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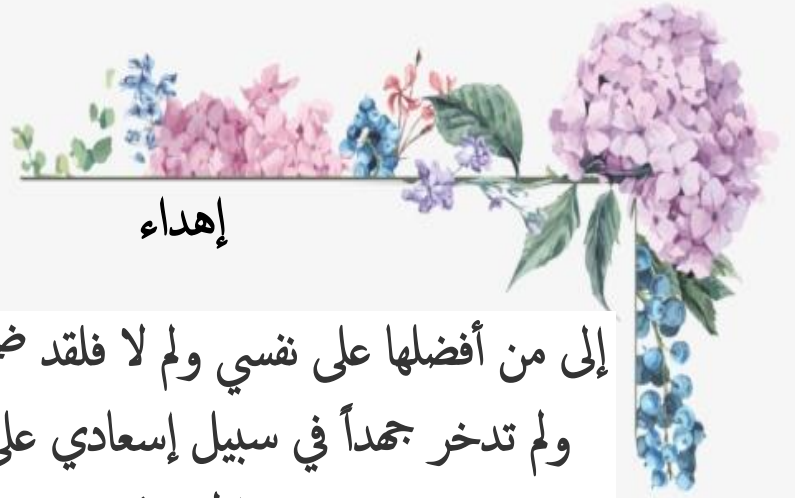
TouaharAbdellatif   ZemitAbdelmalek

Title

DTC-SVM Control of induction motor
Fed by PWM inverter

Before the jury

MrDjallalAbdessemed	**President**	**UKM Ouargla**
MrKadriFarid	**Supervisor**	**UKM Ouargla**
Miss Souri Samira	**Examiner**	**UKM Ouargla**
MrTamissaYounes	**Supervisor**	**UKM Ouargla**

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إهداء

إلى من أفضلها على نفسي ولم لا فلقد ضحت من أجلي، ولم تدخر جهداً في سبيل إسعادي على الدوام (أمي الحبيبة).

نسير في دروب الحياة، ويبقى من يسيطر على أذهاننا في كل مسلك نسلكه.

صاحب الوجه الطيب والأفعال الحسنة، فلم يبخل علي طيلة حياته (والدي العزيز).

إلى أصدقائي وجميع من وقفوا بجواري وساعدوني بكل ما يملكون وفي أصعدة كثيرة.

أقدم لكم هذا البحث وأتمنى أن يحوز على رضاكم

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نحمد الله عز جل الذي وفقنا في اتمام هذا البحث العلمي فالحمد لله حمدا كثيرا.

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كما نتقدم بجزيل الشكر الى اعضاء لجنة المناقشة الى كل من الدكتور جلال عبدالصمد و الدكتورة سوري سميرة ، وكل من ساهم في هذا العمل و أخص بالذكر الاستاذ الدكتور طيبي جمال.

دون نسيان كل من علمنا من اساتذة و معلمين   في أطوار سابقة .

أقول شكرا لكم جميعا.

طواهر عبداللطيف

زميط عبدالمالك

Abstract:

Direct Torque Control (DTC) is a technique used to obtain excellent performance of electromagnetic torque and stator flux in induction motors. Therefore, we presented this work to improve DTC through space vector modulation (DTC-SVM), and adding a controller PI, the effect of which we show by comparing the results obtained for both the classical DTC technique and the DTC-SVM.The comparison was made on speed, stator flux, electromagnetic torque and stator current, which showed the effectiveness of DTC-SVM technology against classical DTC results in almost all comparisons.

Key words: DTC, SVM, IM, PI controller, stator flow, Electromagnetic Torque, PWM.

ملخص :

التحكم المباشر في عزم الدوران(DTC) هو تقنية تستخدم للحصول على أداء ممتاز لعزم الدوران الكهرومغناطيسي وتدفق الجزء الثابت في المحركات الحثية . لذلك ، قدمنا هذا العمل لتحسين التحكم التقليدي في عزم الدوران من خلال تعديل متجه الفضاء (DTC-SVM) ، وإضافة وحدة تحكم PI ، والتي نظهر تأثيرها من خلال مقارنة النتائج التي تم الحصول عليها لكل من تقنية DTC الكلاسيكية و DTC-SVM.تم إجراء المقارنة على السرعة وتدفق الجزء الثابت وعزم الدوران الكهرومغناطيسي وتيار الجزء الثابت ، مما أظهر فعالية تقنية DTC-SVM مقابل نتائج DTC الكلاسيكية في جميع المقارنات تقريبًا.

كلمات مفتاحية : التحكم المباشر في عزم الدوران – تعديل ناقل الفضاء – المحرك الحثي -وحدة التحكم PI– تدفق الجزء الثابت – عزم الدوران الكهرومغناطيسي-تعديل عرض النبض.

Résumé

Le contrôle direct du couple (DTC) estune technique utilisée pour obtenird'excellentes performances de couple électromagnétique et de flux de stator dans les moteurs à induction. Par conséquent, nous avonsprésentéce travail pour améliorer le DTC grâce à la modulation vectoriellespatiale (DTC-SVM) et en ajoutant un contrôleur PI, dont nous montronsl'effet en comparant les résultatsobtenus à la fois pour la technique DTC classique et le DTC-SVM. La comparaison a étéfaitesur la vitesse, le flux du stator, le couple électromagnétiqueet le courant du stator, ce qui a montrél'efficacité de la technologie DTC-SVM par rapport aux résultats DTC classiquesdanspresquetoutes les comparaisons.

Mots clés : DTC, SVM, IM, régulateur PI, débitstatorique, couple électromagnétique, PWM.

➢ **Contents**

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List of Symbols

MAS : Machine Asynchrone.

DTC : Direct Torque Control

SVM : Space Vector Modulation

PWM: pulse width modulation.

s, r : Axis indices corresponding to the stator and rotor.

a, b, c : Index corresponding to the three phases a, b, c.

V_{as}, V_{bs}, V_{cs}: Stator phase supply voltages.

Var,Vbr,Vcr : Power supply voltages of the rotor phases.

$I_{as}I_{bs}I_{cs}$: Stator currents.

I_{ar}, I_{br}, I_{cr} : Rotor currents.

Φas ,Φbs , Φcs : Stator fluxes.

Φ*as , Φ*bs , Φ*cs : Reference stator fluxes.

Φ ar ,Φbr , Φcr : Rotor fluxes.

Φ*ar , Φ*br , Φ*cr : Reference rotor fluxes.

Lss : The matrix of stator inductors.

Lrr : The rotor inductors matrix.

Rs ,ls : Self-resistance and inductance of a stator phase.

Rr ,lr : Self-resistance and inductance of a rotor phase.

Msr : Mutual inductance between a stator phase and a rotor phase.

ms : Mutual inductance between stator phases.

mr : Mutual inductance between rotor phases.

θ : Electric angle.

(α , β): Shafts fixed to the stator.

(d,q) : Axes fixed with respect to the rotating field.

θs ,θr : Phase shift of the direct axis with respect to the stator and rotor.

θ*s , θ*r : Phase shift of the direct axis with respect to the stator and reference rotor.

Ω : Mechanical rotation speed [rad/s].

ⱳ$_r$: Electrical rotation speed [rad/s].

p : Number of pole pairs.

C$_r$: Resistant couple.

F : Coefficient of friction.

J : Moment of inertia of the rotating part of the machine.

Te: Electromagnetic couple.

σ: Coefficient de dispersion.

t$_r$: Rotor time constant.

t$_s$: Stator time constant.

V$_s$: Effective voltage value.

ⱳ$_s$: Power pulse.

K$_P$**:** Proportionality factor.

K$_i$ **:** Integral factor.

General introduction

The robustness, low cost, performance, and ease of maintenance make the asynchronous motor an interesting option in many industrial applications. Progress in power electronics with the appearance of fast power components and the development of digital control technology has made possible the use of complex and highly evolved control structures.[1]

This motor must respond effectively to setpoint variations (speed, position, torque) and this, in a wide range of variations of the operating point. Therefore, we must have direct and immediate access to the torque to control it quickly and appropriately to better adapt the motor to the imposed requirements.[2]

On the other hand, its control is more difficult to achieve than for other electrical machines. Many strategies have been developed.

We note the following two typesVector control, proposed by **Hasse** in 1969 and **Blaschke** in 1972, allows AC drives to have uncoupled control of the torque and flux of the machine. Therefore, the torque dynamics can be very fast. Since then, this method has been the source of several industrial achievements in various fields, such as robotics, machine tools, electric traction, etc.[3]The idea of direct torque control (DTC) formulated by Takahashi (1986) and Depenbrock (1988) introduced a new alternative for the control of asynchronous machines.This type of control considers the converter associated with the machine as a set where the control vector is constituted by the switching states. Its main advantages are fast dynamic torque response and low dependence on machine parameters. However, two major drawbacks arise. On the one hand, the determination of the switching states is based on information on the evolution trends of the flux and the torque resulting from the non-linear elements of the hysteresis type. On the other hand, as the duration of the switchings is variable, this leads to torque and flux oscillations.To overcome the severe constraints of computation time and to improve the performance of the classic DTC command, another technique has been developed by imposing a constant modulation frequency. This technique is called DTC Constant Frequency Modulation (DTC-SVM).

The latter was developed to minimize the maximum possible harmonics in the torque and the deformation of the stator flux on the one hand and to improve the THD of the current on the other hand.[4]

We will take in each chapter as follows:

Chapter I: In the first chapter, we will review the working mechanism of DTC and DTC-SVM and the difference between them.

Chapter II: In the second chapter, we will simulate on Matlab to show the effect of these differences on the performance of DTC and DTC-SVM and make a comparison to make sure of the effect of these changes and whether there is an advantage to DTC-SVM regardless of the theoretical differences.

Chapitre I

Direct Torque Control (DTC) and DTC-SVM for induction Motor

I.1.Introduction

In order to manage the performance of induction motors, a novel control approach was created in the area of electrical engineering in the 1980s, namely in power electronics and motor drives. This technique is known as direct torque control (DTC), and it was proposed by Isao Takashi and Noguchi. In terms of dynamic performance response, the DTC approach is simpler in structure and easier to regulate the induction machine. The fundamental notion of managing the motor's performance is derived from field-oriented control (FOC). This approach was first used to control several applications, including elevators, automation robots, traction, and conveyors, in the early 1970s. However, since it needs several motor settings, this system is more complicated and harder to maintain. Direct torque control (DTC) is a control technique used in AC drive systems to obtain high-performance torque control. The conventional DTC drive contains a pair of hysteresis comparators, a flux, and torque estimator, and a voltage vector selection table, the torque, and flux are controlled simultaneously by applying suitable voltage vectors and by limiting these quantities within their hysteresis bands **[15]**. DTC drive using selection table suffers from high torque ripple and variable switching frequency. The aim of this work is to enhance the classical DTC using a space vector modulation technique (SVM) to synthesize the reference voltage vector required to meet the torque and flux demands. Direct torque control (DTC) is one of the actively researched control schemes which are based on the decoupled control of flux and torque providing a very quick and robust response with a simple control construction in Ac drives. **[22]**, **[29]**، **[8]**

I.2.Modeling of induction motor

The electrical equations and magnetic equations for an induction motor are nonlinear in the normal caseAs follows :

> *Electrical equations*

$$[v_{abcs}] = R_s[i_{abcs}] + \frac{d}{dt}[\phi_{abcs}]$$

$$[0\ 0\ 0] = R_r[i_{abcr}] + \frac{d}{dt}[\phi_{abcr}]$$

> *Magnetic equations*

$$[\phi_{abcs}] = [L_{ss}][i_{abcs}] + [M_{sr}][i_{abcr}]$$

$$[\phi_{abcr}] = [L_{rr}][i_{abcr}] + [M_{sr}]^t[i_{abcs}]$$
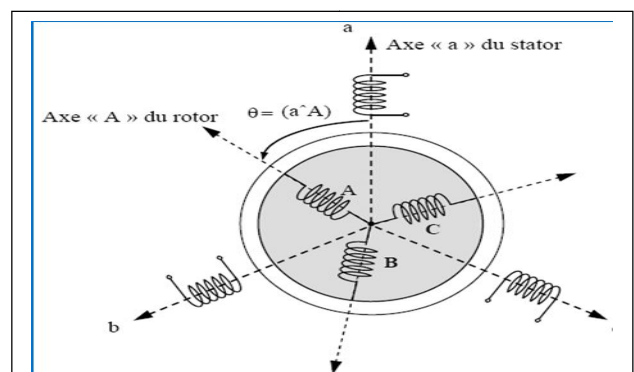
Figure 1Three axes for the stator (fixed) and three for Rotor (rotary).

We use the Park transform to convert electrical equations and magnetic equations into linear equations, which become as follows:

➢ **Electrical equations**

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{os} \end{bmatrix} = R_s \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{os} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \phi_{dr} \\ \phi_{qr} \\ \phi_{or} \end{bmatrix} + \begin{bmatrix} 0 & \dot{\gamma} & 0 \\ \dot{\gamma} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \phi_{ds} \\ \phi_{qs} \\ \phi_{os} \end{bmatrix}$$

➢ **Magnetic equations**

$$\begin{bmatrix} \phi_{ds} \\ \phi_{qs} \\ \phi_{os} \end{bmatrix} = \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_{os} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{os} \end{bmatrix} + \begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{dr} \\ i_{qr} \\ i_{or} \end{bmatrix}$$

After we converted the equations to linear, we can use them.

I.3.General StructureOf The DTC

The general principle of DTC work shown in the Figure(2)

➢ stator flux and torque are calculated

➢ reference torque is calculated from reference speed and actual speed of the motor

➢ the reference stator flux magnitude and the torque are compared with the estimated flux magnitude and torque and the flux error and torque error are delivered to the hysteresis controller
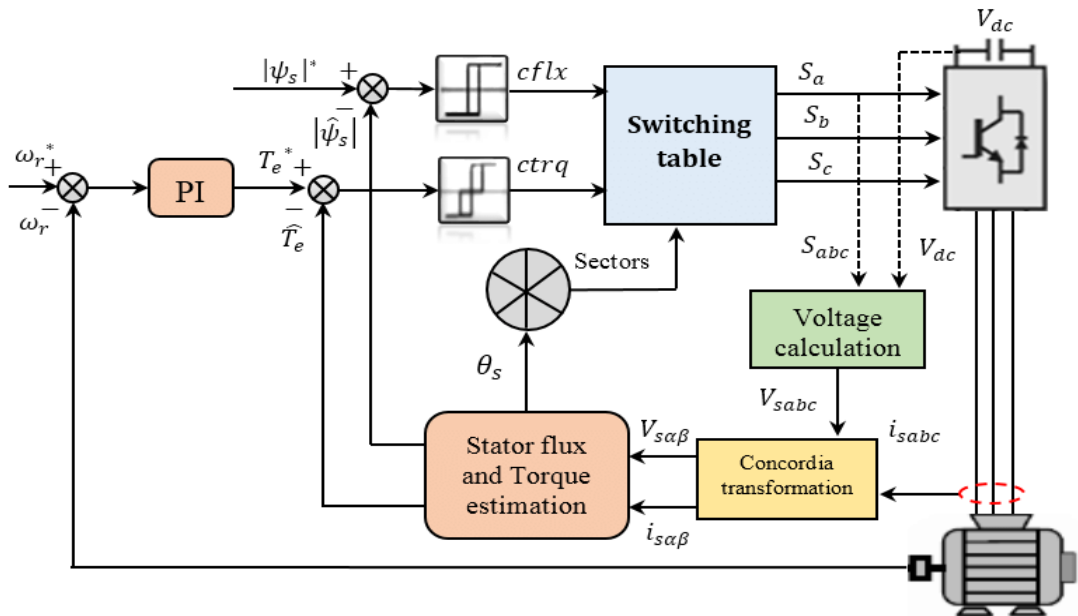
Figure 1General Structure Of The DTC

The direct torque control (DTC) is based on the direction of the stator flux and employs the voltage vector instantaneous values. A three-phase inverter can provide eight instantaneous base voltage vectors, two of which are zero. These vectors are selected from a commutation table based on flux and torque errors as well as the location of the stator flux vector. DTC is therefore distinguished as a technology suitable for operating alternating current devices without the usage of mechanical sensors.**[4]**

The model yields the following values at each moment based on measurements of the DC voltage at the inverter's input and the currents of the stator phases:

- The motor's real stator flux
- The actual torque it generates
- The position of the sector

I.4.Principles of DTC

The premise is the direct management of the machine's torque by the application of the inverter's multiple voltage vectors, which define its state.

The stator flux and electromagnetic torque are the two variables that are regulated by hysteresis regulators. It is desirable to operate with a high calculation frequency in a DTC control to prevent torque oscillations induced by the regulators.[9]

A typical two-level voltage inverter accomplishes seven unique phase plane locations, which correspond to the inverter's eight voltage sequences. The various combinations of the three values (Sa, Sb, and SC) allow for the generation of eight places of the vector VS, two of which correspond to the zero vector.[9]
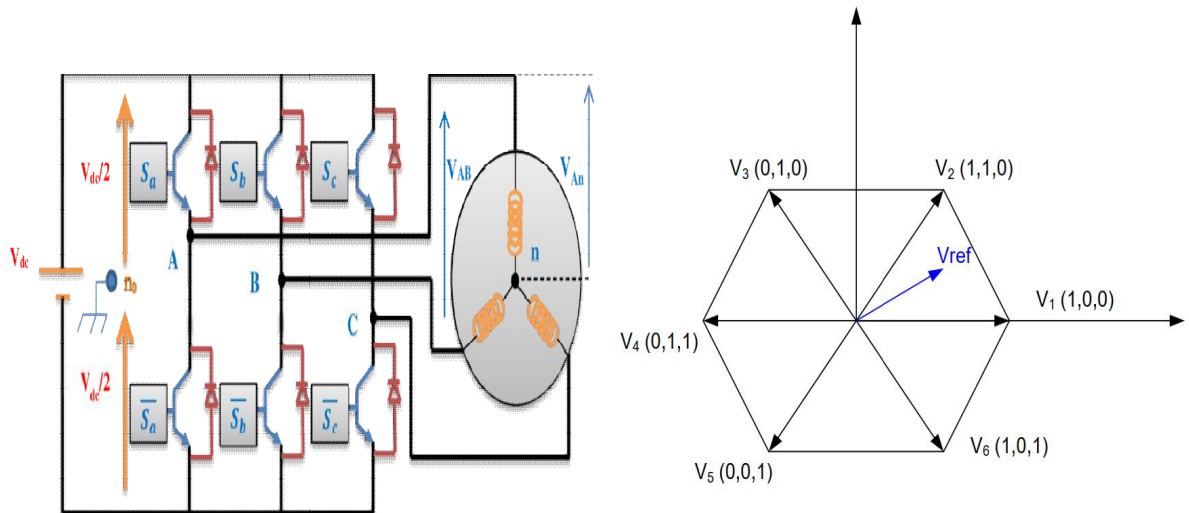
Figure 2The Voltage Inverter and Voltage Vectors Vi

I.4.1.The rule of behavior of the quantities under control (flux, torque)

To effectively manage the torque of an asynchronous machine, the flux must first be accurately adjusted. The stator flux is modified in DTC type control, on the one hand since it has a quicker dynamic than the rotor flux (the rotor time constant is bigger than that of the stator, therefore the fluctuation of the rotor flux is minimal compared to that of the stator flux). [11][12]

I.5.Stator flux vector control

Direct torque control is based on the orientation of the stator flux.The expression of the stator flux in the reference frame linked to the stator of the machine is obtained by the following equation.[13][14]

$$\Phi_s(t) = \int_0^t (V_s - R_s I_s)dt + \Phi_{s0}(1)$$

In the case where a non-zero voltage vector is applied during a time interval [0, Te],

We will have: $V_s \gg R_s I_s$. So (1) can be written:

$$\Phi_s(t) = \Phi_s(0) + V_s T_e(2)$$

$$\Delta\Phi_s = \Phi_s - \Phi_s(0) = V_s T_e(3)$$

As shown in Figure (4), Equation (3) implies that the end of the stator flux vector Φ (t) s moves on a straight line whose direction is given by the applied voltage vector Vs, as shown in Figure (6).
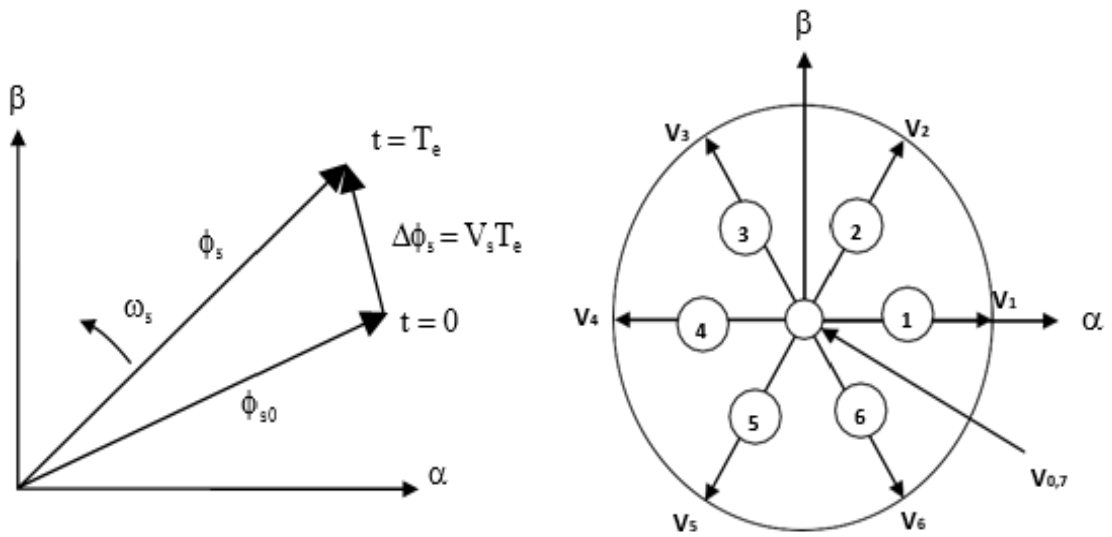
Figure 3 Evolution of the stator flux and operating sequences

The "flux component" of the voltage vector (radial component) varies the amplitude of Φs and its "torque component" (tangential component) varies the position of Φs.

By choosing an adequate sequence of vectors Vs over the control periods Te, it is, therefore, possible to operate with a practically constant flux modulus Φs, by causing the end of Φs to follow an almost circular trajectory if the period Te is very small compared to the rotation period of the stator flux.

When the selected voltage vector Vs is non-zero, the direction of displacement of the end of Φs is given by its derivative dΦs/dt, thus the "speed" of displacement of the end of Φs.

Neglecting the term Rs Is is given by Vs = dΦs/dt.

The speed of rotation of Φs strongly depends on the choice of Vs; it is maximum for a vector VS perpendicular to the direction of Φs and zeroes if a zero vector is applied. It can also be negative.

I.6.ESTIMATORS

I.6.1.Estimation of stator flux

The flux can be estimated from measurements of the stator current and voltage quantities of the machine.

From the equation:

$\bar{\varphi}_s = \int_0^t (\bar{V}_s - \bar{R}_s \bar{I}_s)$ We obtain the components α and β of the vector $\bar{\varphi}_s$:

$$\bar{\varphi}_{s\alpha} = \int_0^t (\bar{V}_{s\alpha} - \bar{R}_s \bar{I}_{s\alpha})$$

And $\quad \bar{\varphi}_{s\beta} = \int_0^t (\bar{V}_{s\beta} - \bar{R}_s \bar{I}_{s\beta})$ (4)

The voltages $V_{s\alpha}$ and $V_{s\beta}$ are obtained from the $S_a S_b S_c$ commands of the measurement of the voltage U_0 and by applying the CONCORDIA transform:

$$\bar{V}_s = V_{s\alpha} + jV_{s\beta}$$

$V_{s\alpha} = \sqrt{\frac{2}{3}} U_0 \left(S_a - \frac{1}{2}(S_b + S_c) \right)$ (5)

$V_{s\beta} = \frac{1}{\sqrt{2}} U_0 (S_b - S_c)$

Similarly, the currents $I_{s\alpha}$ and $I_{s\beta}$ are obtained from the measurement of the real currents i_{sa}, i_{sb} and $i_{sc}(i_{sa} + i_{sb} + i_{sc}) = 0$ by applying the CONCORDIA transformation:

$\bar{I}_s = I_{s\alpha} + jI_{s\beta}$

$I_{s\alpha} = \sqrt{\frac{2}{3}} i_{sa}$ (6)

$I_{s\beta} = \frac{1}{\sqrt{2}} (i_{sb} - i_{sc})$

The modulus of the stator flux is written:

$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2}$ (7)

The zone N_i in which the vector $\bar{\varphi}_s$ is located is determined from the components $\varphi_{s\alpha}, \varphi_{s\beta}$.

The angle α_s between the frame (S) is the vector $\bar{\varphi}_s$, is equal to:

$\alpha_s = \text{arctg} \frac{\varphi_{s\beta}}{\varphi_{s\alpha}}$ (8)

I.6.2.Estimation of electromagnetic torque

The torque T_{em} can only be estimated from the flux and current stator quantities. Their components (α, β), the couple can be put in the form:

$$T_{em} = p\big(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}\big) \qquad\qquad (9)$$

I.7.Elaboration of the control vector

I.7.1.Flow corrector

With this type of controller, one can easily control and trap the extremity of the flux vector in a circular crown, as shown in the figure (5). The output of the controller, represented by a Boolean variable $\left(C_{flx} = 0\right)$ indicates directly if the amplitude of the flow must be increased $\left(C_{flx} = 0\right)$ or decreased $\left(C_{flx} = 0\right)$ in order to maintain [17]:

$$|(\Phi_s)_{ref} - \Phi_s| \le \Delta\Phi_s$$

With:

$\left(\Phi_s\right)_{ref}$: is the reference flow.

$\Delta\Phi_s$: is the hysteresis width of the corrector.
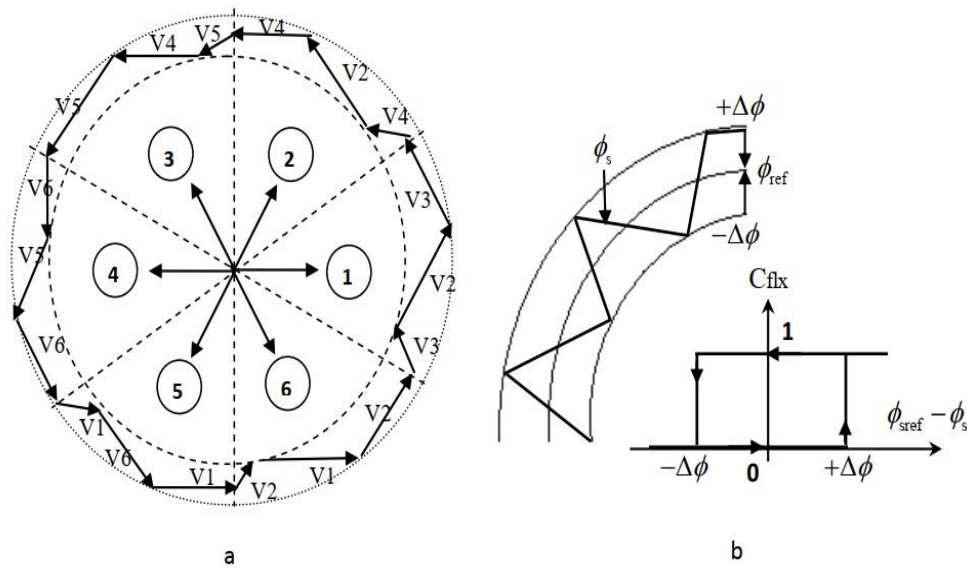
Figure 4 Flux corrector with hysteresis and selection of the corresponding voltage vectors.

$$\begin{cases} \text{if} \quad \Delta\phi_s > \varepsilon_\phi & \text{so} \quad \text{Cflx} = 1 \\ \text{if} \quad 0 \le \Delta\phi_s \le \varepsilon_\phi \text{and } \Delta\phi_s/dt > 0 & \text{so} \quad \text{Cflx} = 0 \\ \text{if} \quad 0 \le \Delta\phi_s \le \varepsilon_\phi \quad \text{and}\Delta\phi_s/dt < 0 & \text{so} \quad \text{Cflx} = 1 \\ \text{if} \quad 0 \le \Delta\phi_s < -\varepsilon_\phi & \text{so} \quad \text{Cflx} = 0 \end{cases}$$

Indeed, if we introduce the difference $\Delta\phi_s$ between the reference flux ϕ_{ref} and the estimated flux $\hat{\phi}_s$ in a two-level hysteresis comparator shown in (II.3.b), this generates at its output the value $C_{flx} = +1$ to increase the flux ($C_{flx} = 0$ to reduce it); this also makes it possible to obtain a very good dynamic performance of the flow.

Thus, only the vectors V_{i+1} or V_{i+2} can be selected to change the stator flux vector ϕ_s.

On the other hand, this corrector does not allow the inversion of the direction of rotation of the flux vector ϕ_s. Thus, to go in reverse, one has to cross one arm of the converter. [18]

I.7.2. Torque corrector
We define the error on the torque, note ε_{Tem}, as the difference between the reference torque and b its estimated value. [19] [20]

$$\varepsilon_{Tem} = |T_{emref} - T_{em}|$$

The purpose of the torque corrector is to maintain the torque within the admissible limits defined as follows:

$$|(Te)_{ref} - Te_s| \leq \Delta Te$$

With:

$(Te)_{ref}$: is the reference torque.

ΔTe: is the corrector hysteresis band.

However, a difference with flux control is that the torque can be positive or negative depending on the direction of rotation of the machine.

Two solutions can be envisaged :

- A three-level hysteresis corrector.
- A two-level hysteresis corrector.

I.7.3. Two-level corrector:
This controller is identical to the one used for flux vector control. The two-level controller is used in the case of torque control in only one direction of rotation. Only the voltage vectors $\bar{V}_{i+1}$ and $\bar{V}_{i+2}$ and zero vectors can be selected to evolve the flux vector. The torque reduction is ensured by the selection of zero voltage vectors. [21]
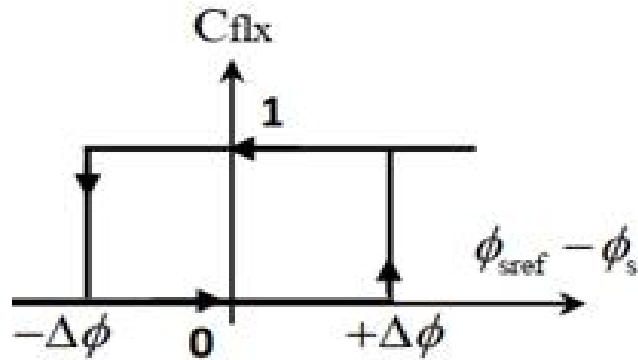
Figure 5 Two-level Flux corrector

I.7.4.Three-level corrector:

It allows the motor to be controlled in both directions of rotation, either for positive or negative torque.

The corrector output, represented by the Boolean variable Ccpl indicates directly whether the torque amplitude must be increased in absolute value (Ccpl=1 for a positive setpoint and C_{flx}=-1 for a negative setpoint) or reduced (C_{flx}=0). [21]
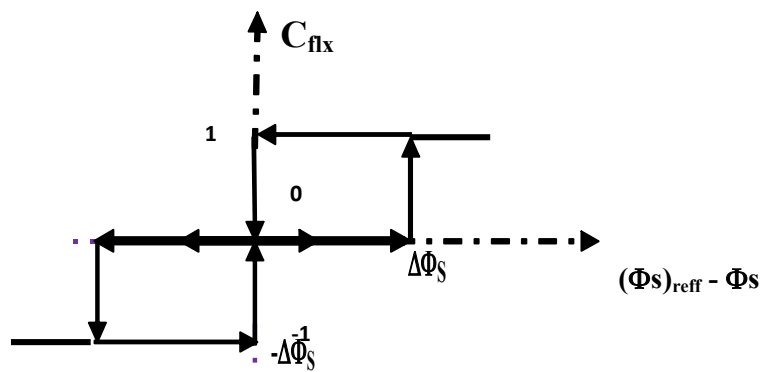
Figure 7 Three-level Flux corrector

I.7.5.Elaboration of the commutation table

The command table is constructed according to the state of the variables Cflx and Ccpl, and the position zone of N_i It therefore takes the following form:

N		1	2	3	4	5	6	COMPARATOR	
$C_{flx}=1$	$C_{trq}=1$	V2	V3	V_4	V_5	V_6	V_1	2LEVELS	
	$C_{trq}=0$	V_7	V_0	V_7	V_0	V_7	V_0		
	$C_{trq}=-1$	V_6	V_1	V_2	V_3	V_4	V_5	3LEVELS	
$C_{flx}=0$	$C_{trq}=1$	V_3	V_4	V_5	V_6	V_1	V_2	2LEVELS	
	$C_{trq}=0$	V_0	V_7	V_0	V_7	V_0	V_7		
	$C_{trq}=-1$	V_5	V_6	V_1	V_2	V_3	V_4	3LEVELS	

Table 1 Command table considering both cases of the torque controller

I.8. Disadvantages of DTC

- The existence of low-speed problems (influence of the resistive term).
- The need to have estimates of stator flux and torque.
- The existence of torque oscillations.
- The switching frequency is not constant (use of hysteresis regulators), which leads to a content rich in harmonics which increases the losses and leads to acoustic noise and torque oscillations which can excite mechanical resonances.

However, the DTC is a command which is based on the estimation of the stator flux and the electromagnetic torque. Only the variation of the resistance of the stator, due to changes in temperature or operation at low rotational speeds, degrades the performance of the DTC control. [23]

I.9. Structure of the command DTC-SVM

This technique retains the basic idea of the conventional DTC control technique. The control voltages can be generated by PI regulators of torque and stator flux and imposed by the close control technique PWM vector (SVM) .[26]

The synoptic diagram of the DTC-SVM control technique applied to the asynchronous machine is represented in **Fig8**. In this structure, two PI controllers are used for torque and stator flux control instead of hysteresis controllers (case of conventional DTC control engineering structure). These regulators calculate the required reference voltage components $vdref$ and $vqref$ in the frame (d-q). These components are then transformed into the stationary frame (α-β), and the $v\alpha ref$ and $v\beta ref$ components obtained will then be injected into the SVM vector modulation block which in turn generates the inverter control orders **[27]**
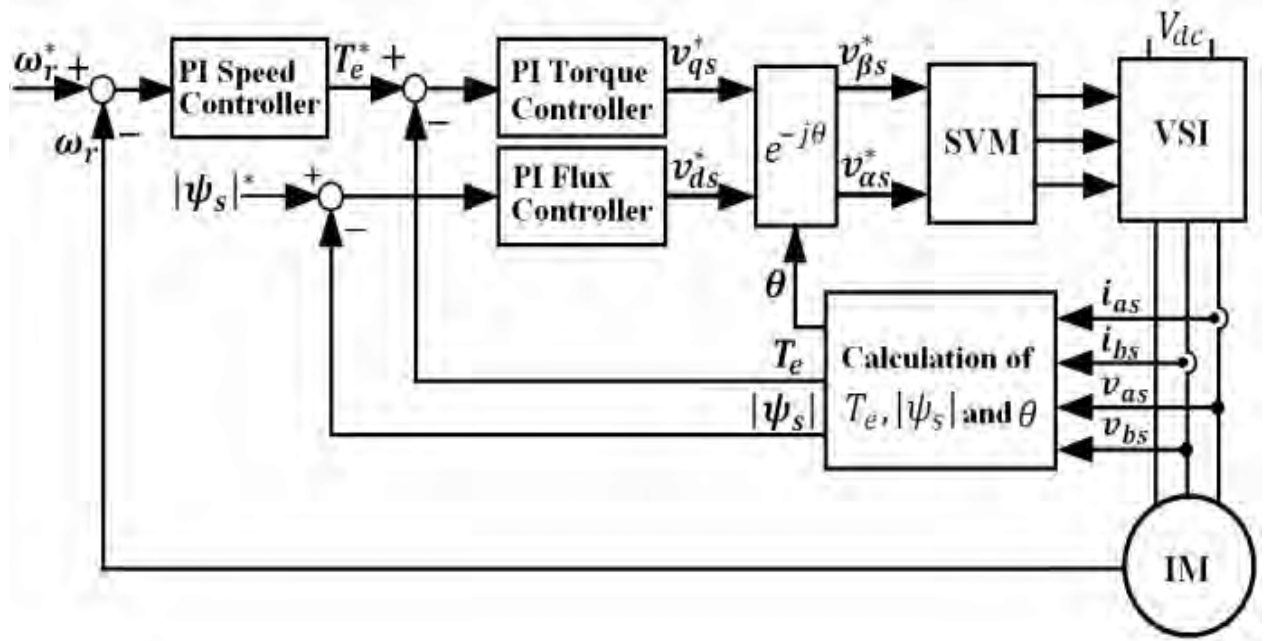
Figure 8 Diagram of the structure of the DTC-SVM command of the asynchronous machine

I.10.Principle of Vector PWM

For each period of modulation of the inverter, the three-phase voltages provided by the control algorithm can be expressed in a fixed reference linked to the stator, through their projections Vsα and Vsβ. The inverter has six switching cells, giving eight possible switching configurations. These eight switching configurations can be expressed in the plane (α, β) by 8 vectors of tensions. Knowing that in the graduation phase voltages (V_a, V_b, V_c) are represented in the plane by a vector Vs. The principle of vector MLI is to project the desired stator voltage vector Vs on the two adjacent vectors corresponding to two switching states of the inverter. The values of these projections provide the desired commutation times.

I.10.The steps for making SVM blocks

Therefore, Vector PWM (SVM) can be implemented through the following steps:

Step 1: determination of the reference voltage.

Step 2: sector determination.

Step 3: calculates application times of inverter states.

Step 4: calculates switching duty cycles for each sector.

I.10.1.Step 1: determination of reference voltage:

The outputs of the PI regulators are voltages in the two-phase reference (d-q) ,the

transformation is applied between the latter and the reference (α-β)

$$V_\alpha = V_d \cdot \cos(\theta) - V_q \sin(\theta)$$
$$V_\beta = V_d \cdot \sin + V_q \cos(\theta) \tag{10}$$

From where: $V_{\text{ref}} = \sqrt{V_\alpha^2 + V_\beta^2}$ (11)

The reference vector $Vref$ is evaluated over the modulation period Tm, by generating an

average vector determined by applying the adjacent inverter control vectors and zero vectors.

We use the eight available vectors [13].

I.10.2.Step 2: determination of sectors:

From the coordinates $V\alpha$, $V\beta$ and the angular position θ we deduce in which sector (s), and in which

region (r) is the vector $Vref$ in the plane (α-β)

$$-\frac{\pi}{6} + (N-1)\frac{\pi}{3} \leqslant \theta(N) < \frac{\pi}{6} + (N-1)\frac{\pi}{3} \tag{12}$$

I.10.3.Step 3: calculate application times of inverter states [13]

The determination of the instants $T1$ and $T2$ is given by a simple projection on the axes α and
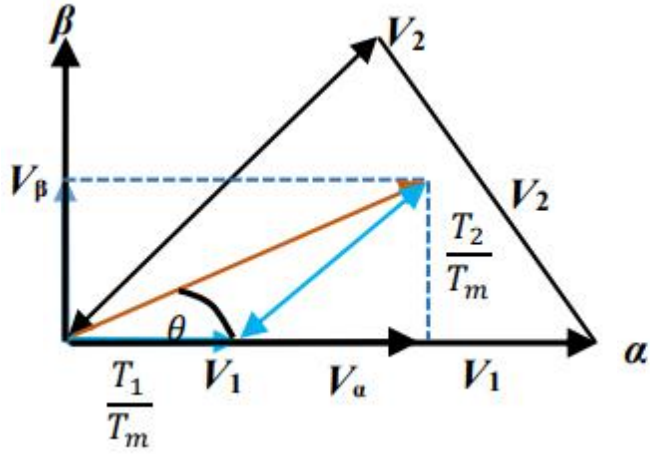
β figure (9)

Figure 6 Projection of the reference vector (sector 1).

On a:

$$\int_0^{T_m} V_{ref} \cdot dt = \int_0^{T_1} V_1 \cdot dt + \int_{T_1}^{T_1+T_2} V_2 \cdot dt + \int_{T_1+T_2}^{T_m} V_3 \cdot dt$$

$$\rightarrow T_m \cdot \overrightarrow{V_{ref}} = T_1 \cdot \overrightarrow{V_1} + T_2 \cdot \overrightarrow{V_2} + \left(\overrightarrow{V_7} or \overrightarrow{V_8}\right)$$

$$T_m \cdot |V_{ref}| \cdot \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} = T_1 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos(60) \\ \sin(60) \end{bmatrix} \tag{13}$$

Or $(0 \leqslant \theta \leqslant 60°)$ we will have:

$$T_1 = T_m \cdot \frac{|V_{ref}|}{\frac{2}{3} \cdot V_{dc}} \cdot \frac{\sin\left(\frac{\pi}{3}-\theta\right)}{\sin\left(\frac{\pi}{3}\right)} \tag{14}$$

$$T_2 = T_m \cdot \frac{|V_{ref}|}{\frac{2}{3} \cdot V_{dc}} \cdot \frac{\sin(\theta)}{\sin\left(\frac{4}{3}\right)} \tag{15}$$

For the rest of the period, the zero vector is applied during T_3:

$$T_3 = T_0 = T_m - T_1 + T_2$$

I.10.4.Step 4: calculate switching duty cycles for each sector [14]

The calculation of the cyclical switching ratios is as shown in the figure (10):

Sector 1   Sector 2

18
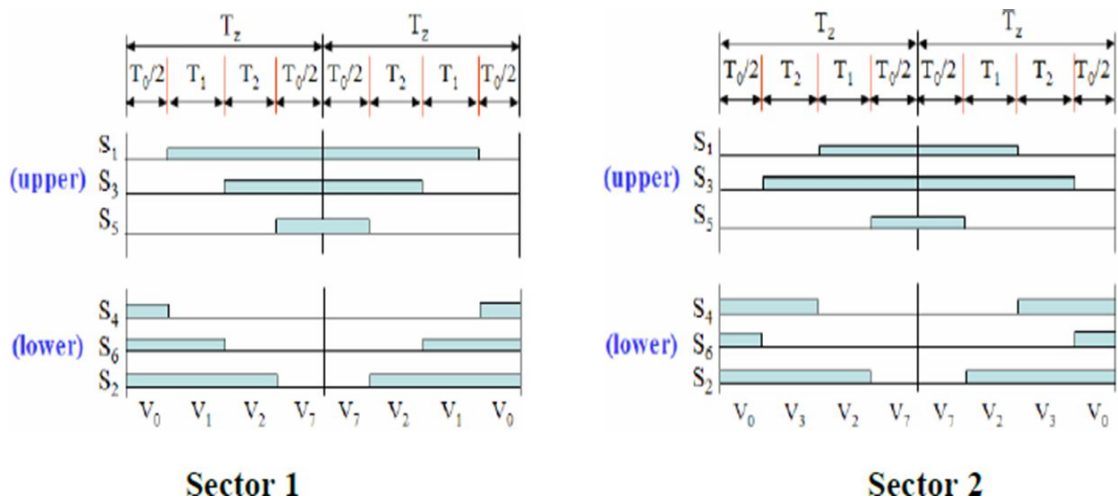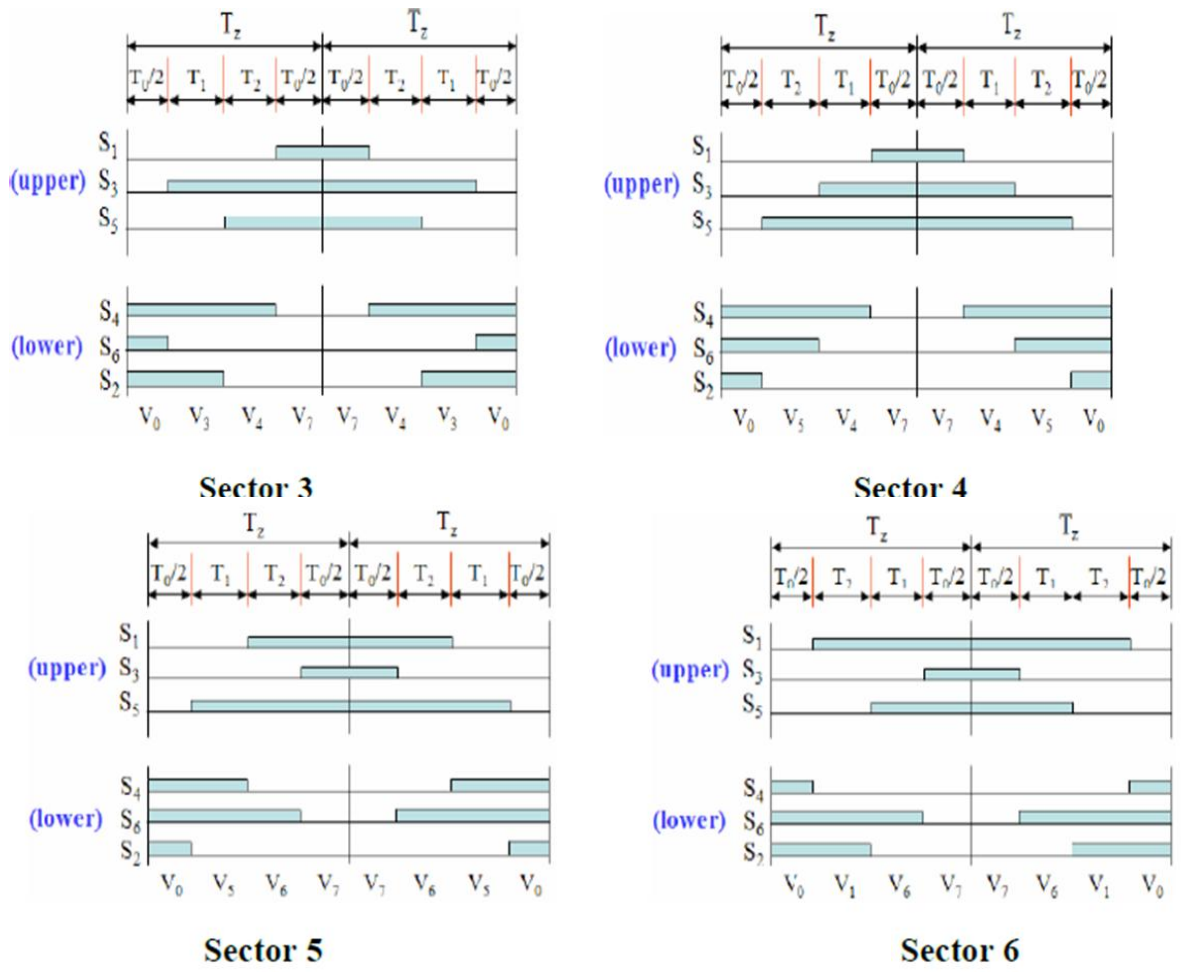
Figure 7 Pulse width shape for the six sectors.

I.11.Tableau Switch closing times per sector

This table shows the closing time for each sector

Sector	Upperswitch S_1, S_3, S_5	Lowerswitch S_4, S_6, S_2
1	$S_1=T_1+T_2+T_0/2$ $S_3=T_2+T_0/2$ $S_5=T_0/2$	$S_4=T_0/2$ $S_6=T_1+T_0/2$ $S_2=T_1+T_2+T_0/2$
2	$S_1=T_2+T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5=T_0/2$	$S_4=T_1+T_0/2$ $S_6=T_0/2$ $S_2=T_1+T_2+T_0/2$
3	$S_1=T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5=T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_0/2$ $S_2=T_1+T_0/2$
4	$S_1=T_0/2$ $S_3=T_1+T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_1+T_0/2$ $S_2=T_0/2$
5	$S_1=T_2+T_0/2$ $S_3=T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_2+T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2=T_0/2$
6	$S_1=T_1+T_2+T_0/2$ $S_3=T_0/2$ $S_5=T_2+T_0/2$	$S_4=T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2=T_1+T_0/2$

Table 2 Switch closing times per sector

I.12.Conclusion

The principle of direct torque control (DTC) presents a very interesting solution to the problems of robustness and dynamics. it is very efficient and does not require any mechanical sensor to know the position of the rotor or the speed of the machine.

In addition, this control does not require the application of a pulse width modulation (PWM) control on the inverter, which significantly improves the quantities controlled. Similarly, it is not necessary to know the angular position of the rotor because only the position of the stator flux is used.

But these issues were resolved by DTC-SVM technology, with a space vector modulation control, as well as a PI control at the Flux stator and another for the electromagnetic torque, which improved the ripples in the stator flux and the electromagnetic torque. Thus, we have solved a number of problems related to noise, durability, and others.

Chapitre II

Comparative between DTC and DTC with Space Vector Modulation (DTC-SVM)

II.1.Introduction

In the previous chapter, we talked about the DTC technology and its characteristics, as well as its defects that cause damage to the induction motor. We also talked about an alternative technique (DTC-SVM) to mitigate these damages by solving the problems and defects of the DTC.

In this chapter, we will simulate the two systems on Matlab and then compare the results obtained.

II.2.Parameters for DTC and DTC-SVM

The values presented are the ones that were adopted in obtaining these results.

II.2.1.Parameters for Induction motor

Nominal power, voltage (line-line), and frequency [Pn(w),Vn(Vrms),fn(Hz)]:

Pn= 1.5 (Kw) ,Vn= 280 (Vrms) , Fn=50 (Hz)

Stator resistance and inductance [Rs(ohm) Lls(H)]:

Rs= 0.5 (ohm), LIs= 0.005 (H)

Rotor resistance and inductance [Rr(ohm) Llr(H)]:

Rr= 1 (ohm),   LIr= 0.005(H)

Mutual inductance Lm (H):

Lm= 0.1(H)

Inertia, friction factor, pole pairs [J(kg.m^2) F(kg.m^2/s) p()]:

J=0.002(kg.m^2), F=0.05 (kg.m^2/s), P= 2

II.2.2.Parameters for PI Controller

II.2.2.1.Calculating Parameters of the PI Regulator of The Flux

So the stator flux can be controlled by the **d** component of the stator voltage. Figure (11) shows the relationship between $\mathbf{\Phi_s}$ and $\mathbf{V_{ds}}$,an equivalent second-order system with a perturbation Ed. A PI regulator can be used to obtain the desired performance and maintain the stator flux at its reference value $\mathbf{\Phi_{sref}}$.
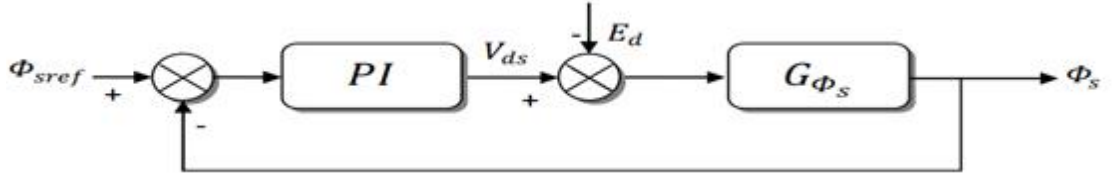
Figure 8 Flow control block diagram

The PI transfer function is given by:

$$C(s) = K_{p\Phi} + \frac{K_{i\Phi}}{s} = K_{p\Phi}\left(1 + \frac{1}{\tau_\Phi s}\right) = K_{p\Phi}\frac{(1+\tau_\Phi s)}{\tau_\Phi s} \tag{16}$$

Where K_{pf}, K_{if} denote respectively the proportional and integral gains of the corrector, and $\tau_\Phi = \frac{K_{p\Phi}}{K_{i\Phi}}$ its time constant.

The transfer function of the open loop (TFOL) is given by:

$$\text{TFOL} = C(s) \cdot G_{\Phi_s}$$

$$= K_{p\Phi}\frac{(1+\tau_\Phi s)}{\tau_\Phi s} \cdot \frac{t_s(1+\sigma t_r s)}{1+(t_r+t_s)s+\sigma t_r t_s s^2} \tag{17}$$

From the command "roots" in Matlab ,one can find the roots of the polynomial:

$1+ (tr + ts)\, s + \sigma t_r t_s s^2$ as following:

$$P_1 = f(t_r t_s \sigma)$$
$$P_2 = f(t_r t_s \sigma)$$

By eliminating the pole dominating, which is the polenearest to the secondary axis (either the pole P2). We canwrite the relation (17) in form 'pole-zero' as follows:

$$\text{TFCL} = K_{pf}\frac{\left(\frac{1}{\tau_\Phi}+s\right)}{s} \cdot \frac{\sigma t_r t_s\left(\frac{1}{\sigma t_r}+s\right)}{(s-P_1)(s-P_2)} \tag{18}$$

To eliminate the dominant pole is placed:

$$(s - P_2) = \left(\frac{1}{\tau_\Phi}+s\right) \tag{19}$$

We have:

$$\text{TFOL} = \frac{K_{p\Phi}}{s} \cdot \frac{t_s(1+\sigma t_r s)}{(s-P_1)} \tag{20}$$

The transfer function in closed loop (TFCL) is written asfollows:

$$\text{TFCL} = \frac{\text{TFOL}}{1+\text{TFOL}} \tag{21}$$

24

Substituting (20) into (21) and after simplificationWe have:

$$\text{TFCL} = \frac{K_{p\Phi}t_s(1+\sigma t_r s)}{s^2+(K_{p\Phi}t_s\sigma t_r-P_1)s+K_{p\Phi}t_s}(22)$$

To control the closed loop system, it is necessary to choosethe coefficients $K_{pf}$and K_{if}. For this, we use the methodof the imposition of the poles. The transfer function of astandard second order system is characterized by:

$$F(s) = \frac{k\omega_n^2}{s^2+2\varepsilon\omega_n s+\omega_n^2}(23)$$

Where ε and $\omega_n$are the damping coefficient and the natural angular frequency of the system. By analogy between the expressions (22) and (23) taking into account the expression (19), we find:

$$\begin{cases} (s-P_2) = (s+\frac{1}{\tau_\Phi}) \\ 2\varepsilon\omega_n = (K_{p\Phi}t_s\sigma t_r - P_1) \end{cases} \Rightarrow \begin{cases} \frac{1}{\tau_\Phi} = -P_2 \Rightarrow K_{i\Phi} = -K_{p\Phi}P_2 \\ K_{p\Phi} = \frac{2\varepsilon\omega_s+P_1}{t_s\sigma t_r} \end{cases}(24)$$

Gains are obtained for the corrector that has a minimum response time while ensuring the absence of overshoot. This technique involves the imposition of values damping and the pulsation to determine the coefficients $K_{p\Phi}$and $K_{i\Phi}$.

II.2.2.2.Calculating Parameters of the PI Regulator of the torque

As well as the torque can be controlled by the stator pulsation.(Figure 12) shows the relationship between T_e and ω_s. A PIcontroller is used to achieve the desired performance andmaintain the torque reference value$T_{e\,ref}$.
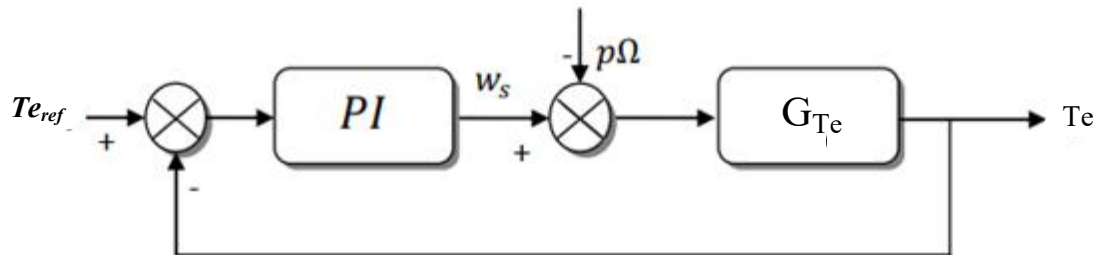

Figure 9 Block diagram of torque control

The transfer function of the PI is given by:

$$C(s) = K_{pTe} + \frac{K_{iTe}}{s} = K_{pTe}\left(1+\frac{1}{i_{Te}s}\right) = K_{pTe}\frac{(1+t_{Te}s)}{i_{Te}s}(25)$$

Where denote proportional and integral gains ofthe corrector, and $\tau_T = \frac{K_{pT}}{K_{iT}}$ its time constant.

The transfer function in a closed loop (TFCL) is given asfollows:

$$TFCL = \frac{C(s) \cdot G_{T_e}}{1 + C(s) \cdot G_{T_e}} \quad (26)$$

We have $G_{T_e} = p \frac{t_r(1-\sigma)}{L_s} \frac{\Phi_s^2}{(1+2\sigma t_r s)}$ (27)

Substituting (27) and (25) into (26) and, after simplification one finds:

$$TFCL = \frac{k_{iTe}Pt_r(1-\sigma) + \frac{2}{s}(1 + \tau_{Te}s)}{2\sigma t_r L_s S^2 + (K_{iTe}\tau_{Te}Pt_r(1-\sigma)\Phi_s^2 + L_s)s + K_{iTe}Pt_r(1-\sigma)\Phi_s^2}$$

$$= \frac{(1+\tau_{Te}s)}{\frac{2\sigma t_r L_s}{K_{iTe}Pt_r(1-\sigma)\Phi_s^2}S^2 + \frac{(K_{iTe}\tau_{Te}Pt_r(1-\sigma)\Phi_s^2 + L_s)}{K_{iTe}Pt_r(1-\sigma)\Phi_s^2}s + 1} \quad (28)$$

TFCL the form of a second order system is characterized by:

$$F(s) = \frac{k}{\frac{1}{\omega_n^2}s^2 + \frac{2\varepsilon}{\omega_n^2}s + 1}(29)$$

Identification by the equations (28) and (29) we will have:

$$\begin{cases} \frac{1}{\omega_n^2} = \frac{2\sigma t_r L_s}{K_{iTe}Pt_r(1-\sigma)\Phi_s^2} \\ \frac{2\varepsilon}{\omega_n^2} = \frac{(K_{iTe}\tau_{Te}Pt_r(1-\sigma)\Phi_s^2 + L_s)}{K_{iTe}Pt_r(1-\sigma)\Phi_s^2} \end{cases} \Rightarrow \begin{cases} K_{iTe} = \frac{2\sigma t_r L_s \omega_n^2}{Pt_r(1-\sigma)\Phi_s^2} \\ \tau_{Te} = \frac{K_{pTe}}{K_{iTe}} = \frac{2\varepsilon}{\omega_n^2} - \frac{L_s}{K_{iTe}Pt_r(1-\sigma)\Phi_s^2} \end{cases} \quad (30)$$

The technique is always about the imposition of values andpulsation ω_n and damping ε to determine the coefficients $K_{iTe} K_{pTe}$.

II.2.2.3.Calculating Parameters of the PI Regulator of the speed

The speed control is an essential need in the industry againstundesirable variations in the load. For this closed loopcontrol we use a type corrector (PI), which combines theproportional and integral action to improve the steady stateand transient response speed. The (figure.13) shows the blockdiagram of the speed control.
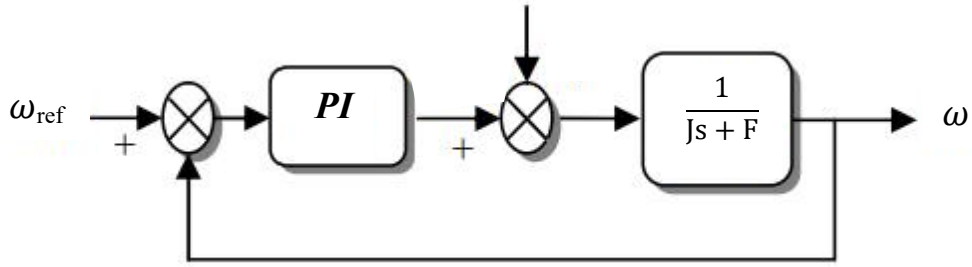
Figure 10 Conventional Control Speed

The equation in the temporal mode of this corrector is givenbelow:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau \quad (31)$$

Where $u(t)e(\tau)K_p$ and $K_i$denote respectively the error attime t, the command generated and gains of the corrector.

The corresponding transfer function is given by

$$PI(s) = K_p + \frac{K_i}{s} = K_p \left(1 + \frac{1}{\tau s}\right)(32)$$

Where s is the Laplace operator derived,$\tau = \frac{K_p}{K_i}$: Time-constant

The transfer function in a closed loop is given by:

$$\text{TFCL} = \frac{PI(s)\frac{1}{js+F}}{1+PI(s)\frac{1}{js+f}}(33)$$

Substituting equation (32) in (33), with$t_r = 0$ aftersimplification is obtained as follows :

$$\text{TFCL} = \frac{(1+\tau S)}{\frac{j}{ki}s^2+\left(\frac{f+K_p}{K_i}\right)s+1}(34)$$

To control the closed loop system, it is necessary to choose the coefficients K_p and $K_i$in this case we use the method ofthe imposition of the poles.

The transfer function of a second order system closed loop is characterized by:

$$F(s) = \frac{K}{1 + \frac{2\varepsilon}{\omega_n}s + \frac{1}{\omega_n^2}s^2}(35)$$

The characteristic equation is: $1 + \frac{2\varepsilon}{\omega_n}s + \frac{1}{\omega_n^2}s^2$ where: ω_n the damping coefficient and ω_n the natural angular frequency of the system. By identifying the relationship (34) we will have the following system:

$$\begin{cases} \frac{1}{\omega_n^2} = \frac{J}{ki} \Longrightarrow Ki = J\omega_n^2 \\ \\ \frac{2\varepsilon}{\omega_n} = \frac{Kp+F}{ki} \Longrightarrow Kp = \frac{2\varepsilon Ki}{\omega_n^2} - F \end{cases}$$

The Gains of the corrector are obtained to have a minimal response time while ensuring the absence of overshoot. This technique involves the imposition of values of damping and the pulsation ε and ω_n to determine the K_p and K_i coefficients.**[28]**

II.2.3. PI Controller for DTC
- PI Speed: Kp= 2, Ki= 5

II.2.4. PI Controller for DTC-SVM
- PI Speed:Ki=5, Kp=2
- PI Electromagnetic torque:Ki=25422.4, Kp= 7844.5
- PI stator flux:Ki=315, Kp=25.2

II.3.Matlab Simulation

Figure 11Matlab Diagram for DTC-SVM

II.4.Simulation Results

The simulation of the DTC and the DTC-SVM is achieved using the Matlab.

DTC-SVM   **DTC**
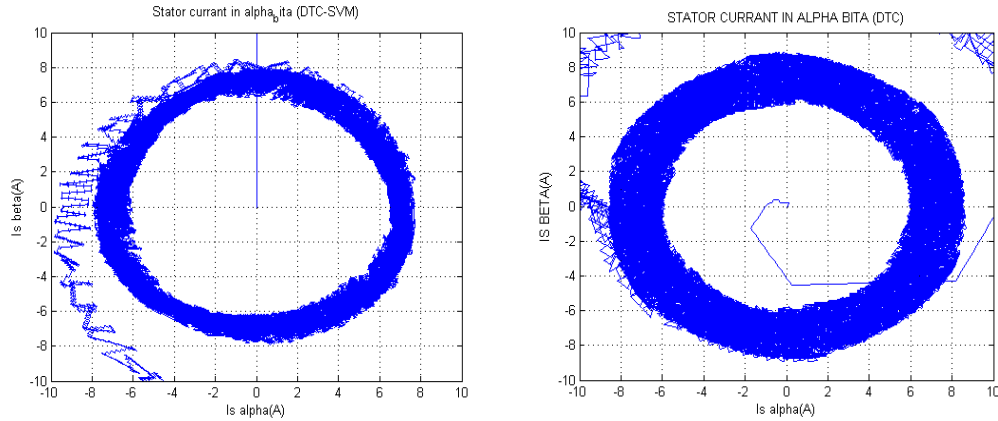
Figure 12 Trajectory of the extremity of the stator

Obtained results have been showing in **Fig.19**.that the DTC-SVM strategy offer lower commutation frequencies than the DTC strategy.

DTC-SVM   **DTC**
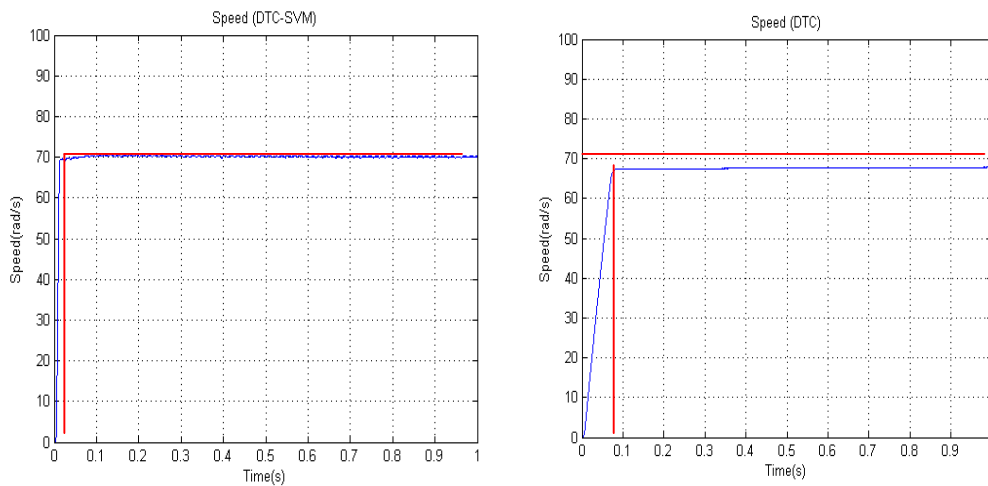
Figure 13 Evolution of the real stator flux for: DTC-SVM, DTC

From **Fig20**it is shown that the latency to Reference SpeedIt is noticeably faster in the DTC-SVM, and the error rate is also very low.But there is a little better stability in speed when using DTC technology.

DTC-SVM   DTC
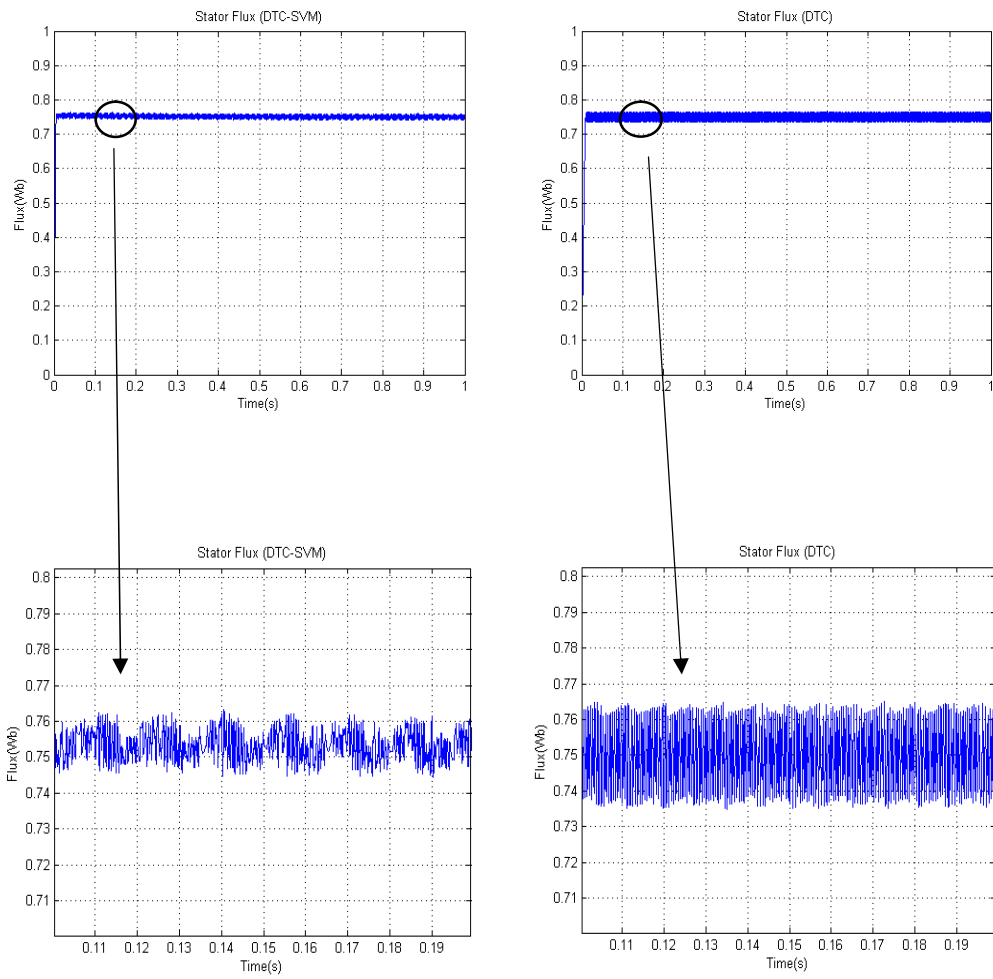
Figure 14 Evolution of the real stator flux for: DTC-SVM, DTC

DTC-SVM   DTC
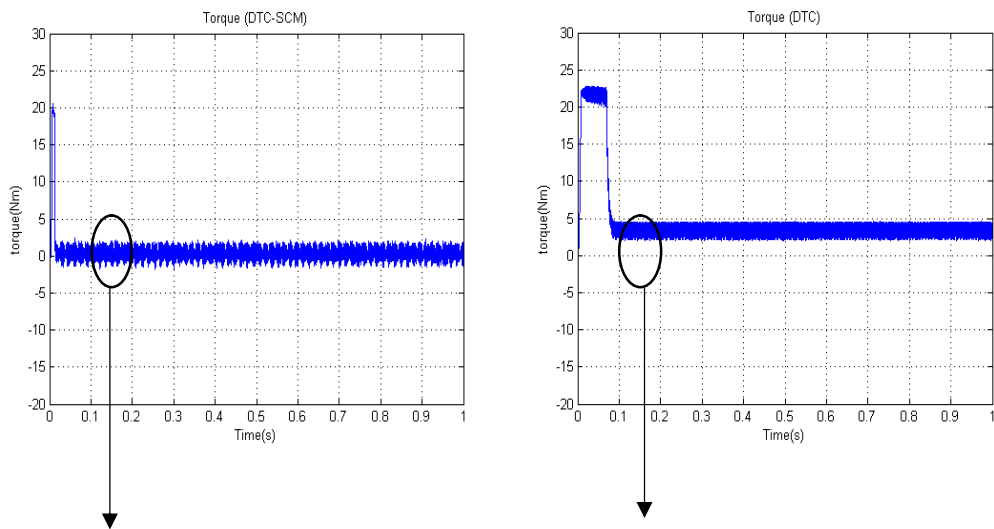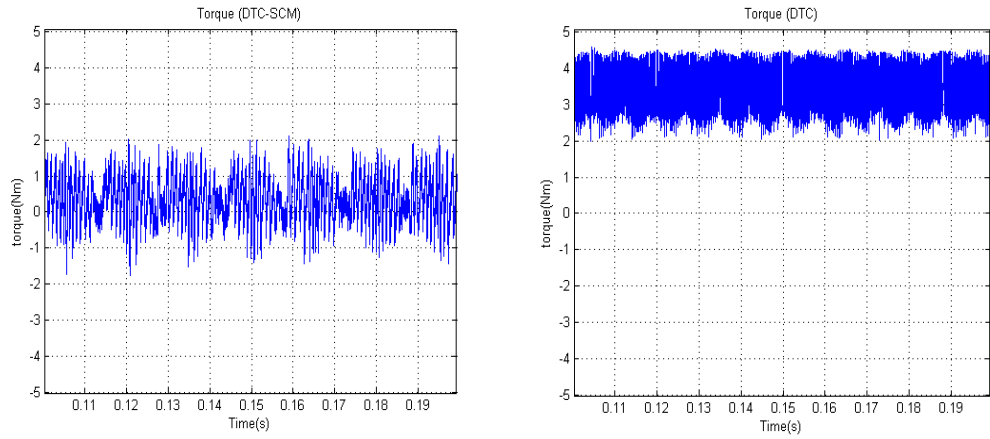
Figure 15 Electromagnetic torque for: DTC-SVM , DTC
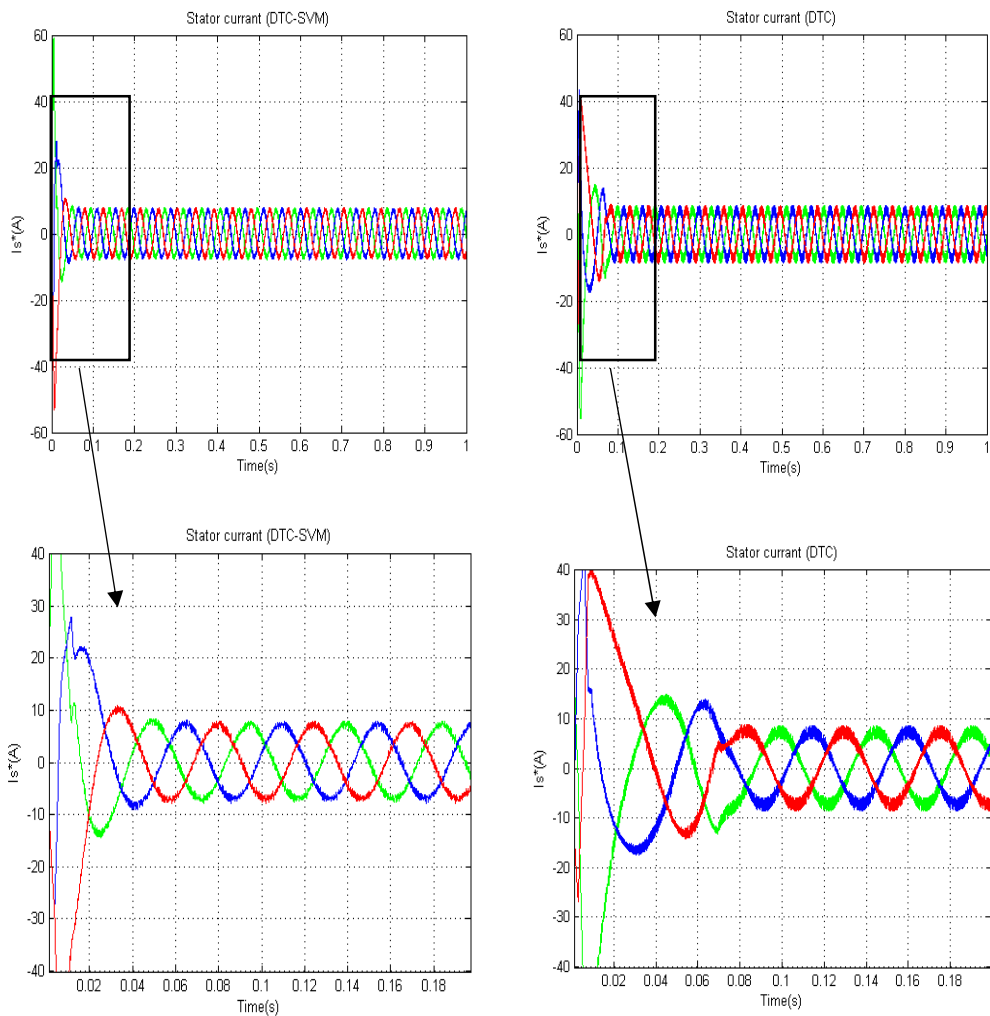
Figure 16 Evolution of the stator current for: DTC-SVM, DTC

Through **Fig21** and **Fig22** for every From traditional DTC and DTC-SVM. These results show the effectiveness of the DTC-SVM control relative to the conventional DTCcontrol in terms of ripples in the stator flux and electromagnetic torque and in terms of distortion in the stator current. In **Fig23**

II.5.Conclusion

In this chapter, the superiority of DTC-SVM technology over DTC is confirmed by comparing the results obtained from simulation. Where the comparison was made between speed, electromagnetic torque, stator flux, stator current, and Trajectory of the extremity of the stator, and we got very good results for DTC-SVM in almost all comparisons, although there is a problem in the values of both ki and kp (Pi controller for electromagnetic torque, stator flux) .

Conclusion General

We have done this work in order to solve the problems of induction motors represented by electromagnetic torque ripple and flux stator ripple using SVM-DTC technology, which is the technology developed from the classic DTC, showing the difference between the two mentioned techniques in terms of the mechanism of work and the results of each of our technology, where to two chapters.

In the first chapter, we showed the schematic diagram and the working mechanism of each technique (DTC and SVM-DTC), where the difference appears in the presence of a special PI controller for each of the Flux Stator and Block SVM, Torque Electromagnetic in SVM-DTC only. And we have explained the importance of this addition in the first chapter, and they share in the rest of the components.

As for the second chapter, we moved to the practical side, where it was necessary to confirm the theoretical aspect that we talked about in the first chapter, and this is what we did, after we simulated each of the classic SVM-DTC and DTC technology using Matlab program, where the results showed the superiority of SVM-DTC in a way It is clear in all comparisons, and this is what we have been talking about since the beginning by proposing technology SVM-DTC as an alternative solution to problems Resulting from the use of traditional DTC technology.

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