the stator resistance is neglected (5). The voltage vector plane is divided into six regionsas shown in figure 3 in order to select the voltage vectors for controlling the amplitude of the stator flux linkage. the magnitudes of stator flux and electromagnetic torque will be kept within the hysteresis band by properly selecting the voltage vectors [3] [7].

Stator flux and torque estimation

The magnitude of stator flux, which can be estimated by (6).

$$\begin{cases} \overline{\varphi}_{Sd} = \int_0^t (\overline{V}_{Sd} - R_S \overline{I}_{Sd})\,dt \\ \overline{\varphi}_{Sq} = \int_0^t (\overline{V}_{Sq} - R_S \overline{I}_{Sq})\,dt \end{cases} \tag{6}$$

The stator flux linkage phasor is given by

$$\varphi_S = \sqrt{\varphi_{Sd}^2 + \varphi_{Sq}^2} \tag{7}$$

By comparing the sign of the components stator flux (φsd. φsq.) and the amplitude of stator flux, we can localize the zone where we find the flux. Electromagnetic torque calculation uses flux components (6), current components (3) and *P*, pair pole number of the induction machine [2][8]:

$$\Gamma_{em} = p\left(\varphi_{sd} I_{sq} - \varphi_{sq} I_{sd}\right) \tag{8}$$

As shown in Fig.3, eight switching combinations can be selected in a voltage source inverter, two of which determine zero voltage vectors and the others generate six equally spaced voltage vectors having the same amplitude. According to the principle of operation of DTC, the selection of a voltage vector is made to maintain the torque and stator flux within the limits of two hysteresis bands. The switching selection table for stator flux vector lying in the first sector of the d-q plane is given in Tab.1[1][2].

Table 1: Switching table for Conventional DTC.

Sector		1	2	3	4	5	6
Flux orque							
Δф = 1	ΔT = 1	V2	V3	V4	V5	V6	V1
	ΔT = 0	V7	V0	V7	V0	V7	V0
	ΔT = -1	V6	V1	V2	V3	V4	V5
Δф = 0	ΔT = 1	V3	V4	V5	V6	V1	V2
	ΔT = 0	V0	V7	V0	V7	V0	V7
	ΔT = -1	V5	V6	V1	V2	V3	V4

Improvement of the Switching Table

While being inspired by the zone shift strategy, the idea is to improve the DTC by a change of the operation table and to modify the six zones of the Conventional DTC (Tab.1) [1], as instead of taking the first sector of.-30° to 30°, it is taken of 0° to 60° one gets the new operation table of the modified DTC (Tab.2), [3][5]. The positions of the zones for the two strategies are shown by the Fig.5 [7][8].

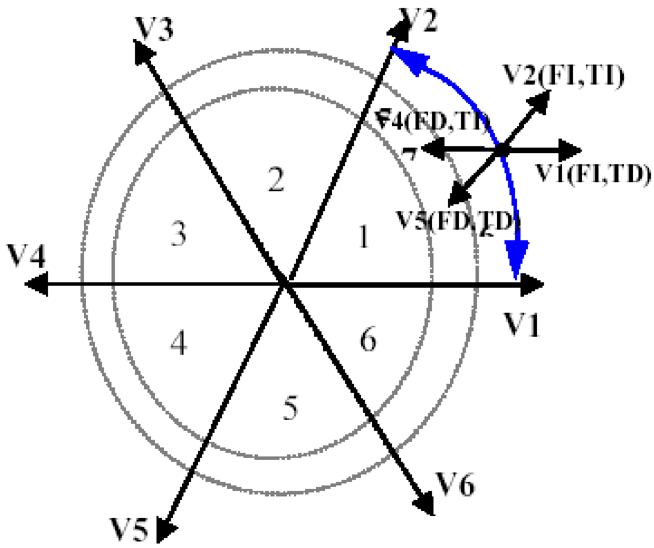

Figure 5: Modified DTC and its new six sectors.

In accordance with the Figs (3)-(5) the general Tab.1 can be written

Table 2: Behaviour of each state just in the first zone for the Conventional DTC (C_DTC)andthe modified DTC (M_DTC). TI/ID: Torque increase/decease.FI/FD: Flux increase/Decrease.

	CLASSICAL DTC -30°→30°	MODIFIED DTC 0°→60°
V_1	30°→-30° Torque ambiguity	0°→-60° TD, FI
V_2	90°→30° TI, FI	60°→0° TI, FI
V_3	150°→90° TI, FI	120°→60° Flux ambiguity
V_4	-150°→150° Torque ambiguity	180°→120° TI, FD
V_5	-90°→-150° TD, FD	-120°→-180° TD, FD
V_6	-30°→-90° TD, FI	-60°→-120° Flux ambiguity

It can be seen that the states V1 and V4, are not used in the Conventional DTC (C_DTC). The reason of this; is that they can increase or decrease the torque at the same sector depending on if the position is in its first 30 degrees or in its second ones.

In the modified DTC (M_DTC), the vectors V3 and V6 are not used. However, now the reason is the ambiguity in flux instead of torque, as it was in the C_DTC. This considered being an advantage in favor of the M_DTC as the main point it to control the torque. Therefore, it is better to loose the usage of two for flux ambiguity that for torque one [5][6].

Table (1)-(3) show the Conventional DTC and the modified DTC look up table for all its six sectors.

Table 3: The switching table for Modified DTC.

Sector		1	2	3	4	5	6
Flux torque							
$\Delta\phi = 1$	$\Delta T = 1$	V2	V3	V4	V5	V6	V1
	$\Delta T = 0$	V7	V0	V7	V0	V7	V0
	$\Delta T = -1$	V1	V2	V3	V4	V5	V6
$\Delta\phi = 0$	$\Delta T = 1$	V4	V5	V6	V1	V2	V3
	$\Delta T = 0$	V7	V0	V7	V0	V7	V0
	$\Delta T = -1$	V5	V6	V1	V2	V3	V4

New Sector Table (N_DTC)

In Conventional DTC there are two states per sector that present a torque ambiguity. Therefore, they are never used. In a similar way, in the modified DTC there are two states per sector that introduce flux ambiguity, so they are never used either. It seems a good idea that if the stator flux locus is divided into six sectors with new angle. Consequently, it is arisen the idea of New sector DTC (N_DTC). This novel stator flux locus is introduced in Fig.6 [6].

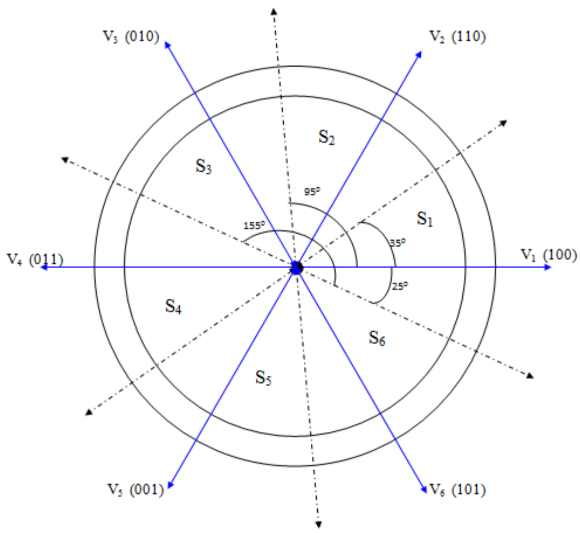

Figure 6: New sector DTC (N_DTC) and its sectors. (figure with 35to -25).

Table 4: The switching table for New Sector N_DTC.

Sector / Flux torque		1	2	3	4	5	6
$\Delta\phi = 1$	$\Delta T = 1$	V3	V2	V4	V5	V6	V1
	$\Delta T = 0$	V0	V7	V0	V7	V0	V7
	$\Delta T = -1$	V6	V1	V2	V3	V4	V5
$\Delta\phi = 0$	$\Delta T = 1$	V3	V4	V5	V6	V1	V2
	$\Delta T = 0$	V7	V0	V7	V0	V7	V0
	$\Delta T = -1$	V6	V5	V1	V2	V3	V4

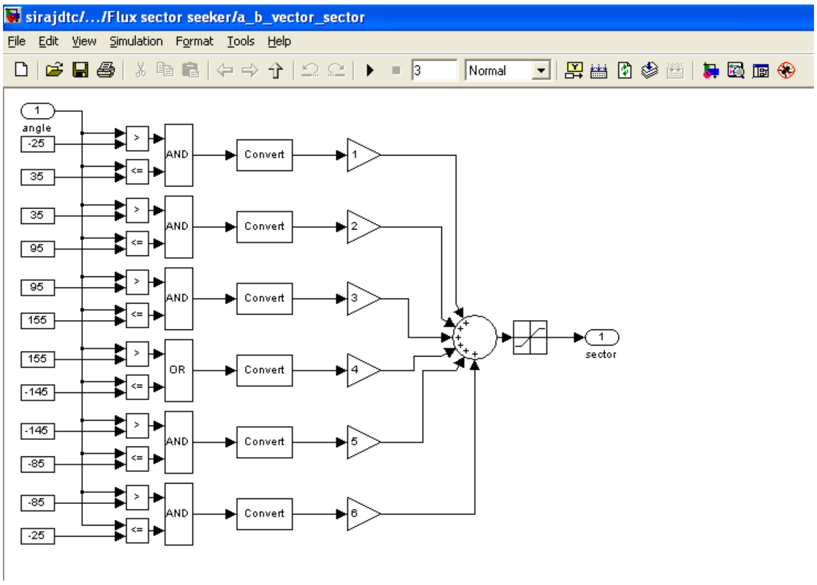

Figure 7: Simulink model of New Sector DTC(N_DTC).

Simulation Results

The results of simulation of conventional DTC (C_DTC), Modified DTC (M_DTC) and New sector DTC (N_DTC) of induction motor is shown in figures 8,9 10 and 11. The simulation was done using MATLAB Simulink . The Induction motor used in this case study is a 119 KW,460V , 3600 rpm, 2-pole, 50 Hz, 3- phase induction motor having the following parameters

$Rs = 14.85 \times 10^{-3}$ ohm , $Rr = 9.295 \times 10^{-3}$ ohm

$Ls = Lr = 0.3027 \times 10^{-3}$ H , $Lm = 10.46 \times 10^{-3}$ H

From 0 to 0.02s the torque increases slowly, that is the acceleration torque produced by the induction motor, at time t = 0.02s the torque and its ripple increases. At time t = 0.04s the torque oscillation increases and then settles to a minimum value, after 0.05s there will be slight variation in the torque ripple which is much less when compared with C_DTC and M_DTC.. The flux and torque oscillation amplitudes are slightly higher than 0.02 Wb and 10 Nm respectively. This is due to the combined effects of the 15 μs DTC controller sampling time, the hysteresis control, and the switching frequency limitation. The simulation results show that the torque responses are very good dynamic response for three DTC methods, but the response of the torque conventional DTC and modified DTC presented the ripple. In New sector DTC shown in figure 11, the ripple of torque is reduced remarkably compared with conventional and modified DTC.

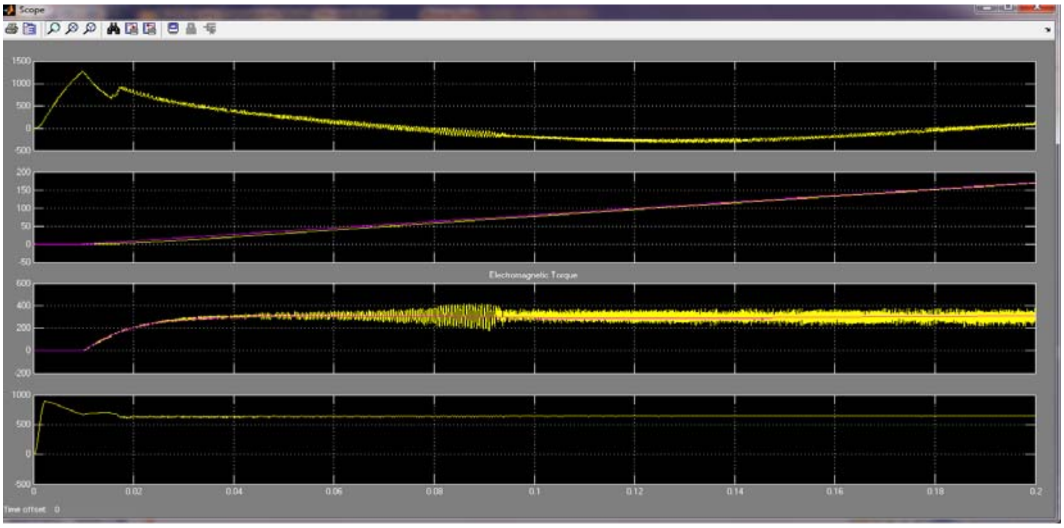

Figure 8: Simulation of New Sector DTC.

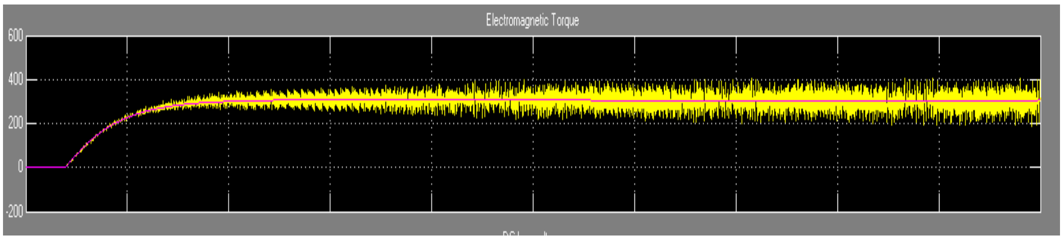

Figure 9: Electromagnetic Torque of Conventional DTC (C_DTC).

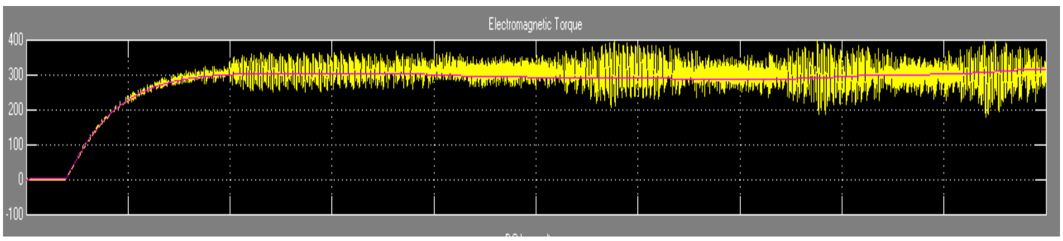

Figure 10: Electromagnetic Torque of Modified DTC(M_DTC).

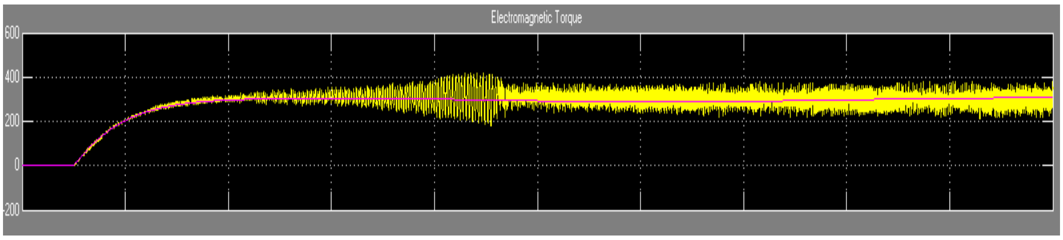

Figure 11: Electromagnetic Torque New Sector DTC (N_DTC).

Note: X-axis represents "Time" in seconds
Y-axis represents "Electromagnetic Torque" in Nm
Maximum Electromagnetic Torque Ripple

Time "t" in secs	C_DTC	M_DTC	N_DTC
0<t<0.05	5 %	7.5 %	4.2%
0.05 < t < 0.1	11.6 %	16.6 %	8.5%
0.1 < t < 0.15	11.6 %	10.8 %	10 %
0.15 < t < 0.2	12.5 %	22 %	10 .5 %

Figure 12: Comparison of different DTC torque ripples.

Conclusion

The proposed work presents various DTC methodologies (Conventional DTC (C_DTC), modified DTC (M_DTC) and New sector DTC (N_DTC)) and also evaluate their influence on the motor operating condition (transient state performance).An increased emphasis on stator flux torque ripple has been done. The simulation results suggest that modification of conventional DTC of induction motor can achieve precise control of the stator flux and torque. Compared to conventional DTC, the presented method can be easily implemented and the steady performances of ripples of both torque and flux are shown to considerably improve.

To summarize, the main improvements shown in this research are

1. Reduction of torque both in transient and steady state response.
2. No flux droopings caused by sector circular trajectory changes.
3. Faster stator flux response in transient state.

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