TECHNIQUES FOR IMPROVEMENTS OF THE PERFORMANCES OF DIRECT TORQUE CONTROL STRATEGY FOR INDUCTION MOTOR

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ABSTRACT

The basic concept of direct torque control of induction machines is investigated in order to emphasize the effects produced by a given voltage vector on stator flux and torque variations. The low number of voltage vectors which can be applied to the machine using the basic DTC scheme may cause undesired torque and current ripple. An improvement DTC schemes proposed in the research literature is presented and compared with the classical. In this paper, we propose two approach's of improvement of Direct Torque Control (DTC) of Induction motor, first is Discrete Space Vector Modulation (DSVM_DTC) Where the Stator flux and torque are controlled using respectively by five-level hysteresis comparators, second is and The discrete time direct torque control (DTDTC) requires voltage and current measurements to calculate the back-EMF, and address the problem with torque ripple in the basic DTC system is introduced. Numerical simulations tests have been carried out to validate the proposed method.

Keywords: *induction motor, direct torque control, stator flux, three phase inverter, look-up table, controller, Discrete Space Vector Modulation*

1. INTRODUCTION

Alternating current motors are getting more and more popular for applications in industrial environments [3-7]. Particularly in speed control systems, ac induction motors are more widely used nowadays due to the characteristics of higher efficiency, less inertia, smaller volume and lower cost. Moreover, in contrast to dc motors, induction motors can be used for a long time without maintenance because of their brushless structures [1-3]. The capabilities to operate at higher speeds, higher torques and larger power ratings make the induction motors more attractive than dc motors for medium and high power motor drives.

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.

In recent years, research interest in IM sensorless drives has grown significantly due to some of their advantages, Such as mechanical robustness, simple construction and maintenance [1]. Present efforts are devoted to improve the sensorless operation, especially for low speed and to develop robust control strategies [3-9],.

The DTC is one of the actively researched control schemes which are based on the decoupled control of stator flux and torque providing a quick and robust response with a simple control construction in ac drives[1-9],. However, the conventional DTC strategy using only one switching table at high and low speed present notable torque, flux, current and speed ripple. In this paper, we propose two approach's of improvement of Direct Torque Control (DTC) of Induction motor [3-7], first is Discrete Space Vector Modulation (DSVM_DTC) Where the Stator flux and torque are controlled using respectively by five-level hysteresis comparators, second is and The discrete time direct torque control (DTDTC) requires voltage and current measurements to calculate the back-EMF, and address the problem with torque ripple in the basic DTC system is introduced [7-9],. Numerical simulations tests have been carried out to validate the proposed method.

2. MACHINE EQUATIONS

The dynamic behavior of an induction machine is described by the following equations written in terms of space vectors in a stator reference frame.

$$\overline{V}_s = R_s \overline{I}_s + \frac{d\overline{\varphi_s}}{dt} \tag{1}$$

$$0 = R_r \overline{I}_r + \frac{d\overline{\varphi_r}}{dt} - j\omega m \overline{\varphi}_r \tag{2}$$

$$\overline{\varphi}_s = L_s \overline{I}_s + M \overline{I}_r \tag{3}$$

$$\overline{\varphi}_r = L_r \overline{I}_r + M \overline{I}_s \,(1) \tag{4}$$

Where R_s *and* R_r represents the stator and rotor resistances; L_s , Lr and M self and mutual inductances; ω_m rotor angular speed expressed in electrical radians.

The electromagnetic torque is expressed in terms of stator and rotor fluxes as

$$\Gamma_{em} = \frac{3Mp}{2\sigma L_s L_r}\left(\overline{\varphi_s} \cdot j\overline{\varphi_r}\right) \tag{5}$$

Where P is the pole pair number and

$$\sigma = 1 - \frac{M^2}{L_s L_r}$$

3. DIRECT TORQUE CONTROL STRATEGY

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.

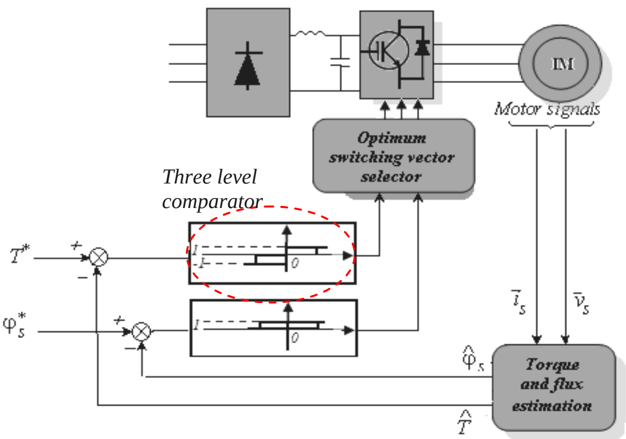

Fig. 1 Basic direct torque control scheme

3.1. 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. Figure 2 show, 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).

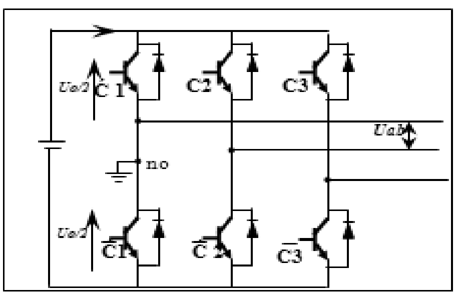

Fig. 2 Three phase voltage inverter

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

$$\overline{V}_s = \sqrt{\frac{2}{3}}U_0\left[C_1 + C_2 e^{j\frac{2\pi}{3}} + C_3 e^{j\frac{4\pi}{3}}\right] \tag{6}$$

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].

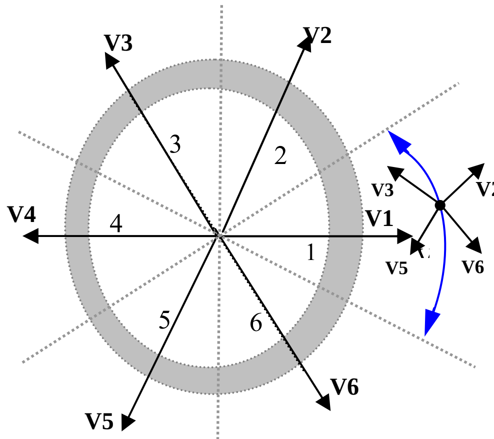

Fig. 3 Partition of the d,q plane into six sectors

3.2. 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]:

$$\begin{cases} V_{Sd} = \sqrt{\frac{2}{3}}U_0\left(C_1 - \frac{1}{2}(C_2 + C_3)\right) \\ V_{Sq} = \frac{1}{\sqrt{2}}U_0\left(C_2 - C_3\right) \end{cases} \tag{7}$$

And stator current components (I_{sd}, I_{sq}) :

$$\begin{cases} I_{Sd} = \sqrt{\frac{2}{3}}Isa \\ I_{Sq} = \frac{1}{\sqrt{2}}\left(Isb - Isc\right) \end{cases} \tag{8}$$

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 Ts. 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 (10):

$$\overline{\varphi}_S = \int_0^t (\overline{V}_S - R_S \overline{I}_S)\,dt \tag{9}$$

During the switching interval, each voltage vector is constant and (9) is then rewritten as in (10):

$$\overline{\varphi}_S(t) \approx \overline{\varphi}_{S0} + \overline{V}_s T_s \tag{10}$$

In equation; φ_{s0} stands for the initial stator flux condition.

In fact, we have $\frac{d\overline{\varphi}_S}{dt} \approx \overline{V}_s$ .The following Figure 4 is established for the case $V_s=V_3$.

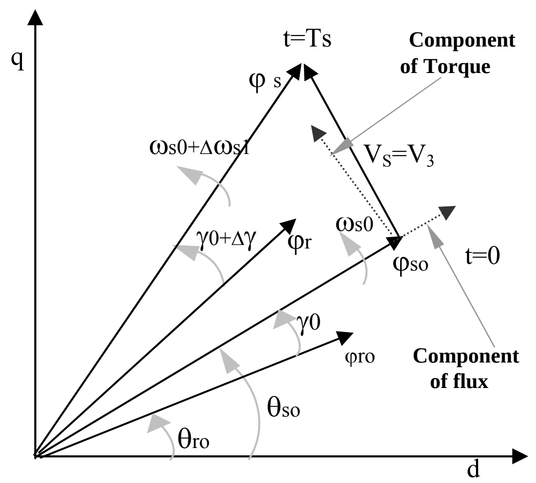

Fig. 4 An example for flux deviation

Neglecting the stator resistance, (10) 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 magnitude stator flux and electromagnetic torque within a hysteresis band [3][7].

3.3. Stator flux and torque estimation

The magnitude of stator flux, which can be estimated by (12).

$$\begin{cases} \overline{\varphi}_{Sd} = \int_0^t (\overline{V}_{Sd} - R_S \overline{I}_{Sd})\,dt \\ \overline{\varphi}_{Sq} = \int_0^t (\overline{V}_{Sq} - R_S \overline{I}_{Sq})\,dt \end{cases} \tag{11}$$

The stator flux linkage phase is given by

$$\varphi_S = \sqrt{\varphi_{Sd}^2 + \varphi_{Sq}^2} \tag{12}$$

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 (11), current components (8) and *P*, pair-pole number of the induction machine [2][8]:

$$\Gamma_{em} = \frac{3}{2} p\left(\varphi_{sd} I_{sq} - \varphi_{sq} I_{sd}\right) \tag{13}$$

As shown in Figure 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 Table 1 [1][2].

Table 1 Switching table for Conventional DTC

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

4. DTC DSVM STRATEGY

The function blocks of DSVM-DTC system main of electric drives is shown in Figure 5, respectively. DSVM-DTC is based on the traditional direct torque control system and the differences between them are the switching table and the principle of choosing voltage vectors, which will be illustrated in 4.4.[5] The main circuit of Figure 5 consists of four main parts: transformer, rectifier, inverter and induction motor. The input power supply of electric drive is that of 50Hz single-phase voltage via a transformer, which is converted to a DC power supply by the rectifier which can operate in four quadrants. It can maintain the DC output voltage with constant value by regulating the rectifier when input voltage changes. The inverter is constituted of GTO devices, which operate in low switching frequency [3,6,7].

4.1. Speed voltage

The DSVM calculates this voltage and use it to choose an appropriate voltage vector [7]. The increased number of voltage vectors allows the definition of switching tables according to the rotor speed (Fig. 2e) the flux and torque errors, shown Figure 6 [5].

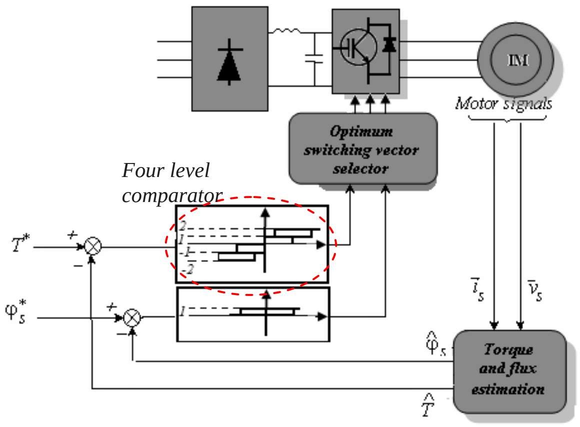

Fig .5 DSVM-DTC control scheme.

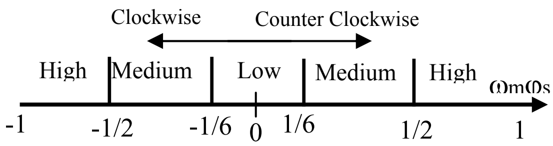

Fig. 6 Speed voltage regions]

The voltage induced is

$$\omega_r \begin{bmatrix} \varphi_{sd} \\ -\varphi_{sq} \end{bmatrix} \tag{13}$$

But only its value is used, so calculated voltage is

$$\overline{V}_s = \omega_r \overline{\varphi}_S \tag{14}$$

This is then compared to the regions.

4.2. Sector calculation

The DSVM requires a 12-sector angular representation of the (α,β) plane. The finer division of sectors is used in the high-speed region. At medium and low speed range only six sectors are used, Show Figure7,[7].

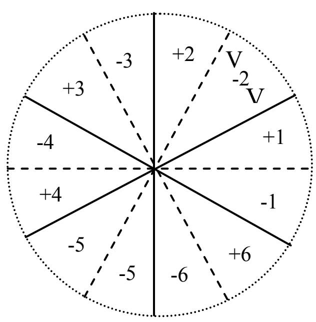

Fig. 7 DSVM sectors

4.3. Torque hysteresis controller

The DSVM can produce height number voltage vectors which if properly applied produce less ripple, the Stator flux and torque are controlled using respectively a two-level and a five-level hysteresis comparators [4][7].

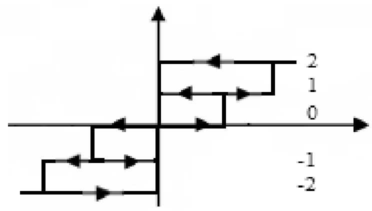

Fig. 8 5-level hysteresis comparator

- If torque error is in state 0, a voltage vector is chosen trying to maintain torque at its actual level.
- If hysteresis is in state +/– 1, a vector just as big as to push torque into the small region is chosen.
- If hysteresis is in state +/–2, a vector compensating for the error as fast as possible is chosen, [4][7].

4.4. Look-up Table

The look-up table in this case has four input variables; flux and torque hysteresis state, sector number and speed voltage. Since the system chose voltage vectors depending on the ***emf***, each speed region uses different switch tables. When the system operates in the high speed region two switch tables for each sector are used. Because the ***emf*** introduces an asymmetry, the switch tables also become asymmetric. Hence, different tables must be used for positive and negative rotational directions [3-7].

With DSVM-DTC strategy, 19 voltage vectors can be selected for each sector, according to the rotor speed, the flux and the torque errors range as is represented in Figure.9 and Table.2.[3][5] The switching period is divided into three equal time intervals and one voltage vector is applied at each time interval [3].

For example, the label "23Z" denotes the voltage vector which is synthesized by using the voltage space vectors V_2, V_3 and V_0 or V_7, each one applied for one third of the cycle period [3-7].

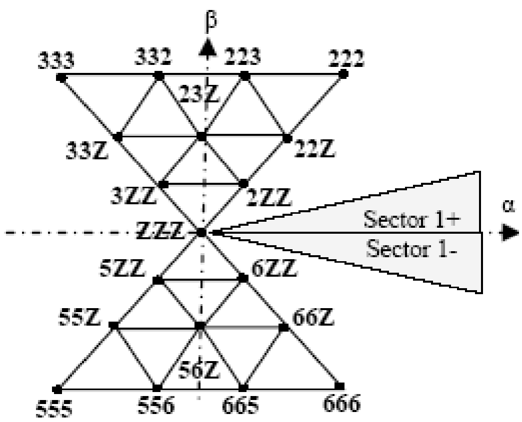

Fig. 9 Voltage vectors obtained by using DSVM with three equal time intervals per cycle period.

Table 2 DSVM-DTC switching table (ωm>0)

Low emf range						
C_φ	C_T	-2	-1	0	1	2
0		555	5ZZ	ZZZ	3ZZ	333
1		666	6ZZ	ZZZ	2ZZ	222
Medium emf range						
C_φ	C_T	-2	-1	0	1	2
0		555	ZZZ	3ZZ	33Z	333
1		666	ZZZ	2ZZ	22Z	222
High emf range sector 1+						
C_φ	C_T	-2	-1	0	1	2
0		555	3ZZ	33Z	333	333
1		666	2ZZ	23Z	223	222
High emf range sector 1-						
C_φ	C_T	-2	-1	0	1	2
0		555	3ZZ	23Z	332	333
1		666	2ZZ	22Z	222	222

5. DISCRETE TIME DIRECT TORQUE DTDTC

Discrete time direct torque control for induction motor Belongs of dead beat control algorithm of torque and flux over a sampling period. Therefore the voltage applied to the motor should change the stator flux and current in such a way as to fulfil the following conditions [6-7]:

$$T_{k+1} = T_k^* \qquad \varphi_{k+1} = \varphi_{sk}^* \tag{15}$$

The stator voltage can be written in the form

$$\overline{V}_s = R_s \overline{I}_s + \sigma L_S \frac{d\overline{I}_s}{dt} + \overline{E}s \tag{16}$$

$$\frac{d\overline{\varphi}_s}{dt} = \overline{V}_s - R_s \overline{I}_s = \sigma L_S \frac{d\overline{I}_s}{dt} \tag{17}$$

Where

$$E_S = L_m \frac{d}{dt}(I_s + I_r) \tag{18}$$

The discrete time direct torque control method requires a discrete time description of the motor model,thus the sampling period Ts is considered constant. With reference to a generic K-th interval [kT_s,$(k+1)T_s$]. The back ***emf*** can be assumed constant, where a constant voltage space vector V_{sk} is applied [6]. The stator current difference equation derived from (16) becomes [6-7]

$$I_s(k+1) = aI_s(k) + bV_s(k) - be(k) \tag{19}$$

Where

$$a = e^{\frac{Ts}{\tau}}; \quad b = \frac{1}{R_s}(1-a); \quad \tau = \frac{\sigma L_s}{R}$$

Equation (17) of the stator flux vector becomes

$$\begin{aligned} \varphi_s(k+1) &= \varphi_s(k) + (T_s - \sigma L_s b)e(k) \\ &\quad + \sigma L_s(a-1)I_s(k) + \sigma L_s b V_s(k) \end{aligned} \tag{20}$$

In the case if Ts<<τ One with following simplifications

$$a \approx 1 - \frac{T_s}{\tau}; \quad b = \frac{T_s}{\sigma L_s}$$

And equation (20) can be simplified.

$$\varphi_s(k+1) = \varphi_s(k) + T_s(V_s(k) - R_s I_s(k)) \tag{21}$$

The desired voltage *Vsk* can be more easily evaluated if the auxiliary variable wk is introduced:

$$w_k = V_{sk} - E_{sk} - R_s I_{sk} \tag{22}$$

$$\begin{aligned} &\left(\varphi_{sqk} - L_s I_{sqk} + T_s E_{sqk}\right) b w_{dk} - (\varphi_{sdk} - L_s I_{sdk} + T_s E_{sdk}) b w_{qk} = \\ &T_s(E_{sdk} I_{sqk} - E_{sdk} I_{sdk}) - \frac{T_k^* - T_k}{3/2p} \end{aligned} \tag{23}$$

$$\begin{aligned} &T_s^2 w_{dk}^2 + 2T_s\left(\varphi_{sdk} + T_s E_{sdk}\right) w_{dk} + T_s^2 w_{qk}^2 + 2T\left(\varphi_{sqk} + T_s E_{sqk}\right) w_{qk} = \\ &\varphi_{sk}^{*2} - (\varphi_{sdk} + T_s E_{sdk})^2 - (\varphi_{sqk} + T_s E_{sqk})^2 \end{aligned} \tag{24}$$

The algorithm requires the values of E_{sk} .this is linked to be previous value $E_{s,k-1}$ that can be estimated by (25) [6].

$$E_{S,k-1} = V_{s,k} - 1 + (aI_{s,k-1} - I_{s,k})/b \tag{25}$$

For the discrete time direct torque control also the knowledge of the back-EMF *E(k)* during the interval $[kT_s,(k+l)T_s]$ is required when only measurements are available until instant kT_s. Thus a prediction of the back-EMF is required [9]. Since in steady-state the back-EMF will move along a circular trajectory the back-EMF can be predicted using a predicted change in angle over a sampling period $w_s T_s$; as [6-9].

$$E(k) = e^{jwsTs} E_s(k-1) \tag{26}$$

The Changing in angle of the stator flux during sampling interval allowed calculating the predicted change in the angle $w_s T_s$ [6-9], given by:

$$\cos(\omega_s T_s) = \frac{\varphi_{sd}(k)\varphi_{sd}(k-1) + \varphi_{sq}(k)\varphi_{sq}(k-1)}{\sqrt{\|\varphi_s(k)\|^2 \|\varphi_s(k-1)\|^2}}$$
$$\cos(\omega_s T_s) = \frac{\varphi_{sq}(k)\varphi_{sd}(k-1) - \varphi_{sd}(k)\varphi_{sq}(k-1)}{\sqrt{\|\varphi_s(k)\|^2 \|\varphi_s(k-1)\|^2}} \quad (27)$$

6. INTERPRETATION RESULTS

To verify the technique proposed in this paper, digital simulations based on Matlab/Simulink. have been implemented. The induction machine used for the simulations has the following parameters: P_N=3K*W*,U_N=230*V*, f_N=60*Hz*, *Rs*=2.89Ω, *Rr*=2.39Ω, *P*=2, *Ls*=*Lr*=0.225*H*, *Lm*=0.214*H*, *J*=0.005*kgm2*. The Sampling period of the system is 10 μ*s*. To compare with conventional C_DTC, DTC_DSVM and DTC_DT for IM are simulated. In two cases, the dynamic responses of speed, flux, torque and stator current for the starting process with [5→7→3]Nm. The simulation results show the response of electromechanical torque amplitude of the stator flux, stator current and their harmonic spectrum, are shown in Figure (10-14) respectively.

Show Fig 10c in As shown in Fig. 10(c) DTC_DT the torque ripple is dramatically reduced as compared with those shown in Fig. 10(a) and (b) for the C_DTC and DTC_DSVM system, but the oscillation and the torque ripple is bigger in C_DTC shown Figure 11a. However, the large torque ripple in steady-state operation is one of its major drawbacks. The steady-state performances of the conventional DTC, DTC_DSVM and DTC_DT are compared in Fig.11(a, b and c) under the same operation condition. It is seen that there is almost no ripple in the estimated flux linkage under the DTC_DSVM and DTC_DT. However, the torque and flux ripple under the conventional DTC is 0.5 Nm and 0.02Wb, respectively. It can be seen Fig12.a and b that the stator flux trajectory of the DTC_DSVM and DTC_DT is more approximately circle than it of the conventional DTC Fig12.a. Consequently, as illustrated in Figure.13b and c, the current have less harmonic distortion that compared with C_DTC show Figure13a.

Fig.14 (a,b and c) .Shows the spectrums under the C_DTC, DTC_DSVM and DTC_DT. It is seen that under the DTC_DSVM and DTC_DT , harmonics in the current are greatly reduced. The amplitude of the seven harmonic is less than of the conventional DTC, what results to in reducing the total harmonic distortion (THD).

7. CONCLUSION

In this paper, a DTC_DSVM and DTC_DT scheme was investigated by simulation using Simulink. The simulation results suggest that DTC_DSVM and DTC_DT of induction machine can achieve precise control of the stator flux and torque. Compared to conventional DTC, presented method is easily implemented, and the main improvements shown are: The ripple of the torque and current is reduced. Especially, the ripple of the torque is reduced obviously. No flux droppings caused by sector changes circular trajectory. The use of this technique is very useful in applications where the maximum frequency is limited by large computational time.

8. SIMULATION RESULTS

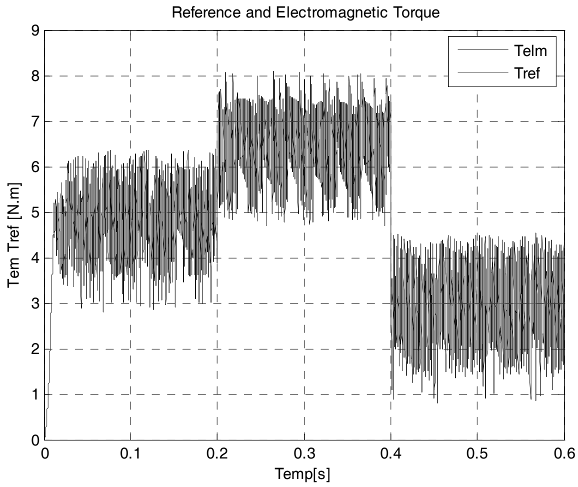

Fig. 10a Electromagnetic Torque Response in C_DTC

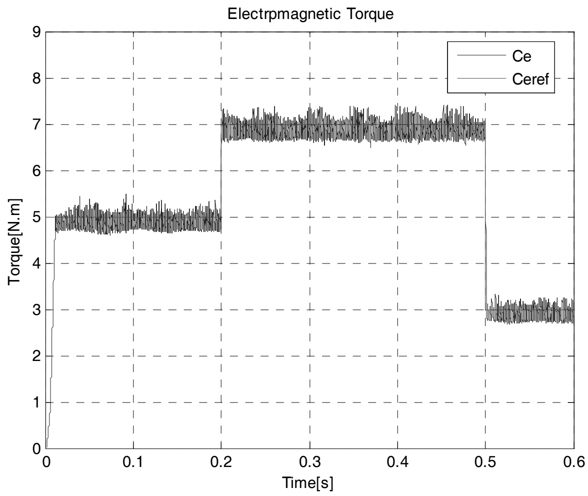

Fig. 10b Electromagnetic Torque Response in DSVM_DTC

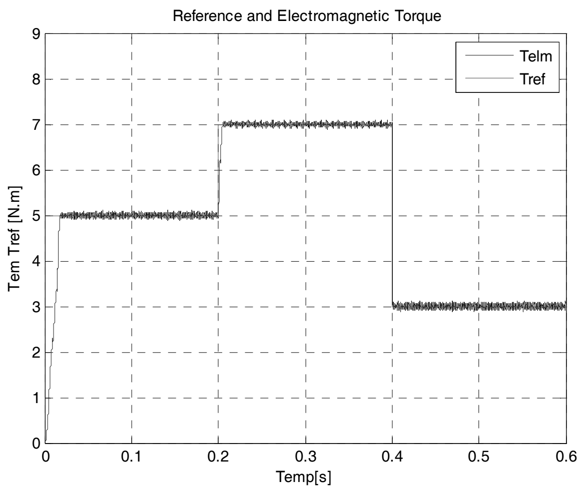

Fig. 10c Electromagnetic Torque Response in DTC_DT

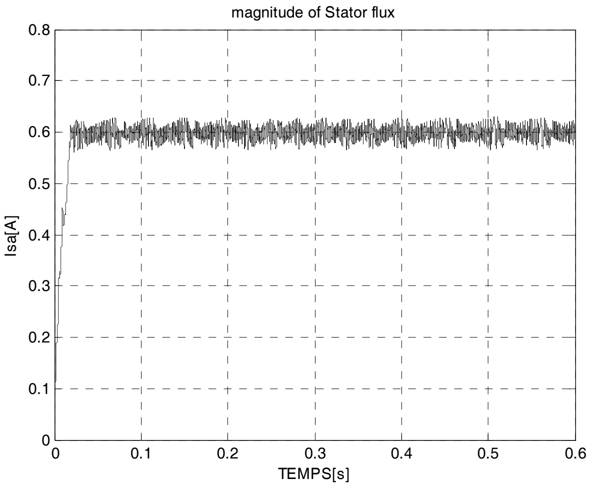

Fig. 11a The magnitude of stator flux in C_DTC

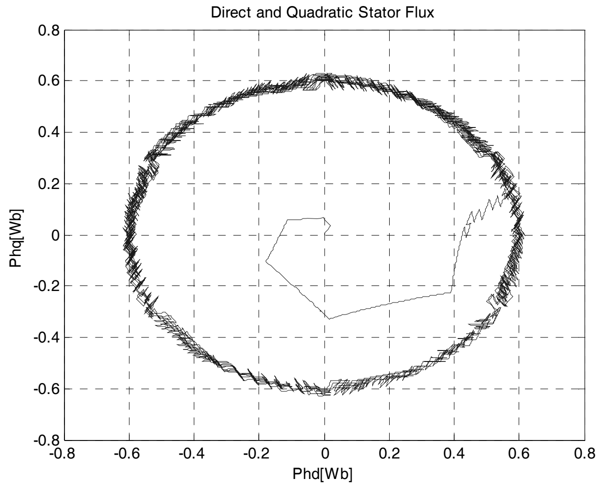

Fig. 12a Circle stator flux in DTC_TC

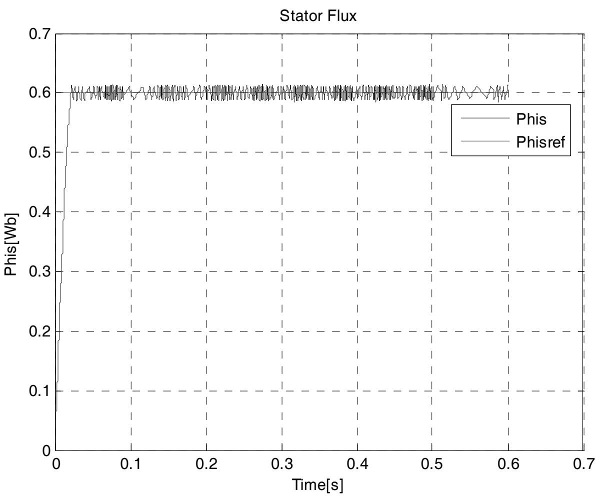

Fig. 11b The magnitude of stator flux in DTC_DSVM

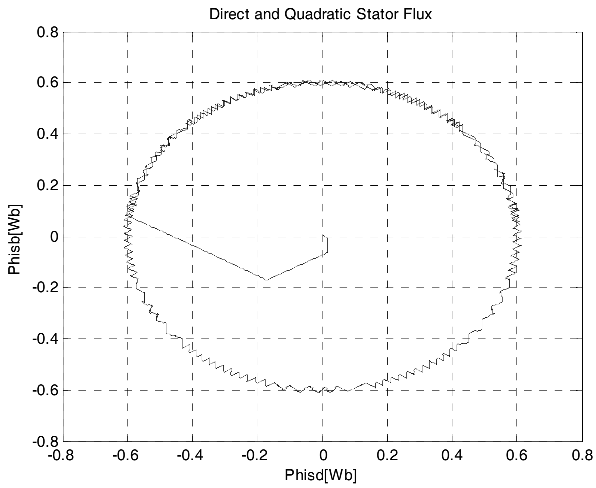

Fig. 12b Circle stator flux in DTC_DSVM

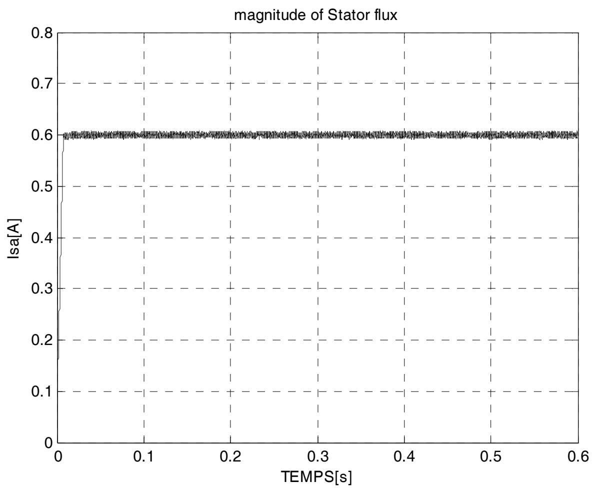

Fig . 11c The magnitude of stator flux in DTC_DT

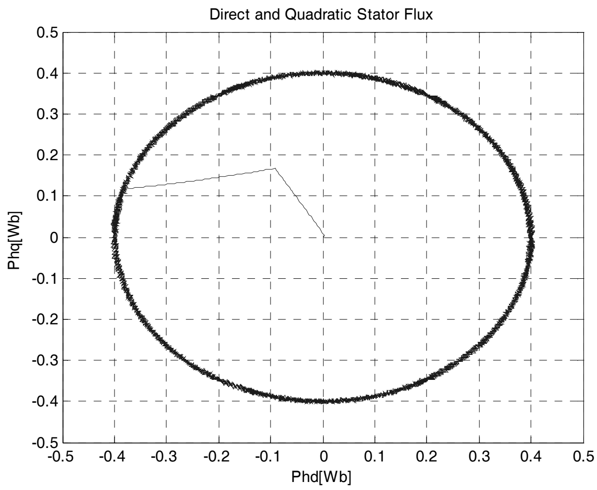

Fig. 12c Circle stator flux in DTC_DT

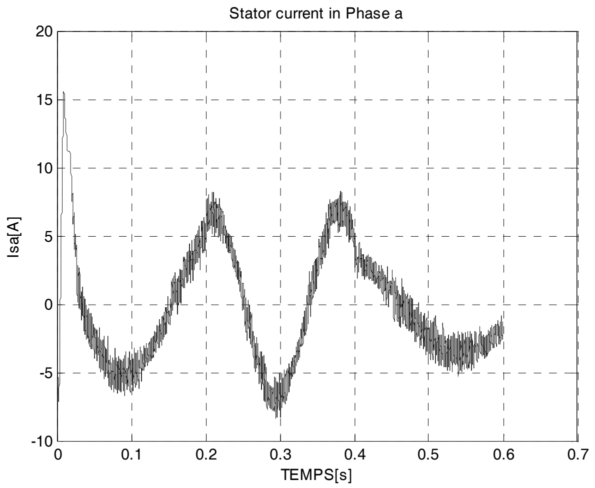

Fig. 13a The stator current in C_ DTC

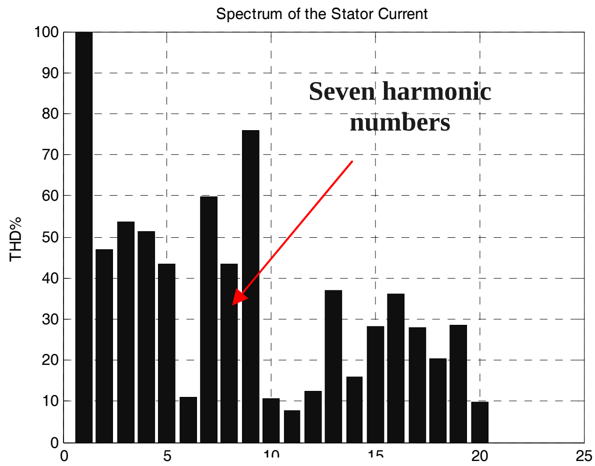

Fig. 14a Harmonic spectrum of stator current in C_ DTC

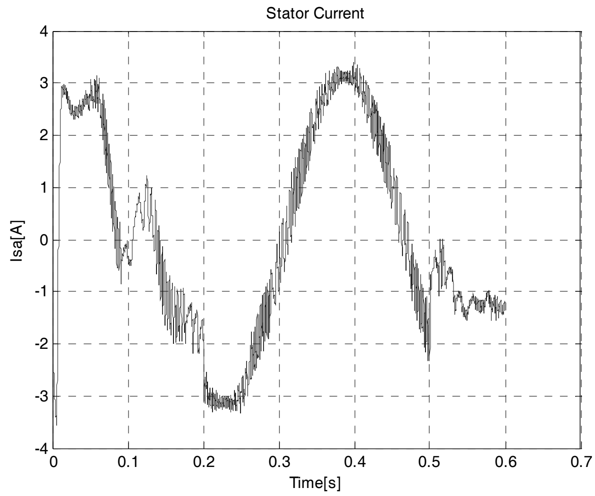

Fig. 13b The stator current in DTC_DSVM

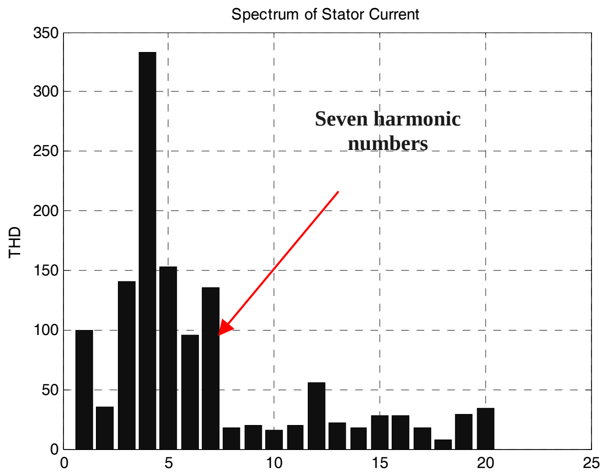

Fig. 14b Harmonic spectrum of stator current in DTC_DSVM

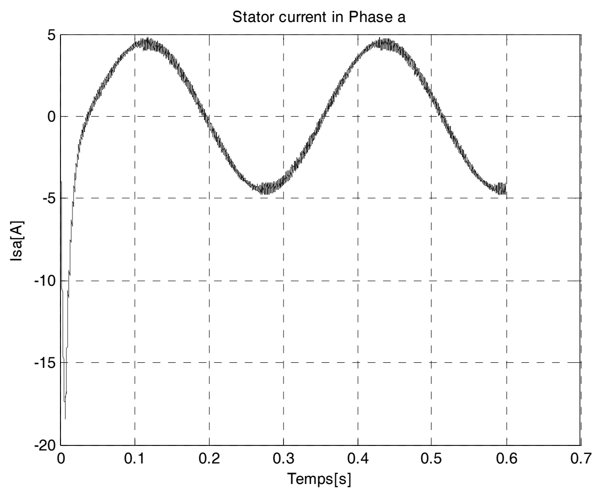

Fig. 13c The stator current in DTC_DT

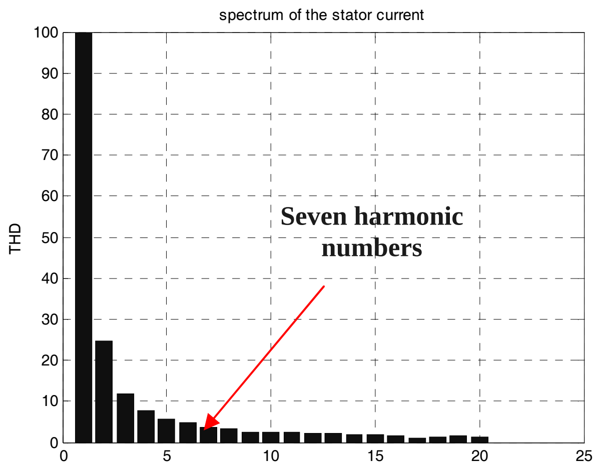

Fig. 14c Harmonic spectrum of stator current in DTC_DT

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