DIRECT TORQUE CONTROL STRATEGY OF INDUCTION MOTORS

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SUMMARY

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 twelve sectors (12_DTC) have been analysed 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.

Keywords: *induction motor, direct torque control, three phase inverter, look-up table.*

1. INDRODUCTION

Advanced control of electrical machines requires an independent control of magnetic flux and torque. For that reason it was not surprising, that the DC-machine played an important role in the early days of high performance electrical drive systems, since the magnetic flux and torque are easily controlled by the stator and rotor current, respectively. The introduction of Field Oriented Control [1] meant a huge turn in the field of electrical drives, since with this type of 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: The Direct Torque Control (DTC) method is characterised by its simple implementation and a fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e. a modulation technique for the inverter is not needed. However if the control is implemented on a digital system (which can be considered as a standard nowadays); the actual values of flux and torque could cross their boundaries too far [2] [3], which is based on an independent hysteresis control of flux and torque. The main advantages of DTC are absence of coordinate transformation and current regulator absence of separate voltage modulation block. Common disadvantages of conventional DTC are a sluggish response (slow 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 twelve sectors DTC (12_DTC). In this paper a comparison of various direct torque control methodologies (Conventional TC, M-DTC, and 12_DTC) have been presented with evaluation of the influence on the transient performances of induction motor.

2. DIRECT TORQUE CONTROL WITH THREE-LEVEL INVERTER

The basic functional blocks used to implement the DTC scheme are represented in Figure.1. The instantaneous values of the stator flux and torque are calculated from stator variable by using a closed loop estimator [1]. Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration.

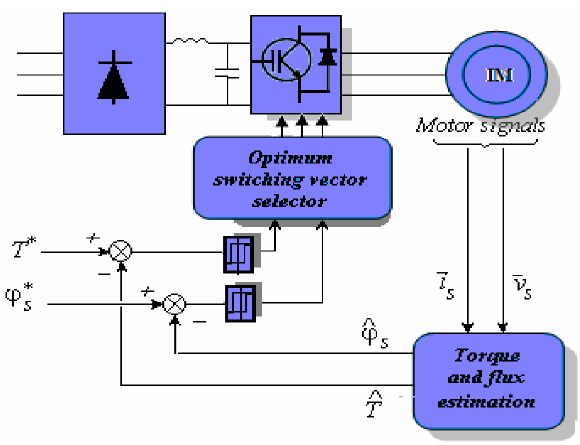

Fig. 1 Basic direct torque control scheme for AC motor drives

3. VECTOR MODEL OF INVERTER OUTPUT VOLTAGE

In a voltage fed three phases, the switching commands of each inverter leg are complementary. So for each leg a logic state C_i (i=a,b,c) can be defined. C_i is 1 if the upper switch is commanded to be closed and 0 if the lower one in commanded to be close (first).

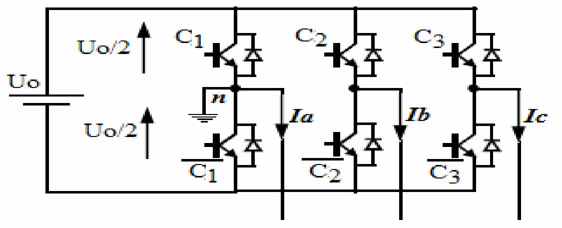

Fig. 2 Three phase voltage inverter

Since three are 3 independent legs there will be eight different states, so 8 different voltages. Applying the vector transformation described as:

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

As it can be seen in second, there are six non-zero voltage vectors and two zero voltage vectors which correspond to (C_1, C_2, C_3)= (111)/ (000) as shown by Figure.3 [1][3].

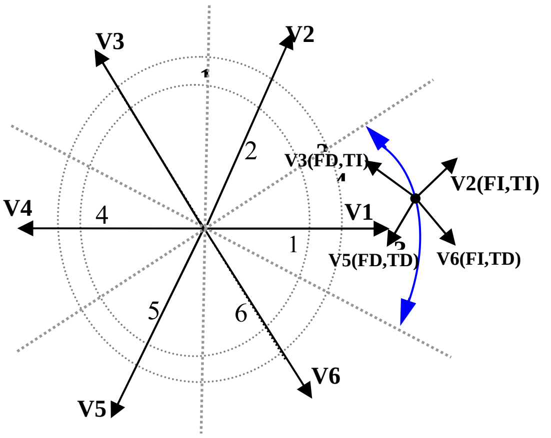

Fig. 3 Partition of the d, q plane into six sectors

3.1. Stator flux control

Stator voltage components (V_{sd},V_{sq}) on perpendicular (d,q) axis are determined from measured values (U_o and I_{sabc}). Boolean switching controls (C_1,C_2 ,C_3,) 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 (I_{sd},I_{sq}) :

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

The stator resistance can be assumed constant during a large number of converter switching periods Te. The voltage vector applied to the induction motor remains also constant during one period T_e. 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; φ_{s0} stands for the initial stator flux condition.

In fact, we have $\frac{d\varphi_S}{dt} \approx V_s$. The following Fig.4 is established for the case V_s=V_3.

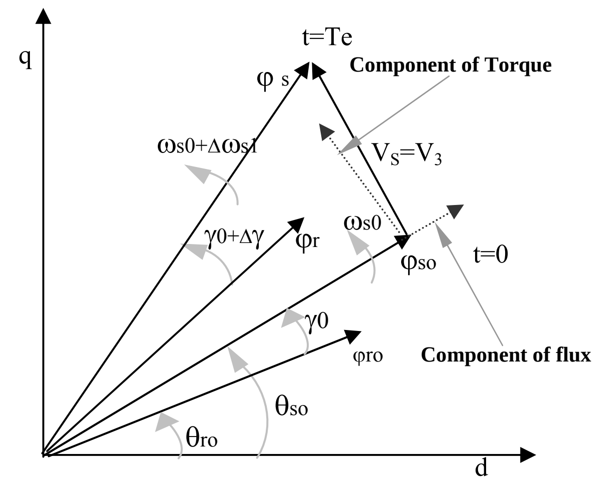

Fig. 4 An example for flux deviation

Neglecting the stator resistance, (5) implies that the end of the stator flux vector will move in the direction of the applied voltage vector, as shown in Figure.4. φ_{so} is the initial stator flux linkage at the instant of switching. To select the voltage vectors for controlling the amplitude of the stator flux linkage, the voltage vector plane is divided into six regions, as shown in Figure.3. In each region, two adjacent voltage vectors, which give the minimum switching frequency, are selected to increase or decrease the amplitude of stator flux , respectively. For instance, the vectors V4 and V3 are selected for to increase or to decrease the amplitude of stator flux when it is in region number 1. In this way, can be controlled at the required value by selecting the proper voltage vectors. The voltage vectors are selected for keeping the magnitud stator flux and electromagnetic torque within a hysteresis band [3][7].

3.2. 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 (φ_{sd} φ_{sq}) 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].

Sector		1	2	3	4	5	6
Flux	**Torque**						
Δφ=1	**ΔΓ=1**	V_2	V_3	V_4	V_5	V_6	V_1
	ΔΓ=0	V_7	V_0	V_7	V_0	V_7	V_0
	ΔΓ=-1	V_6	V_1	V_2	V_3	V_4	V_5
Δφ=0	**ΔΓ=1**	V_3	V_4	V_5	V_6	V_1	V_2
	ΔΓ=0	V_0	V_7	V_0	V_7	V_0	V_7
	ΔΓ=-1	V_5	V_6	V_1	V_2	V_3	V_4

Tab. 1 Switching table for Conventional DTC

4. 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].

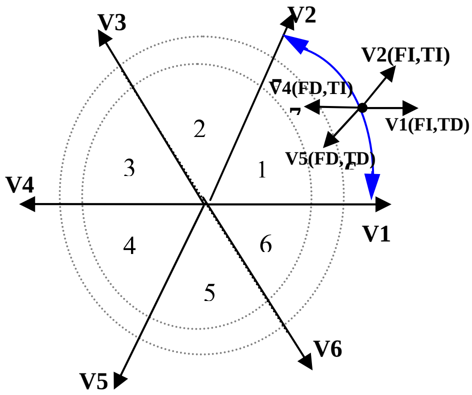

Fig. 5 Modified DTC and its new six sectors

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

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

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

It can be seen that the states V1 and V4, are not used in the Conventional DTC (C_DTC). The raison 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 V_3 and V_6 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 favour 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].

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

Sector		1	2	3	4	5	6
Flux	**Torque**						
Δφ=1	**ΔΓ=1**	V_2	V_3	V_4	V_5	V_6	V_1
	ΔΓ=0	V_7	V_0	V_7	V_0	V_7	V_0
	ΔΓ=-1	V_1	V_2	V_3	V_4	V_5	V_6
Δφ=1	**ΔΓ=1**	V_4	V_5	V_6	V_1	V_2	V_3
	ΔΓ=0	V_7	V_0	V_7	V_0	V_7	V_0
	ΔΓ=-1	V_5	V_6	V_1	V_2	V_3	V_4

Tab. 3 The switching table for Modified DTC

5. DTC TWELVE SECTOR TABLE (DTC_12)

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 twelve sectors instead of just six, all six active states will be used per sector. Consequently, it is arisen the idea of the twelve sector modified DTC (DTC12). This novel stator flux locus is introduced in Fig.6 [6].

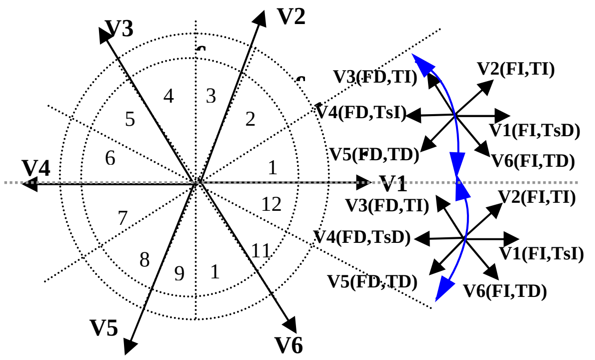

Fig. 6 Twelve sector modified DTC (12_DTC) and its sectors.FD/FI: flux decrease/increase. TD/TI: torque decrease/increase. TsD/TsI: torque small decrease/increase. Notice how all six voltage vectors can be used in all twelve sectors, disappearing all ambiguities.

Tab.4 can be written when a twelve-sector locus is used.

S_{12}	INCREASE	DECREASE
Stator Flux	V_1, V_2, V_6	V_3, V_4, V_5
Torque	V_1, V_2, V_3	V_4, V_5, V_6
S_1	INCREASE	DECREASE
Stator Flux	V_1, V_2, V_6	V_3, V_4, V_5
Torque	V_2, V_3, V_4	V_5, V_6, V_1

Tab. 4 Table for sectors 12 and 1 in the 12_DTC. Notice how all six voltage vectors can be used in all sectors disappearing all ambiguities.

It has been mentioned in the previous paragraph, it is necessary to define small and large variations. It is obvious that V_1 will produce a large increase in flux and a small increase in torque in sector S_{12}. On the contrary, V_2 will increase the torque in large proportion and the flux in a small one. It is reasonable to deduce that the torque error should be divided in the number of intervals that later on will be measured. Therefore, the hysteresis block should have four hysteresis levels at is suggested in Tab.5 [1] [7] [6].

φ	F1				FD			
τ	TI	TsI	TsD	TD	TI	TsI	TsD	TD
S_1	V_2	$*V_2$	V_1	V_6	V_3	V_4	V_7	V_5
S_2	V_3	V_2	$*V_1$	V_1	V_4	$*V_4$	V_5	V_6
S_3	V_3	$*V_3$	V_2	V_1	V_4	V_5	V_0	V_6
S_4	V_4	V_3	$*V_2$	V_2	V_5	$*V_5$	V_6	V_1
S_5	V_4	$*V_4$	V_3	V_2	V_5	V_6	V_7	V_1
S_6	V_5	V_4	$*V_3$	V_3	V_6	$*V_6$	V_1	V_2
S_7	V_5	$*V_5$	V_4	V_3	V_6	V_1	V_0	V_2
S_8	V_6	V_5	$*V_4$	V_4	V_1	$*V_1$	V_2	V_3
S_9	V_6	$*V_6$	V_5	V_4	V_1	V_2	V_7	V_3
S_{10}	V_1	V_6	$*V_5$	V_5	V_2	$*V_2$	V_3	V_4
S_{11}	V_1	$*V_1$	V_6	V_5	V_2	V_3	V_0	V_4
S_{12}	V_2	V_1	$*V_6$	V_6	V_3	$*V_3$	V_4	V_5

Tab. 5 Switching table for the 12_DTC. FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase. (* there is no suitable state. It has been chosen the second most suitable).

6. SIMULATION RESULTS

Induction Machine Equations and data

The Induction motor can be modelled with stator flux and rotor flux as the state variables by (9).

$$\begin{bmatrix} \dfrac{d\,\overline{\varphi s}}{dt} \\ \\ \dfrac{d\,\overline{\varphi r}}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{\sigma Ts} & \dfrac{Lm}{\sigma Ts\,.Lr\,.} \\ \\ \dfrac{Lm}{\sigma Ts\,.Ls} & j\omega r - \dfrac{1}{\sigma Tr} \end{bmatrix} \begin{bmatrix} \overline{\varphi}\,s \\ \\ \overline{\varphi} r \end{bmatrix} + \begin{bmatrix} 1 \\ \\ 0 \end{bmatrix} \overline{u} \qquad (9)$$

Where:

$\overline{\varphi s}$, $\overline{\varphi r}$ Stator and rotor flux vector
Ts =Ls /Rs ,Tr=Lr/Rr :Stator and rotor time constant
Rs, Rr, Stator and rotor résistance
Ls, Lr, Stator and rotor self inductance
Lm Mutual inductance
$\sigma=1-L_m^2/LsLr$ Leakage coefficient
ωr Rotor angular velocity
$\overline{u}$ Stator voltage vector

Pn=3k*W*, *Un*=230*V*, *Rs*=2.89Ω, *Rr*=2.39Ω, *Ls*=*Lr*=0.225*H*, *Lm*=0.214*H*, *P*=2,

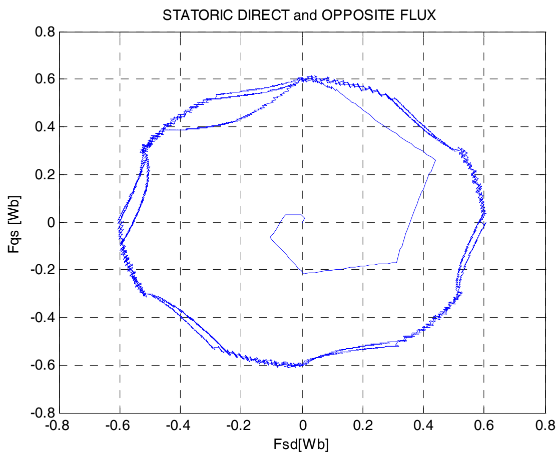

Fig. 8a The stator flux circle C_DTC

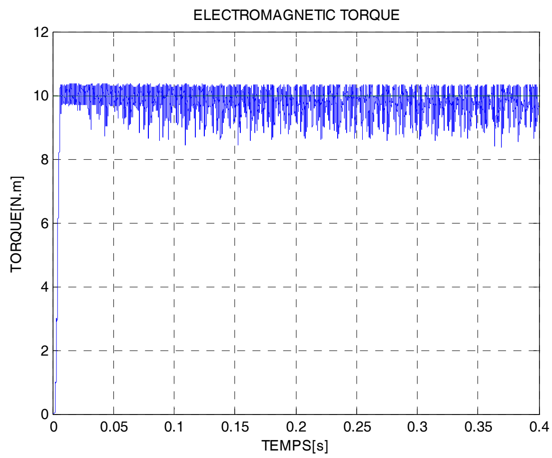

Fig. 9a Torque Response C_DTC

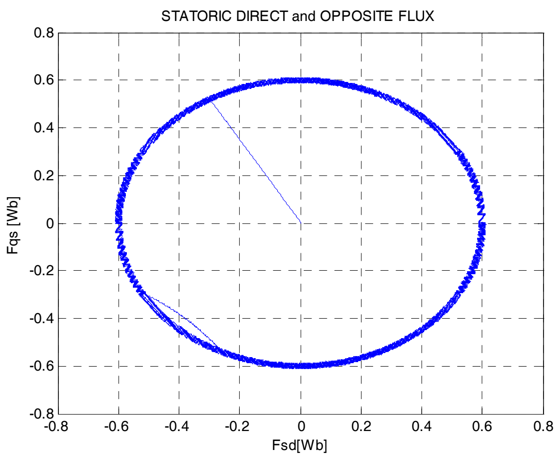

Fig. 8b The stator flux circle M_DTC

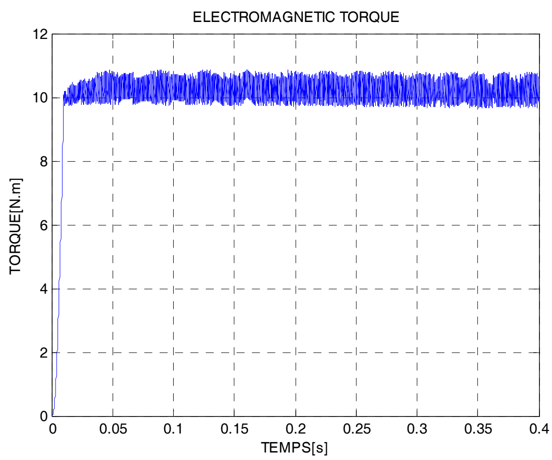

Fig. 9b Torque Response M_DTC

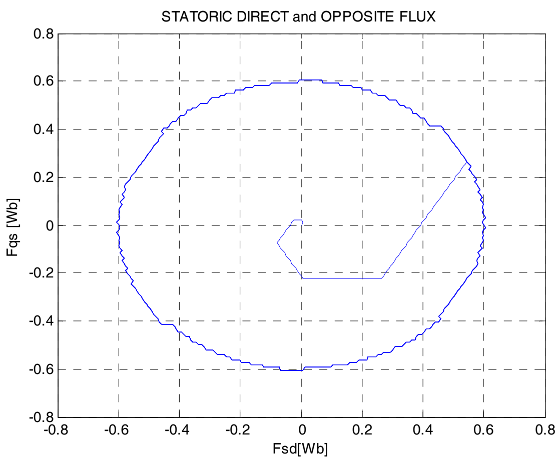

Fig. 8c The stator flux circle 12_DTC

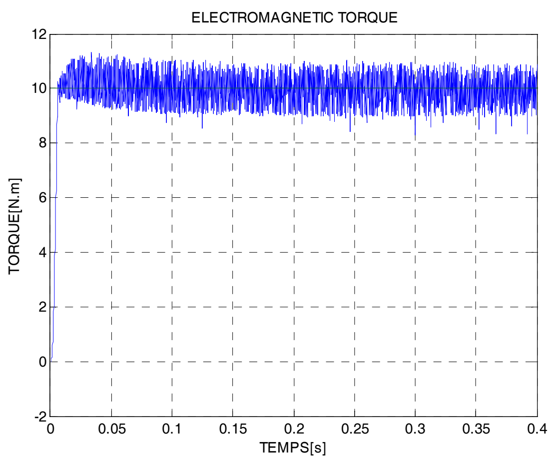

Fig. 9c Torque Response 12_DTC

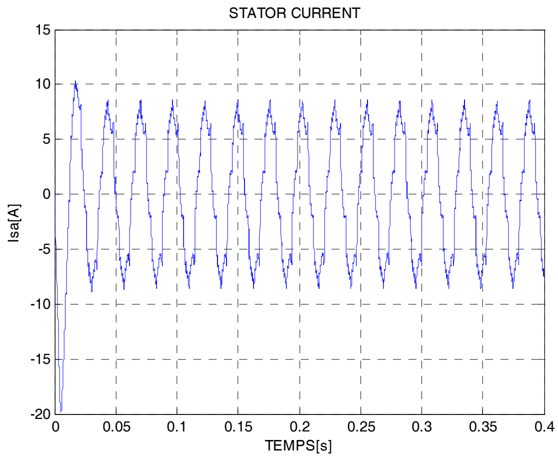

Fig.10a The stator current C_DTC

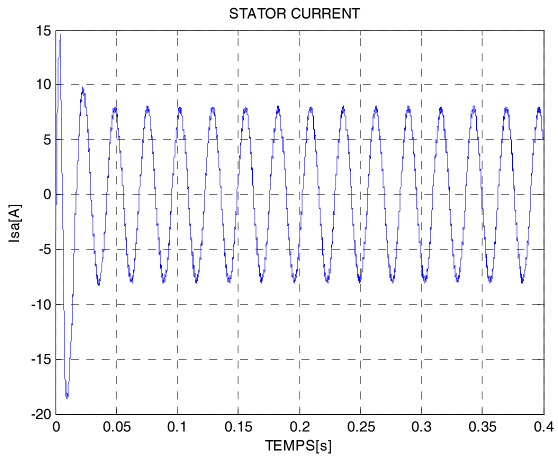

Fig.10b The stator current M_DTC

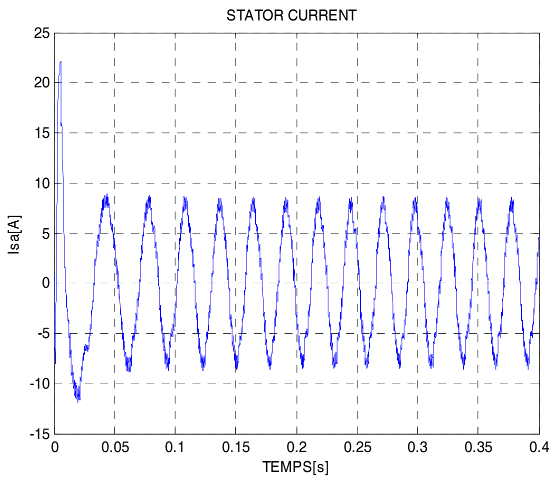

Fig. 10c The stator current 12_DTC

7. INTERPRETATION RESULTS

The results of simulation of Conventional DTC (C_DTC), modified DTC (M_DTC) and twelve sector DTC (12_DTC) of induction motor is shown in Fig 8, 9 and 10 respectively. All three figure are the responses to step change torque command from zero to 10 N.m, which is applied at 0.0 sec. Fig.8 (a, b and c) Shows that the flux of the M_DTC and 12_DTC offers the fast transient responses That means the trajectory of stator flux established more quickly than that of the Conventional C_DTC. The simulation results show that the torque responses are very good dynamic response for four DTC methods, but the response of the torque conventional DTC presented of the ripple; By M_DTC and 12_DTC techniques shown Fig. 9(b and c) the ripple of torque in steady state is reduced remarkably compared with conventional DTC, the torque changes through big oscillation and the torque ripple is bigger in conventional DTC shown Fig. 9a. Fig.9 (a, b, and c) show the stator current in both control schemes. Even though both functions seem to be sinusoidal, it could be expected that the stator current in the Conventional DTC has more harmonic distortion because the effects caused by flux drooping is more evident. In the DTC induction drive, increased switching frequency is desirable since it reduces the harmonic content of the stator currents. However if high switching frequency is used, this will result in significantly increased switching losses (leading to reduced efficiency) and increased stress on the semiconductor devices of the inverter.

From this study, we can conclude that the method of Modified DTC present the maid of performances. The reduction of oscillations of stator flux and torque response, in transient and steady state, is shown by Fig.8 (b), 9(b) and 10(b). Applying a zone shift angular (θ equal to (-0.4) degree, we can observe an optimal reduction of the flux nodulations, as shown in Fig.8 (b), Consequently, Consequently, as illustrated in Fig.10(b), the current have less harmonic distortion . It can be control performances are obtained without degradation, as shown in Fig.9 (b).

8. CONCLUSION

In this paper a comparison of various direct torque control methodologies (Conventional TC, M-DTC, and 12_DTC) have been made in order to evaluate the influence of the motor operating condition on transient state performance.

A particular emphasis on stator flux, torque ripple has been studied. The simulation results suggest that modification by conventional DTC of induction motor can achieve precise control of the stator flux and torque. Compared to conventional DTC, presented method can be easily implemented , and the steady performances of ripples of both torque and flux are considerably improved. The main improvements shown are:

- Reduction of torque and current ripples in transient and steady state response.
- No flux droppings caused by sector changes circular trajectory.
- Fast stator flux response in transient state.

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