The Direct Torque Control of Induction Motor to Basis of the Space Vector Modulation

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Abstract – **This paper presents a new approach to direct torque control (DTC) of induction motor drive based on space vector modulation (SVM) with constant switching frequency. With the proposed strategy, the error between the estimated and the reference for stator flux linkage and torque will be compensated by synthesised voltage space vector accurately. The simulation results verified that the proposed DCT-SVM method can improve the system robustness, evidently reduce the torque and flux ripples, and effectively enhance the steady state performance of this regulation**
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Key words – DTC, Induction Motor, SVM, Regulator hysteresis, switching frequency

1. Introduction

Vectorial control based on rotor flux orientation presents a major disadvantage to be relatively sensible to the machine parameters variation. For such reason, the direct torque control (DTC) methods of the induction machines have been developed during the nineties [1]. The conventional DTC drive contains a pair of hysteresis comparators, a flux and torque estimator and a voltage vector selection table. The stator flux and the electromagnetic torque are estimated from the unique electric parameters of stator that can be handled (accessible) without mechanical sensors.

DTC seems to be a good performance alternative to the classical vector control drives. It is said to be one of the future ways of controlling the induction motors in four quadrants with good results [1, 2]. This method is able to produce fast torque and stator flux response with a well designed flux, torque and speed estimator. This method still required further improvements in order to enhance the motor's performance, as well as achieve a better behaviour regarding environment compatibility as Electro Magnetic Interference, which is required today for all industrial applications [3].

In order to reduce the torque and current pulsations, in steady state, a mixed DTC- SVM control method seems more suitable. SVM techniques, offer better DC link utilisation and they lower the torque ripple. Lower THD in the motor current is also obtained [4]. This work explores direct torque control (DTC) based on Space Vector Modulation (DTC-SVM) applied to induction motor drive systems, in a such a way to achieve constant switching frequency and low torque ripple, hence overcoming the major drawbacks of conventional DTC. The simulation results show that the proposed DCT-SVM method can improve the regulation performance

2. Principle of direct torque control

Using the vectorial expressions, the machine voltages in the reference frame binds to the stator is defined by,

$$\begin{cases} \overline{V}s = Rs\overline{I}_s = \dfrac{d\overline{\Phi}_s}{dt} \\ \overline{V}_r = 0 = Rr\overline{I}r + \dfrac{d\overline{\Phi}_r}{dt} - j\omega\overline{\Phi}_r \end{cases} \qquad (1)$$

From the flux expressions, the rotor current can be written,

$$\overline{I}_r = \frac{1}{\sigma}\left(\frac{\overline{\Phi}_r}{L_r} - \frac{L_m}{L_r L_s}\overline{\Phi}_s\right) \qquad (2)$$

With

$\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$ (Variability (scatter) factor)

The equations become

$$\begin{cases} \overline{V}_s = Rs\overline{I}s + \dfrac{d\overline{\Phi}_s}{dt} \\ \dfrac{d\overline{\Phi}_r}{dt} + \left(\dfrac{1}{\sigma\tau_r} - j\omega\right)\overline{\Phi}_r = \dfrac{L_m}{L_s}\dfrac{1}{\sigma\tau_r}\overline{\Phi}_s \end{cases} \qquad (3)$$

These relations show that:

- It can possibly control the $\overline{\Phi}_s$ vector starting from the $\overline{V}_s$ vector, with the voltage drop $R_s\overline{I}_s$

- The flux $\overline{\Phi}_r$ follows the variation of $\overline{\Phi}_s$ with time constant $\sigma\tau_r$.

- The electromagnetic torque is proportional to the vectorial product of the stator and rotor flux vectors.

$$\Gamma_{elm} = p\frac{L_m}{\sigma L_s L_r}\Phi_s\Phi_r \sin\gamma \qquad (4)$$

With $\gamma = \left(\overline{\Phi}_s \overline{\Phi}_r\right)$

- Thus the torque depends on the amplitude and the relative position of the two vectors $\overline{\Phi}_s$ and $\overline{\Phi}_r$.

- If we manage to control perfectly the flux $\overline{\Phi}_s$ (starting from $\overline{V}_s$) in module and position, we can thus control the amplitude and the relative position of $\overline{\Phi}_s$ and $\overline{\Phi}_r$, consequently the torque. This can be possible only when the control period T_e of the voltage V_s is such as $T_e << \sigma\tau_r$ [4].

3. Choice of voltage vector control V_s

The choice of the vector $\overline{V}_s$ depend on the position of $\overline{\Phi}_s$, the desired variation for the module of Φ_s , the desired variation for the torque, and the direction of rotation of $\overline{\Phi}_s$ .The steady complex plan (α,β) of the stator is

Subdivided into six sectors S_i with: i =1… 6 so that:

$$(2i-3)\frac{\pi}{6} \le S_i \le (2i-1)\frac{\pi}{6} \qquad (5)$$

Each sector S_i contains an active space voltage vector V_i of the inverter as shown on figure (1). Thus the flux rotate in the trigonometrically direction.

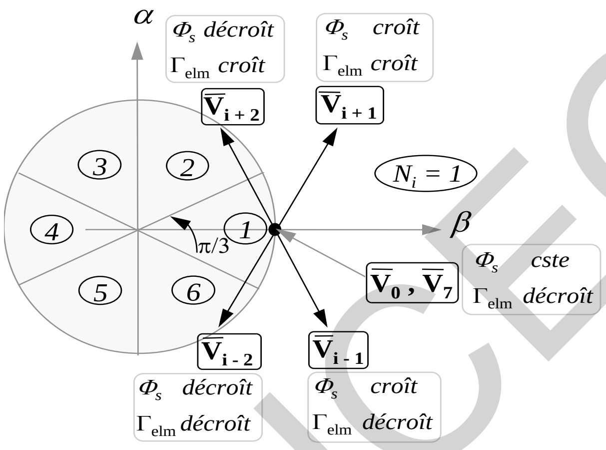


Fig. 1 – Choice of the Voltage

These voltage vectors are selected from a commutation table according to the flux errors, torque and position of the stator flux vector. However, the position of the rotor is not needed for the choice the voltage vector. This particularity is an advantage of the (DTC) since the mechanical sensor is not necessary.

The voltage vector at the inverter output is deduced from the variations of torque and flux estimated relatively to their reference, as well as the position of vector $\overline{\Phi}_s$. An estimator of $\overline{\Phi}_s$ in module and position as well as an estimator of torque are therefore necessary [4].

4. Estimators

4.1 Stator flux estimation

The flux estimation can be obtained from the measurements of current and voltage of the machine stator parameters.

$$\overline{\Phi}_S = \Phi_{S\alpha} + j\Phi_{S\beta}$$

$$\begin{cases} \Phi_{S\alpha} = \int_0^t \left(V_S - R_S I_{S\alpha}\right)dt \\ \Phi_{S\beta} = \int_0^t \left(V_{S\beta} - R_S I_{S\beta}\right)dt \end{cases} \qquad (6)$$

We obtain the voltages $V_{S\alpha}$ and $V_{S\beta}$ from controllers $(S_a S_b S_c)$, of the measured voltage U_0.

4.2 Electromagnetic torque *e*stimation

The torque Γ_{elm} can be only estimated from the stator parameters flux and current, from their components (α,β); so, the torque can be written as,

$$\Gamma_{elm} = p\left[\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}\right] \qquad (7)$$

5. Development of the control vector

5.1 The flux corrector

With this type of controller, the corrector output, represented by a Boolean variable (Cflx), indicates directly if the amplitude of flux must be increased (Cflx=1) or decreased (Cflx=0) in order to maintain the relationship:

$$\left|\left(\Phi_s\right)_{ref} - \Phi_s\right| \le \Delta\Phi_s \qquad (8)$$

with: $\left(\Phi_s\right)_{ref}$ is a reference flux and $\Delta\Phi_s$ is the hysteresis width of the corrector (Fig. 2).

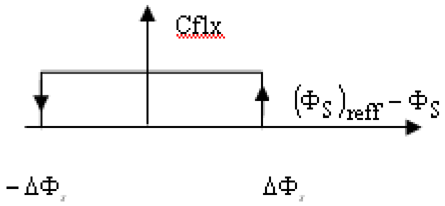


Fig. 2 – Hysteresis flux corrector

5.2 Electromagnetic torque corrector

The torque corrector maintains the torque within the following limits:

$$\left|\left(\Gamma_{elm}\right)_{ref} - \Gamma_{elm}\right| \le \Delta\Gamma_{elm} \qquad (9)$$

with: $\left(\Gamma_{elm}\right)_{ref}$ is the reference torque and $\Delta\Gamma_{elm}$ is the corrector hysteresis band.

5.3 Three levels comparators

The comparator allows the motor control in the two directions of rotation, either for positive or negative torque (Fig. 3). It indicates directly if the torque amplitude must be increased in absolute value (ccpl=1), for a positive order and (Ccpl=-1), for a negative order, or decrease (Ccpl=0).

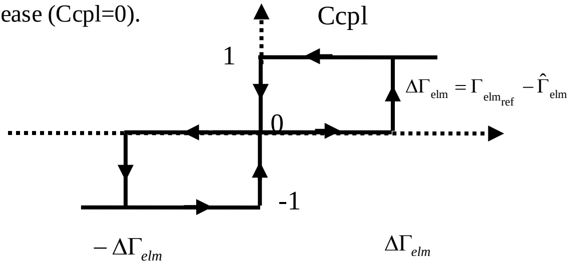


Fig. 3 : Three levels torque corrector

6. Takahashi DTC control strategy

The choice of the inverter states is carried out in a table of commutation (Table 1) built according to the variables states (cflx), (ccpl) and the area of the flux position $\left(\Phi_s\right)$. By selecting one of the vectors null, the rotation of stator flux is stopped and involves therefore a decrease of torque. We choose V_0 or V_7 in a manner to minimize the number of commutation of the same inverter switch [6].

Table 1
DTC commutation table

CFLX	1	1	1	0	0	0
Ccpl	1	0	-1	1	0	-1
S1	V2	V7	V6	V3	V0	V5
S2	V3	V0	V1	V4	V7	V6
S3	V4	V7	V2	V5	V0	V1
S4	V5	V0	V3	V6	V7	V2
S5	V6	V7	V4	V7	V0	V3
S6	V1	V0	V5	V2	V7	V4

7. DTC general control structure

The control structure of the direct torque control is represented as shown in Fig. 4 [7].

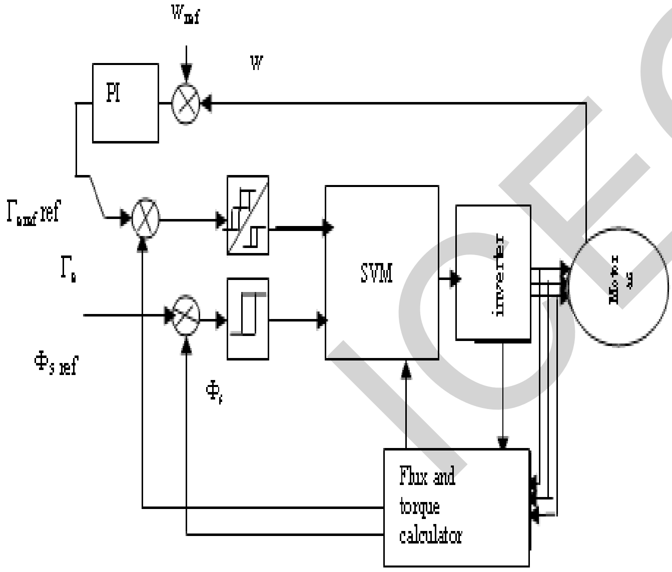


Fig. 4: General Structure of DTC with SVM

8. DTC space vector modulation (SVM)

8.1 Advantage of DTC-SVM

In the DTC system, the same active voltage vectors are applied during the whole sample period, and possibly several consecutive samples which give rise to relatively high ripple levels in stator current, flux linkage and torque. One of proposals to minimise these problems is to introduce Space Vector Modulation (SVM), which is a pulse width modulation technique that able to synthesise any voltage vector lying inside the sextant spanned by the six PWM voltage vectors.

In the DTC–SVM scheme, the hysteresis comparators are replaced by an estimator which calculates an appropriate voltage vector to compensate for torque and flux errors. This method has proved to generate very low torque and flux ripples while showing almost as good dynamic performance as the DTC system. The DTC-SVM systems, though being a good performer, but introduce an extra complexity [7, 8].

8.2 Voltage space vector modulation

The reference stator flux vector in polar form, α-β directions, is calculated by the following equations [5],

$$\begin{cases} V_{s\alpha\ ref} = \dfrac{\Phi_{s\ ref}\cos\left(\delta+\Delta\delta\right) - \Phi_{s\ ref}\cos\left(\delta\right)}{T_s} + R_s I_{s\alpha} \\ V_{s\beta\ ref} = \dfrac{\Phi_{s\ ref}\sin\left(\delta+\Delta\delta\right) - \Phi_{s\ ref}\sin\left(\delta\right)}{T_s} + R_s I_{s\beta} \end{cases} \tag{10}$$

Where the vector magnitude and angle are given as,

$$\begin{cases} V_{s\ ref} = \sqrt{V_{s\alpha\ ref}^{2} + V_{s\beta\ ref}^{2}} \\ \delta = \arctan\left(\dfrac{V_{s\beta\ ref}}{V_{s\alpha\ ref}}\right) \end{cases} \tag{11}$$

The voltage vectors, produced by a 3-phase inverter, divide the space vector plane into six sectors as shown in Fig. 5. In every sector, the arbitrary voltage vector is synthesised by basic space voltage vector of the two side of sector and one zero vector. For example, in the first sector, V_s is a synthesised by the voltage space vector equations (10) and (11) [6],

$$\begin{cases} V_s T_s = V_0 T_0 + V_1 T_1 + V_2 \\ T_s = T_0 + T_1 + T_2 \end{cases} \tag{12}$$

Where, T_s is the sample time of system, T_0 , T_1 and T_2 are the work times of basic space voltage vector V_0 , V_1 and V_2 respectively (Fig. 6); with T_1 and T_2 are given the equation (12).

$$\begin{cases} T_1 = \dfrac{T_S}{2E}\left(\sqrt{6}V_{S\beta}^{*} - \sqrt{2}V_{S\alpha}^{*}\right) \\ T_2 = \sqrt{2}\,\dfrac{T_S}{E}V_{S\beta}^{*} \end{cases} \tag{13}$$

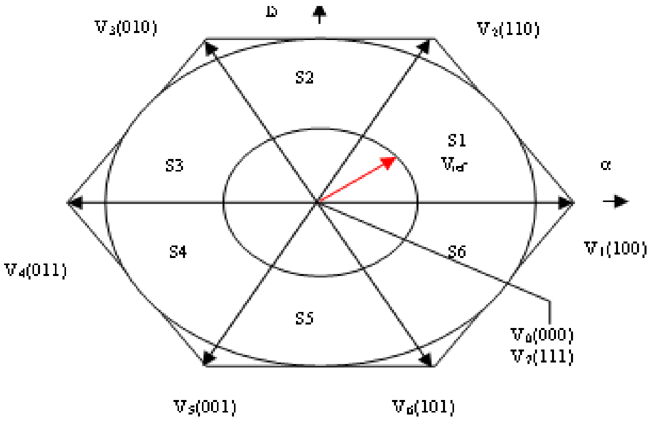


Fig.5 - diagram of the inverter exported SVM

The determination of the amount of times T1 and T2 is given by simple projections [7].

$$\begin{cases} X = \frac{T_S}{E}\sqrt{2}V_{S\beta}^{*} \\ Y = \left(\frac{\sqrt{2}}{2}V_{S\beta}^{*} + \frac{\sqrt{6}}{2}V_{S\alpha}^{*}\right) \\ Z = \left(\frac{\sqrt{2}}{2}V_{S\beta}^{*} - \frac{\sqrt{6}}{2}V_{S\alpha}^{*}\right) \end{cases} \quad (14)$$

Table 2

Applications durations of the sectors boundary

SECTORS	T1	T2
1	Z	Y
2	Y	-X
3	-Z	X
4	-X	Z
5	X	-Y
6	-Y	-Z

The third step is to compute the three necessary duty cycles as:

$$\begin{cases} T_{aon} = \frac{T_S - T_1 - T_2}{2} \\ T_{bon} = T_{aon} + T_1 \\ T_{con} = T_{bon} + T_2 \end{cases} \quad (15)$$

The last step is to assign the right duty cycle (T_{xon}) to the right motor phase according to the sector.

Table 3

Assigned duty cycle to the PWM outputs

SECTOR	1	2	3	4	5	6
Ta	Tbon	Taon	Taon	Tcon	Tbon	Tcon
Tb	Taon	Tcon	Tbon	Tbon	Tcon	Taon
Tc	Tcon	Tbon	Tcon	Taon	Taon	Tbon

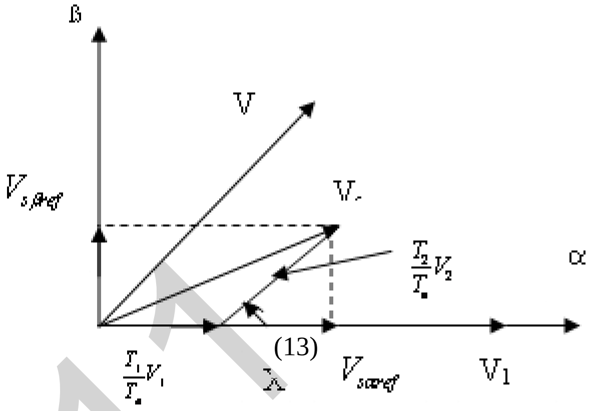
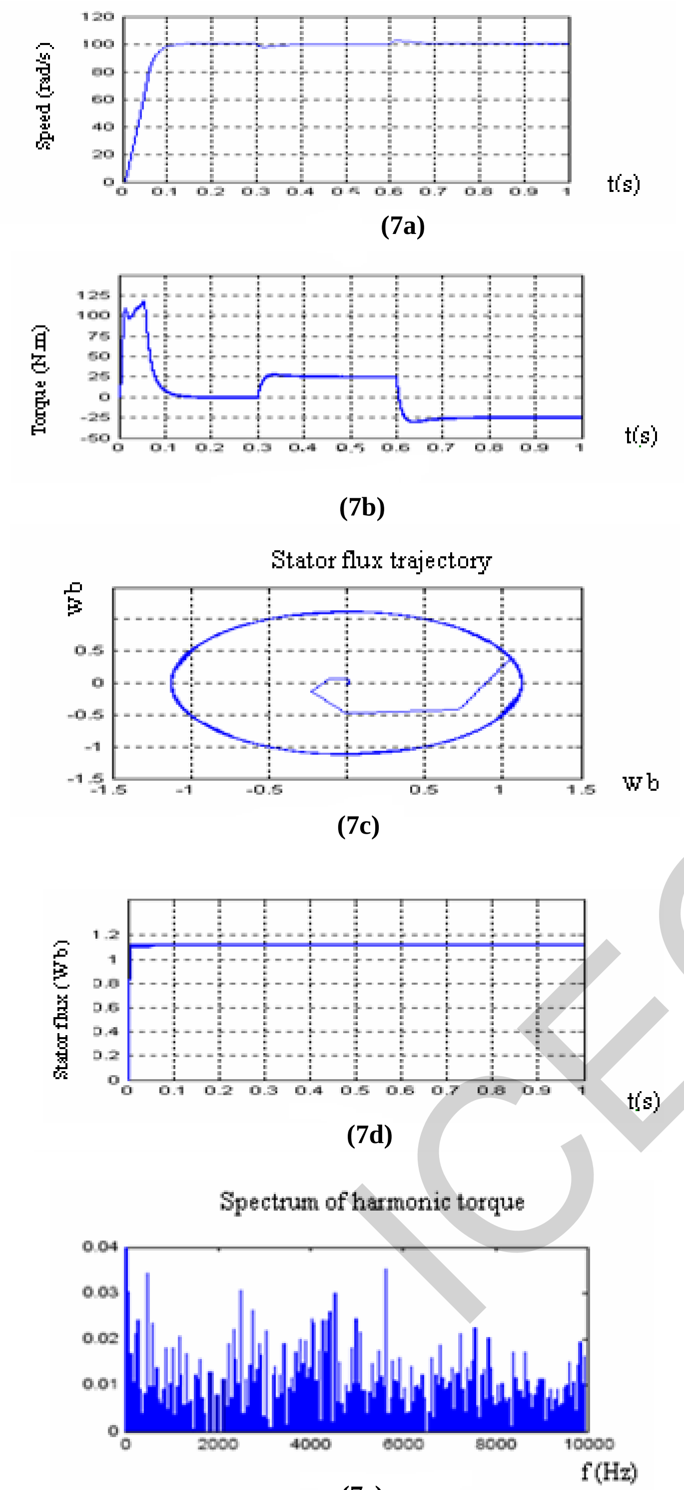


Fig. 6 – Projection of the reference voltage vector

9. Simulation results

In order to illustrate the improvements that DCT-SVM regulator offers, with regards to the conventional DTC for the static and dynamic performances of the asynchronous machine control, a simulation studies using Matlab/Simulink environment, for the same conditions, is carried out. It is noted that, the test of the robustness control is realised with respect to the parameter variations.

Simulation results of the conventional DTC, which is depicted in Fig. 7, show that the torque exceeds the lower and upper limits of the band control (Fig.7a). There is an important torque ripple rate; which is due to the application of zero voltage vectors without the knowledge of the initial rotor position and consequently the stator flux. On the other side, using DTC with SVM, the results illustrated in Fig. 8, show that the stator flux locus (Fig. 8c) is almost circular and its amplitude remains within the range defined by the hysteresis band. Also, the torque does not exceed the limits of the control strip (Fig. 8b) [8]. It is also noted that the regulation effect holds on constantly, indeed the electromagnetic torque acts very quickly to follow the profile of the introduced loads, where a remarkable decrease in the harmonic is observed in the spectrum of harmonic torque diagram (Fig. 8e), which is due of constant switching frequency. These harmonic reductions lead diminish in torque ripples significantly, decrease in the converter switching losses and consequently improves the motor performance.



(7a)

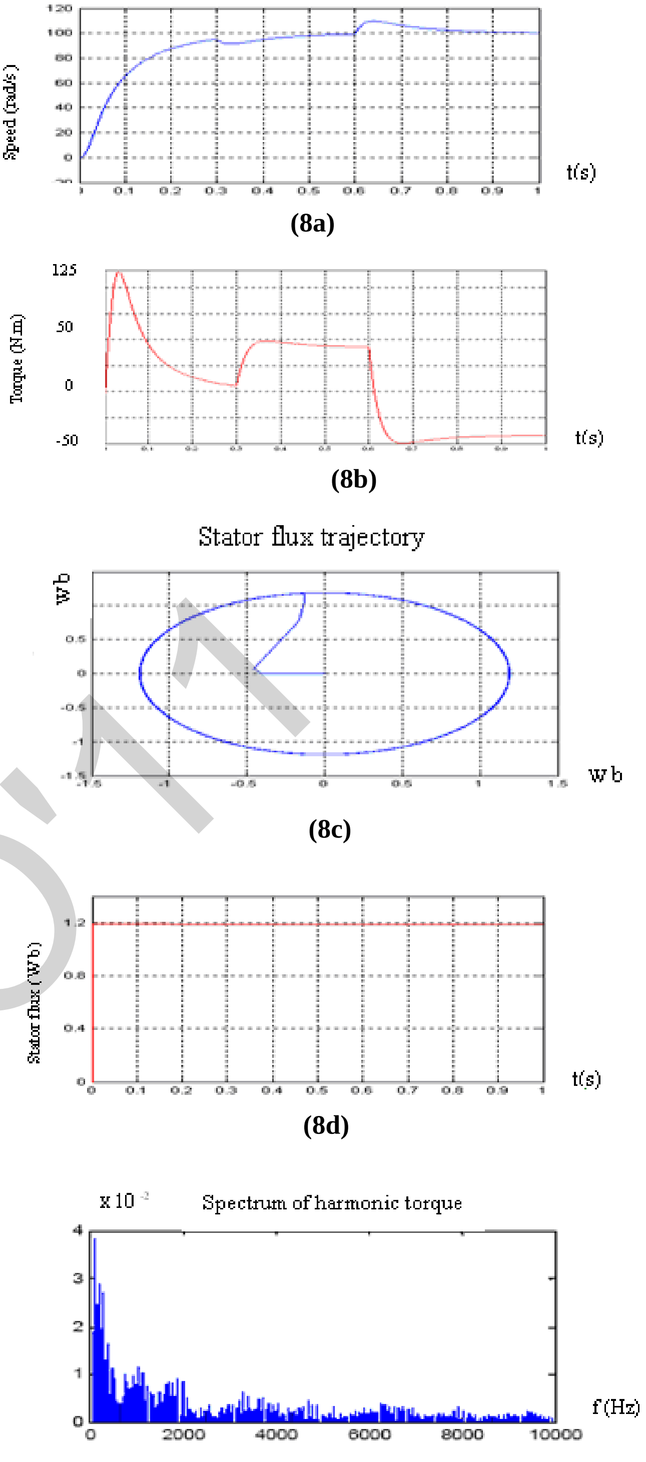
(7b)

(7c)

(7d)

(7e)

Fig. 7: Simulation results of conventional DTC: (7a) speed, (7b) Electromagnetic torque, (7c) Stator flux trajectory, (7d) and (7e) spectrum of harmonic torque



(8a)

(8b)

(8c)

(8d)

(8e)

Fig. 8: Simulation results of Classical DTC with SVM: (8a) speed, (8b) Electromagnetic torque, (8c) Stator flux trajectory, (8d) and (8e) spectrum of harmonic torque

10. Conclusion

In this article we have introduced the DTC-SVM control approach. our choice of this method for the control of asynchronous machines is justified. Having chosen the Matlab/Simulink as tools of simulation, under several operating conditions, to observe difference between DTC and DCT-SVM, the following results are obtained:

It is shown that in the case of direct torque control strategy with SVM the magnetic flux and the torque ripples are smaller as in conventional DTC strategy but the current amplitude is higher.Thus it was clearly shown that DTC SVM regulator exceeds DTC regulator. Also, there is harmonic reduction due to constant switching frequency, which leads a decrease in the converter switching losses. But in spite of the robustness of DTC SVM regulator for the considered variations (load torque) with respect to DTC, nevertheless there are certain reserves on the characteristics of this new control technique about its high performances when the operating conditions change in large band [9].

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