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TOPIC

Direct Torque Control of Dual Star Induction Machine

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فَتَعَالَى اللَّهُ الْمَلِكُ الْحَقُّ

وَلَا تَعْجَلْ بِالْقُرْآنِ

مِنْ قَبْلِ أَنْ يُقْضَىٰ إِلَيْكَ وَحْيُهُ

وَقُلْ رَبِّ زِدْنِي عِلْمًا

طه 114

Thanks

First and foremost, we would like to thank Almighty God for the will, health, and patience He has granted us throughout these long years. Therefore, we also wish to express our deepest thanks and gratitude to our supervisor, ***Mrs. AMEUR FATIMA****, for proposing this topic and for her continuous guidance throughout the completion of this memorandum, which has been invaluable in providing us with advice. Finally, our thanks to those who have contributed directly or indirectly to the development of this memorandum.*

Dedication

To the one whose forehead was drenched in sweat and the one who taught me that success only comes with patience and determination, the one in whom I draw my strength and my pride, my father

To those who have put Paradise under their feet and relieved me of difficulties by their supplications, who wish that their eyes would be refreshed to see me on a day like this. My mother and my grandmother's second mother

To the firm side and hopes of my days, to whom I strengthened my support, and they were for me springs from which I drank, in the best and brightest days of my days........ My brothers and sisters

My second support and refuge in all areas............My aunts and their children, without exception

To all those who have been a help and support on this path, to the friends and faithful companions over the years, to those who go through adversity and crises, to those who have shared with me their feelings and their sincere advice.

To you, my family, I dedicate this achievement and sign of success that I have always desired. Here I am today finishing and completing my first graduate thanks to Him, Glory to Him, praise to God.

Praise to God, thanks, love and gratitude for the beginning, end and last of their prayers........(Praise be to Allah, Lord of the universe)

Bilal

Dedication

To myself, who struggled for years,

To my dear parents, thank you for being the light of my path and my support at every moment, I dedicate my success to you.

To my dear sisters, childhood companions and supporters of my success, I dedicate this modest achievement to you.

To my precious family, a source of tenderness and support, I dedicate to you the fruit of my efforts and the joy of my heart.

To those who taught me the meaning of friendship, my dear friends, I dedicate my gratitude to you.

Thank you all, because you made my trip easier and more beautiful. I dedicate the joy of my graduation to

Louai

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ملخص

في هذه المذكرة نقدم التحكم في محرك غير متزامن نجمي مزدوج مدعوم من محولين تيارين. قدمنا أولاً نموذج الآلة بناءً على تحويل بارك. بعد ذلك، وبهدف تحسين الأداء الإحصائي والديناميكي والمتانة، اخترنا تطبيق إحدى تقنيات التحكم القوية، والتي تسمى DTC للتحكم المباشر في عزم الدوران. أظهرت النتائج التي تم الحصول عليها أن تقنية التعديل هذه توفر تحسينات ملحوظة.

كلمات مفتاحية : محركات كهربائية ثنائية النجم , DTC,محرك غير متزامن

Résume

Dans ce mémoire nous présentons la commande d'un moteur asynchrone double étoile alimentée par deux onduleurs de courants. Nous avons présenté d'abord le modèle de la machine basé sur la transformation de Park. Ensuite, et dans le but d'améliorer les performances statistique et dynamique et de la robustesse, nous avons opté d'appliquer de l'une des techniques de commande robuste, nommée commande directe de couple DTC. Les résultats obtenus ont montré que cette technique de réglage apporte des améliorations remarquables.

Mots clés : Machine asynchrone, DTC, MASDE, Machine asynchrone double étoile

Summary

In this memory we present the control of a double star asynchronous motor powered by two current inverters. We first presented the machine model based on the Park transformation. Then, and with the aim of improving the statistical and dynamic performances and robustness, we opted to apply one of the robust control techniques, called direct torque control DTC. The results obtained showed that this adjustment technique provides remarkable improvements.

Keywords: Asynchronous machine, DTC, DSIM, Dual Star Induction Machine

SYMBOLIC NOTATIONS

SYMBOLIC NOTATIONS

Symbol	Signification	Unit
C_{em}	Electromagnetic torque	N.m
C_r	Resistant torque (load torque)	N.m
F	frequency	Hz
f_C	Cut-off frequency	Hz
J	Machine moment of inertia	Kgm^2
K_f	The coefficient of friction	Kg/m^2
L_m	The magnetization inductance.	H
L_{s1}	The self-inductance of the 1st star	H
L_{s2}	The self-inductance of the 2nd star	H
L_{mr}	The maximum value of the rotor mutual inductance coefficients	H
L_r	The self-inductance of a phase of the rotor	H
L_{ms}	The maximum value of the stator mutual inductance coefficients	H
M_{sr}	The maximum value of the mutual inductance coefficients between a star	H
ω_{coor}	The speed of rotation of the reference frame (d,q) relative to star 1	tr/mn
ω_{roor}	The rotation speed of the mark (d,q) relative to the rotor	tr/mn
Ω_m	Mechanical rotation speed of the rotor	tr/mn
θ_0	The initial position of the rotor relative to star 1	rad
ω_s	Stator electric pulsation	rad/s, tr/mn
ω_r	Rotor electric pulsation	rad/s, tr/mn
$\mathcal{G}$	Sliding	Without unit
P	The number of pole pairs per machine	Without unit
C_{ref}	Reference torque	Without unit
ϕ_{si}	Star flux	Wb
ϕ_r	Rotor flux	Wb
$\Delta\phi_s$	The hysteresis width of the corrector.	
ΔC	the torque hysteresis band	Without unit
$(\phi_s)_{ref}$	The flux instruction	Without unit
ϕ_m	The total magnetizing flux	Wb

$\overrightarrow{\phi_s}$	The stator flux vector.	Without unit
$\overrightarrow{\phi_r}$	The rotor flux vector referred to the stator.	Without unit
R_r	Resistance of a rotor phase	H
R_{S1}	The resistance of a phase of the 1^{st} star	H
R_{S2}	The resistance of a phase of the 2^{nd} star	H
$a_{s1,}\ b_{s1},\ c_{s1}$	The indices corresponding to the three phases of stator 1	Without unit
$a_{s2,}\ b_{s2},\ c_{s2}$	The indices corresponding to the three phases of stator 2.	Without unit
$a_{r,}\ b_r,\ c_r$	The indices corresponding to the three phases of the rotor.	Without unit

GLOSSARY

Acronym	Meaning
DSIM	Dual Star Induction Machine
PWM	Pulse Width Modulation
DTC	Direct Torque Control

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GENERAL INTRODUCTION

GENERAL INTRODUCTION

Recently, alternating current machines occupy an important and central place in the production of electrical energy and the operation of motors. They have largely replaced direct current machines thanks to their advantages in terms of high efficiency and ease of control. Asynchronous machines were mainly used as motors, while synchronous machines were the preferred choice to be used as generators

Increasing demand for electricity and the use of high-power electrical technologies have led to the adoption of multi-stage (three or more phases) machines for power distribution. In addition to this advantage, multi-phase machines have many other benefits, such as power distribution without increasing current per phase and reducing iron losses. Due to these advantages, multi-phase machines are widely used in various fields, especially in high-power applications such as wind power generation.

Dual Star Induction Machine (DSIM) are among the most common examples of polyphase machines. In a typical configuration, two identical three-phase windings, each forming a star, share the same stator with an electrical offset of 30 degrees. These windings have the same number of poles and are powered at the same frequency. The rotor retains the same structure as a three-phase asynchronous machine. In addition to the benefits of power division and redundancy, this machine significantly reduces electromagnetic torque ripple and rotor losses.

The main objective of this study is to control a double star asynchronous machine in order to study how to improve its dynamic and static characteristics with respect to parametric variation.

In this context, this dissertation is divided into three chapters:

The first chapter presents general information (characteristics, uses, advantages and disadvantages) related to multi-phase machines.

The second chapter was devoted to the modelling of asynchronous star machines (DSIM).

The last chapter presents the direct torque control of DSIM and the results of numerical simulations.

At the end of this work, a general conclusion will be presented in which some observations will be presented and possible visions will be presented regarding the continuation of this work.

Chapter I

Introduction to multiphase machines

I.1 INTRODUCTION

Multi-phase machines, or polyphase machines, are electromechanical devices that operate with power systems having more than three phases. Unlike conventional three-phase machines, multi-phase machines can use four, five, six or even more phases. These machines offer several advantages in terms of performance, robustness and control. This chapter presents general information related to multi-phase machines.

I.2 HISTORY OF ELECTRIC MACHINES

We give a historical overview of the discovery of electrical machines:

- In 1821, the Englishman Michael Faraday invented the first electric motor.

The following year, Peter Barlow added material. Faraday explained the principle of electromagnetic induction in 1938. At the same time, Frederick Emil Linz in Russia and Joseph Henry in the United States carried out similar research and contributed to the discovery and to understanding this phenomenon.

-In 1832, Ampère collaborated with the French manufacturer Hippolyte Pixi to create a DC generator.

- In 1836, the Englishman Hyde Clarke built a structure machine opposite the Pisay/Ampère and improved the adjusting switch.

- En 1842, Davidson utilise l'une des premières machines électriques tournant à réactance variable.

- The Froment engine appeared in 1848, with a torque of 500 Nm. These engines were probably the first to be used in industrial applications.

-In 1860, the company "Alliance" industrialized the manufacture of generators with complex structures.

- In 1865, the Italian Antonio Pacinotti built a prototype DC engine with a toroidal armature and a radial current collector.

-1888 Nikola Tesla filed several patents for the whole of his multi-phase system (Transformers, synchronous, asynchrone engines, etc.). Over the years, there has been a debate between Edison and Tesla about the choice of continuous current or alternate current for the production, use and consumption of electricity. From this brief history, we note Researchers and engineers have also continued to improve, develop and invent other machines to meet the needs of a variety of industrial and domestic applications, giving rise to a range ranging from “micro machines” to “micromachines” of many machines. "Gigabit machine." The ability to regulate the electrical energy provided by power electronics technology not only significantly changes the operating conditions of traditional DC and AC engines, but also leads to the emergence of new categories of engines such as DC engines without beam, etc. [1]

I.3 CLASSIFICATION OF ELECTRIC MACHINES

The classification of machines can be carried out in different ways [2]:

- By construction.
- By supplying or transmitting current/voltage.
- The mode of operation.

In reality,

I.3.1 by their construction

- Machine without collector.
- Asynchronous Machines.
- Permanent magnet synchronous machine.
- Machines with collector.
- Continuous current machines.
- Synchronous machines.

I.3.2 By their type of power supply

– Continuous current machines (serial, parallel or combined).

– Alternate Current Machines (Synchronous machines, Asynchronous machines)

I.3.3 By mode of operation

– engine.

– generator or converter.

I.4 MACHINES MULTI-PHASEES

It is a system consisting of multiple alternating currents (AC) that are phase-shifted relative to each other. In the most common three-phase systems, the currents are phase-shifted by 120°. As the number of phases increases, the distribution of the current differs more.

I.5 CHARACTERISTICS OF MULTIPHASE MACHINES

There are generally two types of multiphase machines, depending on whether the number of phases in the stator is a multiple of three or not. They can therefore be classified into two groups called "type 1 multiphase machinery" and "types 2 multiphases". It should be noted that pairs are rarely taken into account, unless they are a multiple of three.

I.5.1 "Type1" Multi-phase Machines

A "type 1" multiphase machine is a machine whose number of phases of the stator q is a multiple of 3 and which can be grouped into n three-phase stars as follows:

$$q = 3\eta \ (\eta = 1,2,3,....) \quad \text{(I. 1)}$$

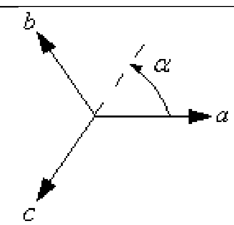
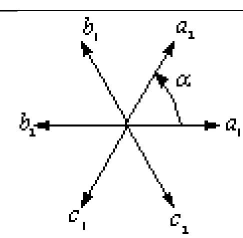
These machines are also called "multi-star machines".

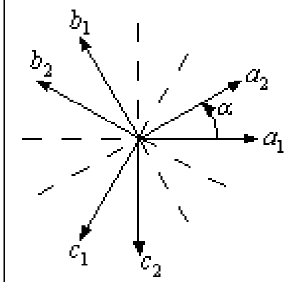
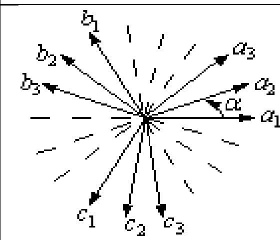
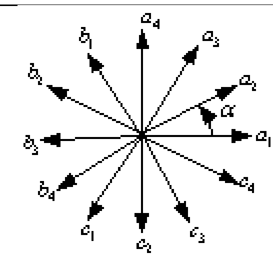
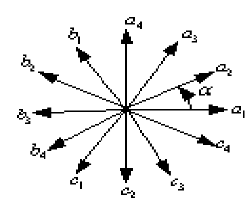
Note that in normal operation, it is generally desirable to have the same number of neutrals as stars, i.e. n isolated neutrals.

For example, a double-star machine (6 phases) with α = 0° has different characteristics from a double star machine with α=30°. In order to take account of these differences between machines and to distinguish possible configurations, a different terminology is introduced. It is defined as follows [2][3]:

$$q_\alpha = \frac{180°}{\alpha} \quad \text{(I. 2)}$$

Table I.1 the following table gives details of some examples of Multi-star machines [3]:

Phase Number(q)	Equivalent number of phases (q_α)	Angular displacement (α)	Schematic representation, Position of coils
3	3	60°	
6	3	60°	

6	6	30°	
9	9	20°	
12	6	30°	
12	12	15°	

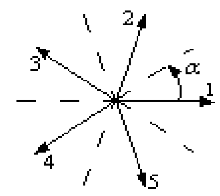
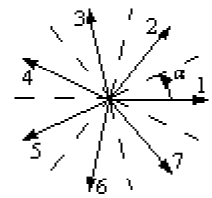
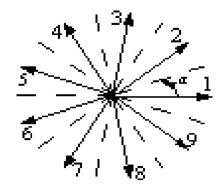
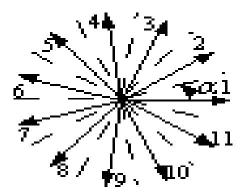
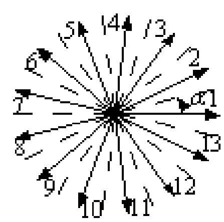
Tab I.1 Multi-phase "Type 1" machine

I.5.2 "Type2" Multi-phase Machines

A multiphase machine of "type2" is a machine whose number of statoric phases is unparalleled. If α represents the angular shift between two adjacent coils, then the q phase is regularly shifted by $2\pi/q = 2\alpha$. So, it is still:

$$\mathbf{q} = \mathbf{q}_{\alpha} = \frac{\mathbf{180°}}{\alpha}$$

Table (I.2) summarizes some examples of type 2 multi-phase machines [2][3]:

Phase Number (q)	Equivalent number of phases (q_α)	Angular displacement (α)	Schematic representation, position of coils
5	5	36°	
7	7	25. 7°	
9	9	20°	
11	11	16.3°	
13	13	13.8°	

Tab I.2 Multi-phase machine "Type2"

I.6 DESCRIPTION OF THE DOUBLE STAR ASYNCHRONOUS MACHINE

The most common example of multiphase machine is the asynchronous double star machine (DSIM). It has two three-phase wrapping systems in the stator, shifted from one to the other by an electric angle α (α = 30° in this model), and a wrapped or squirrel cage rotor. To simplify the study, the electric circuit of the rotor is considered to be equivalent to a short-circuit triphase wrapping.

The following diagram shows the positions of the coil axes of the nine phases that make up the machine. The stator has six phases and the rotor has three phases.[6]

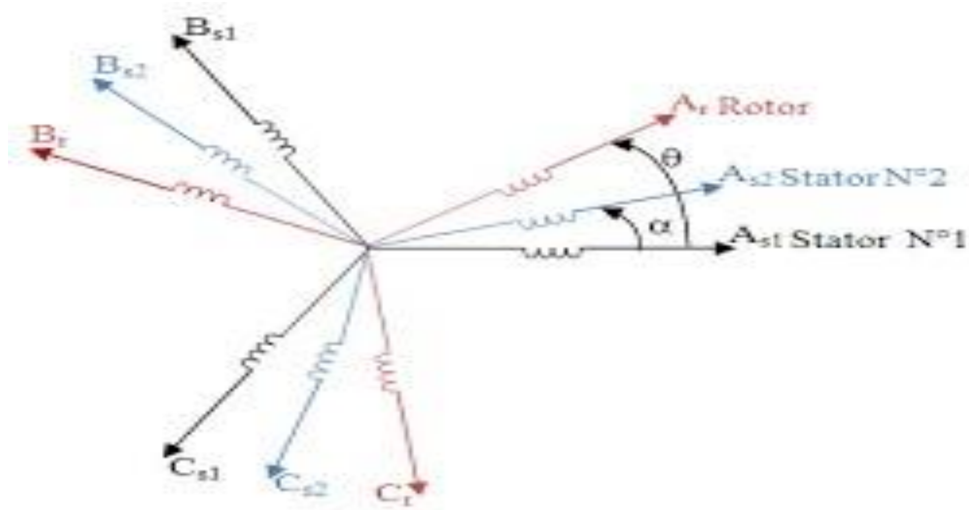


Fig.I. 1.Representation of DSIM rollings

The quantity relative to the first star (stator 1) is marked with an index S_1

And a S2 index for the magnitude relative to the second star (stator 2).

The phases of the first star are designated by $s_{a1,}, s_{b1,}s_{c1,}$,the phases in the second star by $s_{a2,}, s_{b2,}s_{c2,}$and the rotor by $r_{a,}, r_{b,}\ r_{c,}$. $\theta_1$represents the position of the rotor (phase Ar) relative to the star1 Phasea_1, $\theta_2$represents a rotor's position relative to star 2, and these angles are defined as follows: [2]

$$\theta_1 = \Omega_1\, t + \theta_0 \qquad (I.3)$$

$$\theta_2 = \theta_1 - \alpha \qquad (I.4)$$

Or:

Ω_1 : Mechanical speed of the rotor.

θ_0 : Initial position of the rotor by star input1.

The two wrappings of the stator are each powered by a balanced three-phase current, which produces a rotating field along the entrance.

The report: $$\mathcal{G} = {\Omega_s - \Omega_r}/{\Omega_s} \tag{I.5}$$

The different operating modes depend on the value of the slide.

Our study is interested in how the engine works

The contribution of the stator to the rotating field is called the slip of the rotor, and the frequency of the rotor current is as follows:

$$\omega_r = \mathcal{G}\omega_s \tag{I.6}$$

The ratio of the mechanical speed of the rotor Ω_1 depending on the synchronization speed ω_{set} of the number of pairs of p poles of the machine is expressed as follows

$$\Omega_1 = (1 - \mathcal{G})\frac{\omega_s}{p} \tag{I. 7}$$

1.7 APPLICATIONS OF MULTIPHASE MACHINES

Multiphase machines are often used in high-power applications, such as synchronous generators, which generate more power than conventional generators. These applications include pumps, fans, compressors, etc. (Figure I.2). The diagram below shows an example of the application of a 15-phase synchronous machine:

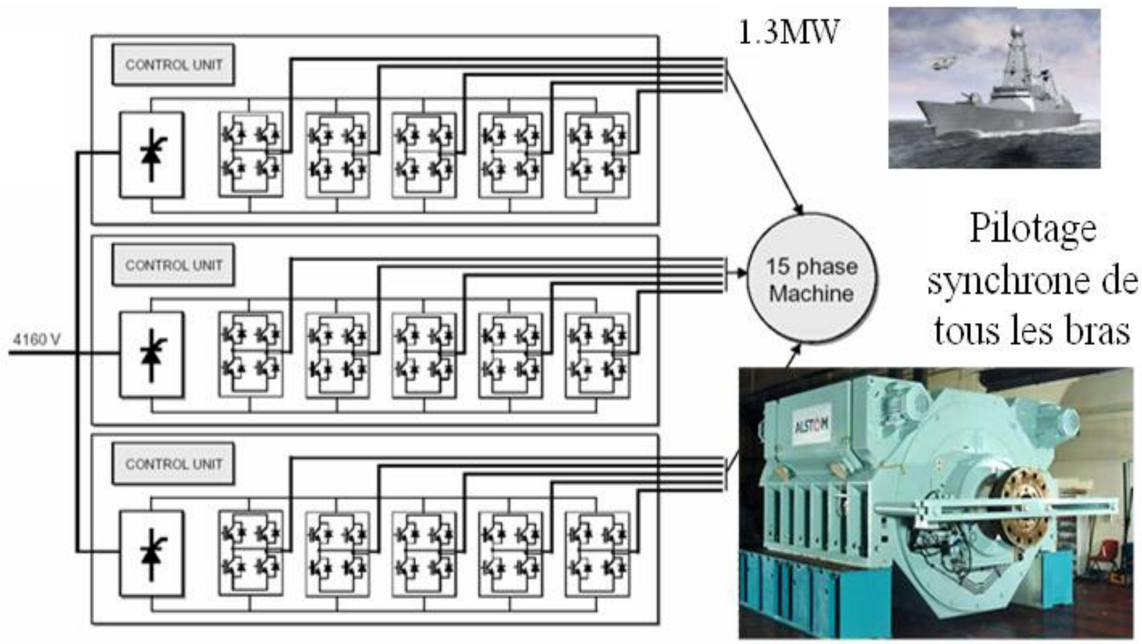


Fig.I. 2.Example of application of a 15-phase synchronous machine.

Another application is related to the use of multiphase machines in wind power generation systems: the double-star machine produces energy through two three-phase systems connected to a transformer to adapt the three-phase voltages to the voltage of the grid (see Fig.I.3) [3].

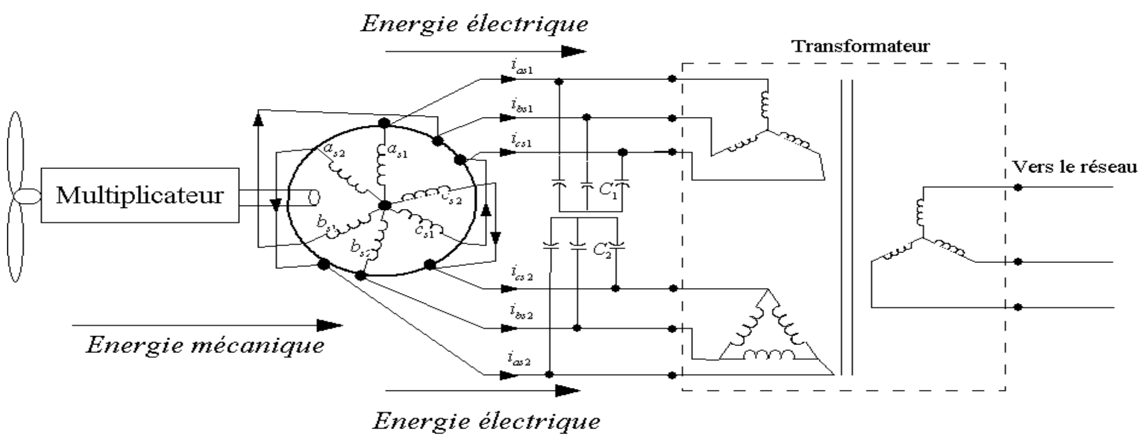


Fig.I. 3.Example of application of a 6 phases asynchronous machines.

1.8 ADVANTAGES OF MULTI-PHASE MACHINES

Multi-Phase machines are more advantageous than traditional machines. Among these advantages we can cite: energy sharing, reliability, reduction of torque fluctuations and reduction of rotational losses [2] [3].

1.8.1 Improved reliability

When inverters power three-phase machines, one of the arms of the inverter may fail, causing the machine to only work on two phases. The control of the machine is then lost and a high amplitude torque wave occurs. One solution for controlling the machine in this degraded mode is to connect the machine's neutral to the medium point of the continuous voltage source, so that the two remaining currents can be controlled independently of each other. In the case of multi-phase machines, this restriction can be avoided if at least three phases remain active. Up to (q-3) open phases are possible without the need to connect a neutral. The more phases there are, the more it is possible to control the machine. This increases the reliability and operation in case of failure [3].

1.8.2 Power segmentation

Increasing the number of phases automatically results in an increase in power. An effective solution to reduce phase currents without having to reduce the power voltage is to increase the number of phases in the stator. As a result, the total required power of the machine will be allocated to each phase, resulting in a reduction in the load on each Phase. This capability allows lower-quality electronic components to drive the machine using a frequency converter operating at a higher switching frequency. This reduces current and torque waves. Power division is the main advantage of the multi-phase machines, which are very popular today.

1.9 DISADVANTAGES OF MULTI-PHASE MACHINES

The main disadvantage of multi-phase machines is their cost. The number of semiconductors increases with the number of phases, which increases the cost of assembling the conversion machine. However, as power increases, this problem loses importance [2].

With the increase in the number of semiconductors, the control system obviously becomes more complex. Consequently, the methods developed for three-phase systems cannot be applied as they are (especially for type 2 machines), and specially adapted proximity control techniques (control of static converters) must be developed. MLI technology represented little

I.10 CONCLUSION

In this chapter, we presented a brief history of electrical machines, we also gave the classification and characteristics of multi-phase machines as well as their advantages and disadvantages.

The next chapter will focus on modelling the DSIM

Chapitre II

DSIM Modeling

II.1 Introduction

Modelling of electrical machines usually involves very complex equations. The distribution of the wrappings and the particular geometry of the DSIM make the implementation of the model difficult. However, this difficulty can be overcome by adopting some simplifying assumptions [3].

Thus, modelling allows us to guide development by quantifying phenomena. It also makes a valuable contribution by providing an image of what is observed experimentally and by predicting the behaviour of more diverse machines than those observing experimentally.

II.2 Simplifying assumptions

To simplify the study of this machine we take the following simplifying assumptions:

- The air gap dimensions are assumed to be constant along the air gap dimensions. This means that the machine is designed in such a way that the distance between the stator and rotor is constant throughout the machine.
- The motor magnetic force is spatially distributed in a sinusoidal way. (This means that the spatial distribution of the motor magnetic force follows the form of a sinusoidal function that ensures the production of a smooth, continuous magnetic field.)
- The saturation of magnetic circuits, hysteresis and Foucault currents are neglected. (The effects of magnetic material saturation, hysteresis and Foucault currents that can be generated in conductive materials when exposed to changing magnetic fields are ignored.)
- Assume that the resistances of the wires in the stator and rotor windings remain constant regardless of temperature changes.
  - The mutual leak induction common to the two circuits (star 1 and 2) is negligible.

II.2.1 General model of DSIM

Given the simplifying assumptions above and the notation of the voltage, current and flux vectors, we can write [2-5]:

For star 1

$$[V_{s1}] = [v_{as1} \quad v_{bs1} \quad v_{cs1}]^T$$

$$[I_{s1}] = [i_{as1} \quad i_{bs1} \quad i_{cs1}]^T \qquad \text{(II.1)}$$

$$[\Phi_{s1}] = [\phi_{as1} \quad \phi_{bs1} \quad \phi_{cs1}]^T$$

For star 2

$$[V_{s2}] = [v_{as2} \quad v_{bs2} \quad v_{cs2}]^T$$
$$[I_{s2}] = [i_{as2} \quad i_{bs2} \quad i_{cs2}]^T \qquad \text{(II.2)}$$
$$[\Phi_{s2}] = [\phi_{as2} \quad \phi_{bs2} \quad \phi_{cs2}]^T$$

For the rotor

$$[V_r] = [v_{ar} \quad v_{br} \quad v_{cr}]^T$$
$$[I_r] = [i_{ar} \quad i_{br} \quad i_{cr}]^T \qquad \text{(II.3)}$$
$$[\Phi_r] = [\phi_{ar} \quad \phi_{br} \quad \phi_{cr}]^T$$

By combining the Ohm law with the Lenz law, we can write the following relationship to the receiver rule which is valid for all operating conditions:

$$[V_{s1}] = [R_{s1}][I_{s1}] + \frac{d}{dt}[\Phi_{s1}] \qquad \text{(II.4)}$$

$$[V_{s2}] = [R_{s2}][I_{s2}] + \frac{d}{dt}[\Phi_{s2}] \qquad \text{(II.5)}$$

$$[V_r] = [R_r][I_r] + \frac{d}{dt}[\Phi_r] \qquad \text{(II.6)}$$

II.2.2 Flux equations

The following equation expresses the magnetic flux of the stator and rotor as a function of current, self-inductance, and mutual inductance.

$$[\Phi_{s1}] = [L_{s1,s1}][I_{s1}] + [M_{s1,s2}][I_{s2}] + [M_{s1,r}][I_r] \qquad \text{(II.7)}$$

$$[\Phi_{s2}] = [M_{s2,s1}][I_{s1}] + [L_{s2,s2}][I_{s2}] + [M_{s2,r}][I_r] \qquad \text{(II.8)}$$

$$[\Phi_r] = [M_{r,s1}][I_{s1}] + [M_{r,s2}][I_{s2}] + [L_{r,r}][I_r] \qquad \text{(II.9)}$$

Or.

Resistance matrix ($[R_{S1}]$,$[R_{S2}]$, $[R_r]$) for the stator (star 1 and star 2) and the rotor respectively for example:

$$[R_{S1}] = R_{s1}[ID]_{3*3}$$
$$[R_{S2}] = R_{s2}[ID]_{3*3} \tag{II.10}$$
$$[R_r] = R_r[ID]_{3*3}$$

With:

$[ID]_{3*3}$: Order Identity Matrix3

R_{s1}: Resistance of a phase of the 1st star.

R_{s2}: Resistance of a phase of the 2nd star.

R_r: Resistance of a rotor phase.

The inductance submatrices in equations (II.7), (II.8) and (II.9) are expressed as follows [2-4] :

$$[L_{s1,s1}] = \begin{pmatrix} L_{s1} + L_{ms} & -L_{ms}/2 & -L_{ms}/2 \\ -L_{ms}/2 & L_{s1} + L_{ms} & -L_{ms}/2 \\ -L_{ms}/2 & -L_{ms}/2 & L_{s1} + L_{ms} \end{pmatrix}$$

$$[L_{s2,s2}] = \begin{pmatrix} L_{s2} + L_{ms} & -L_{ms}/2 & -L_{ms}/2 \\ -L_{ms}/2 & L_{s2} + L_{ms} & -L_{ms}/2 \\ -L_{ms}/2 & -L_{ms}/2 & L_{s2} + L_{ms} \end{pmatrix}$$

$$[L_{r,r}] = \begin{pmatrix} L_r + L_{mr} & -L_{mr}/2 & -L_{ms}/2 \\ -L_{mr}/2 & L_r + L_{mr} & -L_{ms}/2 \\ -L_{mr}/2 & -L_{mr}/2 & L_r + L_{mr} \end{pmatrix}$$

$$[\mathrm{M}_{s1,s2}] = \mathrm{M}_{sr} \begin{pmatrix} \cos\alpha & \cos(\alpha + 2\pi/3) & \cos(\alpha + 4\pi/3) \\ \cos(\alpha + 4\pi/3) & \cos\alpha & \cos(\alpha + 2\pi/3) \\ \cos(\alpha + 2\pi/3) & \cos(\alpha + 4\pi/3) & \cos\alpha \end{pmatrix}$$

$$[M_{s1,r}] = M_{sr} \begin{pmatrix} cos\,\theta_1 & cos(\theta_1 + 2\pi/3) & cos(\theta_1 + 4\pi/3) \\ cos(\theta_1 + 4\pi/3) & cos\,\theta_1 & cos(\theta_1 + 2\pi/3) \\ cos(\theta_1 + 2\pi/3) & cos(\theta_1 + 4\pi/3) & cos\,\theta_1 \end{pmatrix}$$

$$[M_{s2,r}] = M_{sr} \begin{pmatrix} cos\,\theta_2 & cos(\theta_2 + 2\pi/3) & cos(\theta_2 + 4\pi/3) \\ cos(\theta_2 + 4\pi/3) & cos\,\theta_2 & cos(\theta_2 + 2\pi/3) \\ cos(\theta_2 + 2\pi/3) & cos(\theta_2 + 4\pi/3) & cos\,\theta_2 \end{pmatrix}$$

Such as:

$$\left[M_{S2,S1}\right] = \left[M_{S1,S2}\right]^T ; \left[M_{r,S1}\right] = \left[M_{S1,r}\right]^T ; \left[M_{r,S2}\right] = \left[M_{S2,r}\right]^T$$

OR:

L_{s1} : Self-inductance of the 1st star.

L_{s2}: Self-inductance of the 2nd star

L_r : Self-inductance of a phase of the rotor.

L_{ms}: Maximum value of the mutual induction coefficients of the stator.

L_{mr}: Maximum value of the mutual induction coefficients of the rotor.

M_{sr}: Maximum value of the mutual induction coefficients between the star and the rotor.

II.2.3 Expression of electromagnetic torque

The basic equation for rotor rotation is expressed by the following two relationships:

$$\frac{d}{dt}\Omega_m = \frac{1}{J}(C_{em} - C_r - k_f\Omega_m) \tag{II.12}$$

Furthermore, the expression for the electromagnetic torque is obtained by the derivation of the coenergy as follows:

$$C_{em} = \frac{1}{2}\begin{pmatrix} [I_{S1}]^T \\ [I_{S1}]^T \\ [I_r]^T \end{pmatrix} \left\{ \left\{ \frac{\partial}{\partial\theta_m} \begin{pmatrix} [L_{s1,s1}] & [M_{s1,s2}] & [M_{s1,r}] \\ [M_{s2,s1}] & [L_{s2,s2}] & [M_{s2,r}] \\ [M_{r,s1}] & [M_{sr,s1}] & [L_{r,r}] \end{pmatrix} \right\} \begin{pmatrix} [I_{S1}] \\ [I_{S2}] \\ [I_r] \end{pmatrix} \tag{II.13}$$

The inductance submatrix shows that it depends on the following submatrix which gives a simpler expression of the electromagnetic torque than the previous equation (II.14):

$$C_{em} = [I_{S1}]^T \frac{\partial}{\partial\theta_1}\left\{\left[M_{s1,r}\right].[I_r]\right\} + [I_{S2}]^T \frac{\partial}{\partial\theta_1}\left\{\left[M_{s2,r}\right][I_r]\right\} \tag{II.14}$$

After establishing the electromagnetic model of the machine in the three-phase reference frame, taking into account the simplifying hypotheses, we can note its complexity, which forces us to use simpler models in reference frames with a reduced number of axes allowing easy translation mathematics of the machine, the study and analysis of its transient regime

Among these models, the most commonly used is the so-called Park model (1929), which is a mathematical operation that allows the transition from a three-phase system to a more easy to solve biphasic system.

II.3 PARK TRANSFORMATION

The Park transformation is a mathematical tool used to a benchmark change from a three-phase system of axes (a, b, c) to a two-phased equivalent system of the axis (d, q) creating the same magneto motor force. The homopolar component intervenes to balance the processed system [7].

The condition for the transition from a three-phase system to a biphasic system is the creation of an electromagnetic field rotating with equal magneto motor forces. A unique Park transformation matrix has been defined for currents, tensions and fluxes, it is defined by:

$$[A] = \sqrt{\frac{2}{3}}\begin{pmatrix} cos(\theta) & cos(\theta + 2\pi/3) & cos(\theta + 4\pi/3) \\ -sin(\theta) & -sin(\theta + 2\pi/3) & -sin(\theta + 4\pi/3) \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{pmatrix} \qquad \text{(II.15)}$$

And its inverse is given by:

$$[A^{-1}] = \sqrt{\frac{2}{3}}\begin{pmatrix} cos(\theta) & -sin(\theta) & \sqrt{\frac{1}{2}} \\ cos(\theta + 2\pi/3) & -sin(\theta + 2\pi/3) & \sqrt{\frac{1}{2}} \\ cos(\theta + 4\pi/3) & -sin(\theta + 4\pi/3) & \sqrt{\frac{1}{2}} \end{pmatrix} \qquad \text{(II.16)}$$

The two transformations are represented by the following two equations [2 ,8]:

$$\left[G_{dq0}\right] = [\mathrm{A}]\left[G_{abc}\right] \qquad \text{(II.17)}$$

$$\left[G_{abc}\right] = \left[\mathrm{A}^{-1}\right]\left[G_{dq0}\right] \qquad \text{(II.18)}$$

with:

$[G_{abc}]$: Is the vector assemble sizes of the balanced three-phase system

$[G_{dq0}]$: Is the vector assemble the magnitude of the two-phase system.

II.3.1 Application of Park transformation to DSIM

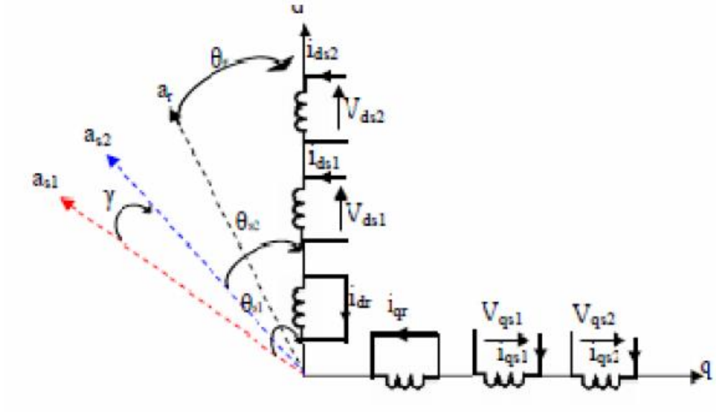


Fig. II. 1.Schematic representation of the DSIM model in the Park benchmark.

II.3.1.1 Voltage Equations

After the above transformation, the DSIM model in the Park frame of reference is given by the following equation [5][8].

For the star 1

$$\begin{aligned} V_{ds1} &= R_s i_{ds1} + \frac{d}{dt}\phi_{ds2} - w_{coor}\phi_{qs1} \\ V_{qs1} &= R_s i_{qs1} + \frac{d}{dt}\phi_{qs2} + w_{coor}\phi_{ds1} \end{aligned} \qquad \text{(II.19)}$$

For the star 2

$$\begin{aligned} V_{ds2} &= R_s i_{ds2} + \frac{d}{dt}\phi_{ds2} - w_{coor}\phi_{qs2} \\ V_{qs2} &= R_s i_{qs2} + \frac{d}{dt}\phi_{qs2} + w_{coor}\phi_{ds2} \end{aligned} \qquad \text{(II.20)}$$

For the rotor

$$\begin{aligned} 0 &= R_r i_{dr} + \frac{d}{dt}\phi_{dr} - (w_{coor} - w_r)\phi_{qr} \\ 0 &= R_r i_{qr} + \frac{d}{dt}\phi_{qr} + (w_{coor} - w_r)\phi_{dr} \end{aligned} \qquad \text{(II.21)}$$

with:

w_{coor} : Is the angular speed of the axes (d, q)

II.3.1.2 Flux equations

Applying this transformation to the magnetic flux equation in the same way that the Park transformation is applied to the voltage equation, we obtain the following [3,5].

For the star 1

$$\begin{aligned}\phi_{ds1} &= L_{s1}i_{ds1} + \frac{3}{2}L_{ms}i_{ds1} + \frac{3}{2}L_{ms}i_{ds2} + \frac{3}{2}M_{sr}i_{dr}\\ \phi_{qs1} &= L_{s1}i_{qs1} + \frac{3}{2}L_{ms}i_{qs1} + \frac{3}{2}L_{ms}i_{qs2} + \frac{3}{2}M_{sr}i_{qr}\end{aligned} \quad (II.22)$$

For the star 2

$$\begin{aligned}\phi_{ds2} &= L_{s2}i_{ds2} + \frac{3}{2}L_{ms}i_{ds2} + \frac{3}{2}L_{ms}i_{ds1} + \frac{3}{2}M_{sr}i_{dr}\\ \phi_{qs2} &= L_{s2}i_{qs2} + \frac{3}{2}L_{ms}i_{qs2} + \frac{3}{2}L_{ms}i_{qs1} + \frac{3}{2}M_{sr}i_{qr}\end{aligned} \quad (II.23)$$

For the rotor

$$\begin{aligned}\phi_{dr} &= L_{r}i_{dr} + \frac{3}{2}L_{mr}i_{dr} + \frac{3}{2}M_{sr}i_{ds1} + \frac{3}{2}M_{sr}i_{ds2}\\ \phi_{qr} &= L_{r}i_{qr} + \frac{3}{2}L_{mr}i_{qr} + \frac{3}{2}M_{sr}i_{qs1} + \frac{3}{2}M_{sr}i_{qs2}\end{aligned} \quad (II.24)$$

OR:

$$\frac{3}{2}L_{ms} = \frac{3}{2}L_{mr} = \frac{3}{2}L_{sr} = L_m$$

L_m : Cyclic mutual inductance between star 1, star 2 and rotor.

Equations (II.22), (II.23), (II.24) are rewritten in this way [2]:

For the star 1

$$\begin{aligned}\phi_{ds1} &= L_{s1}i_{ds1} + L_m(i_{ds1} + i_{ds2} + i_{dr})\\ \phi_{qs1} &= L_{s1}i_{qs1} + L_m(i_{qs1} + i_{qs2} + i_{qr})\end{aligned} \quad (II.25)$$

For the star 2

$$\begin{aligned}\phi_{ds2} &= L_{s2}i_{ds2} + L_m(i_{ds1} + i_{ds2} + i_{dr})\\ \phi_{qs2} &= L_{s2}i_{qs2} + L_m(i_{qs1} + i_{qs2} + i_{qr})\end{aligned} \quad (II.26)$$

For the rotor

$$\begin{aligned}\phi_{dr} &= L_r i_{dr} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \\ \phi_{qr} &= L_r i_{qr} + L_m(i_{qs1} + i_{qs2} + i_{qr})\end{aligned} \tag{II.27}$$

II.3.1.3 Mechanical equation

When changing the reference frame, it is necessary to find the expression of the electromagnetic torque in the new reference frame. To calculate the expression of the instantaneous torque, it is necessary to determine the instantaneous power. The instantaneous power absorbed by the double star asynchronous machine is given by the following expression:

$$P_{abc} = [V_{S1}]^T[I_{S1}] + [V_{S2}]^T[I_{S2}] \tag{II.28}$$

Which give:

$$P_{abc} = V_{as1}i_{as1} + V_{bs1}i_{bs1} + V_{cs1}i_{cs1} + V_{as2}i_{as2} + V_{bs2}i_{bs2} + V_{cs2}i_{cs2} \tag{II.29}$$

Furthermore, we can write

$$P_{abc} = V_{ds1}i_{ds1} + V_{qs1}i_{qs1} + V_{ds2}i_{ds2} + V_{qs2}i_{qs2} \tag{II.30}$$

We replace the axis voltages and currents (d, q) in equation (II.30) with their expressions in equations (II.19), (II.20), (II.21), and we find the following expression for the instantaneous absorbed power. [3][4]:

$$\begin{aligned}P_{abc} = {} & \underbrace{R_{s1}i_{ds1}^2 + R_{s1}i_{qs1}^2 + R_{s2}i_{ds2}^2 + R_{s2}i_{qs2}^2}_{terme1} \\ & \underbrace{+w_{coor}\left(\phi_{ds1}i_{qs1} - \phi_{qs1}i_{ds1} + \phi_{ds2}i_{qs2} - \phi_{qs2}i_{ds2}\right)}_{terme2} \\ & \underbrace{+\frac{d\phi_{ds1}}{dt}i_{ds1} + \frac{d\phi_{qs1}}{dt}i_{qs1} + \frac{d\phi_{ds2}}{dt}i_{ds2} + \frac{d\phi_{qs2}}{dt}i_{qs2}}_{terme3}\end{aligned} \tag{II.31}$$

We see that the instantaneous power developed is made up of three terms [4]:

- The first term is identifiable to losses Stator Joules.
- The second term represents the electrical power transformed into mechanical power (iron losses are assumed to be negligible).

- The third term corresponds to the stored electromagnetic power.

Electromagnetic power and torque can be written in standard form:

$$p_{em} = \Omega_s C_{em} \tag{II.32}$$

From the third term it is clear that the electromagnetic couple is of the following form [3]:

$$C_{em} = p\left(\phi_{ds1} i_{qs1} + \phi_{ds2} i_{qs2} - \phi_{qs2} i_{ds1} - \phi_{qs2} i_{ds2}\right) \tag{II.33}$$

II.4 CHOICE OF REFERENCE

To study the transient theory of double-star asynchronous machines, a three-axis (d, q) plane coordinate system can be used.

II.4.1 Stator-related reference

In this frame of reference, the axes (d, q) are stationary relative to the stator ($w_{coor} = 0$).

In this case, phase A_{s1} and d coincide. This reference system is best suited to the treatment of instantaneous quantities and has the advantage of not requiring conversion to a real system. This system can be used to study the starting and braking speeds of alternating current machines [2][5].

II.4.2 Rotor-related repository

In this frame of reference, the axis (d, q) is stationary relative to the rotor rotating at the speed therefore ($w_{coor} = w_r$). This framework allows the study of transient characteristics of synchronous and asynchronous alternating current machines with asymmetrically connected rotor circuits [4].

II.4.3 Reference linked to the rotating field

In this frame of reference, the axes (d, q) are stationary with respect to the electromagnetic field created by the two stars of the stator ($w_{coor} = w_s$).

As quantities in this frame of reference are continued, this frame of reference is typically used when applying controls such as speed and torque [1].

II.5 Model of the motor in the Park reference frame linked to the rotating field

In our study, a reference frame linked to the rotation field is used to model and control the DSIM. In this case the model is as follows [2].

For the star 1

$$\begin{aligned} V_{ds1} &= R_s i_{ds1} + \frac{d}{dt}\Phi_{ds1} - \omega_s \Phi_{qs1} \\ V_{qs1} &= R_s i_{qs1} + \frac{d}{dt}\Phi_{qs1} + \omega_s \Phi_{ds1} \end{aligned} \quad \text{(II.34)}$$

For the star 2

$$\begin{aligned} V_{ds2} &= R_s i_{ds2} + \frac{d}{dt}\Phi_{ds2} - \omega_s \Phi_{qs2} \\ V_{qs2} &= R_s i_{qs2} + \frac{d}{dt}\Phi_{qs2} + \omega_s \Phi_{ds2} \end{aligned} \quad \text{(II.35)}$$

For the rotor

$$\begin{aligned} 0 &= R_r i_{dr} + \frac{d}{dt}\Phi_{dr} - \left(\omega_s - \omega_r\right)\Phi_{qr} \\ 0 &= R_r i_{qr} + \frac{d}{dt}\Phi_{qr} + \left(\omega_s - \omega_r\right)\Phi_{dr} \end{aligned} \quad \text{(II.36)}$$

II.5.1 Formatting State Equation

The magnetizing flux Φ_m is the sum of the two direct Φ_{md} and quadratic magnetizing fluxes Φ_{mq}, hence [2][4].

$$\Phi_m = \sqrt{\Phi_{md}^{\ 2} + \Phi_{mq}^{\ 2}} \quad \text{(II.37)}$$

The two expressions of the magnetizing fluxes as a function of the stator and rotor currents are expressed by [4]:

$$\begin{aligned} \Phi_{md} &= L_m\left(i_{ds1} + i_{ds2} + i_{dr}\right) \\ \Phi_{mq} &= L_m\left(i_{qs1} + i_{qs2} + i_{qr}\right) \end{aligned} \quad \text{(II.38)}$$

By introducing the expressions for the magnetizing flux (II.38) into the equations (II.25), (II.26), (II.27), we will have:

For the star 1

$$\begin{aligned}\Phi_{ds1} &= L_{s1} i_{ds1} + \Phi_{md} \\ \Phi_{qs1} &= L_{s1} i_{qs1} + \Phi_{mq}\end{aligned} \tag{II.39}$$

For the star 2

$$\begin{aligned}\Phi_{ds2} &= L_{s2} i_{ds2} + \Phi_{md} \\ \Phi_{qs2} &= L_{s2} i_{qs2} + \Phi_{mq}\end{aligned} \tag{II.40}$$

For the rotor

$$\begin{aligned}\Phi_{dr} &= L_r i_{dr} + \Phi_{md} \\ \Phi_{qr} &= L_r i_{qr} + \Phi_{mq}\end{aligned} \tag{II.41}$$

From equations (II.39), (II.40), (II.41), we draw [2]:

For the star 1

$$\begin{aligned}i_{ds1} &= (\Phi_{ds1} - \Phi_{md}) / L_{S1} \\ i_{qs1} &= (\Phi_{qs1} - \Phi_{mq}) / L_{S1}\end{aligned} \tag{II.42}$$

For the star 2

$$\begin{aligned}i_{ds2} &= (\Phi_{ds2} - \Phi_{md}) / L_{S2} \\ i_{qs2} &= (\Phi_{qs2} - \Phi_{mq}) / L_{S2}\end{aligned} \tag{II.43}$$

For the rotor

$$\begin{aligned}i_{dr} &= (\Phi_{dr} - \Phi_{md}) / L_r \\ i_{qr} &= (\Phi_{qr} - \Phi_{mq}) / L_r\end{aligned} \tag{II.44}$$

By replacing the currents in equations (II.42), (II.43), (II.44) by their expressions in equations (II.34), (II.35), (II.36), we will have [5]:

$$\begin{aligned}
\frac{d}{dt}\Phi_{ds1} &= V_{ds1} - \frac{R_{s1}}{L_{s1}}(\Phi_{ds1} - \Phi_{md}) + w_s\Phi_{qs1} \\
\frac{d}{dt}\Phi_{qs1} &= V_{qs1} - \frac{R_{s1}}{L_{s1}}(\Phi_{qs1} - \Phi_{mq}) + w_s\Phi_{ds1} \\
\frac{d}{dt}\Phi_{ds2} &= V_{ds2} - \frac{R_{s1}}{L_{s1}}(\Phi_{ds2} - \Phi_{md}) + w_s\Phi_{qs2} \\
\frac{d}{dt}\Phi_{qs2} &= V_{qs2} - \frac{R_{s2}}{L_{s2}}(\Phi_{qs2} - \Phi_{mq}) + w_s\Phi_{ds2} \\
\frac{d}{dt}\Phi_{dr} &= -\frac{R_r}{L_r}(\Phi_{dr} - \Phi_{md}) + w_{gl}\Phi_{qr} \\
\frac{d}{dt}\Phi_{qr} &= -\frac{R_r}{L_r}(\Phi_{qr} - \Phi_{mq}) + w_{gl}\Phi_{dr}
\end{aligned} \qquad (II.45)$$

OR: $w_{gl} = w_s - w_r$

From the equation (II.25), (II.26) (II.27) the expressions of magnetizing fluxes will have the following expressions [9][10]:

$$\begin{aligned}
\Phi_{md} &= L_a\left(\frac{\Phi_{ds1}}{L_{s1}} + \frac{\Phi_{ds2}}{L_{s2}} + \frac{\Phi_{dr}}{L_r}\right) \\
\Phi_{mq} &= L_a\left(\frac{\Phi_{qs1}}{L_{s1}} + \frac{\Phi_{qs2}}{L_{s2}} + \frac{\Phi_{qr}}{L_r}\right)
\end{aligned} \qquad (II.46)$$

Where he is:

$$L_a = \frac{1}{\left(\frac{1}{L_{s1}}\right)+\left(\frac{1}{L_{s2}}\right)+\left(\frac{1}{L_r}\right)+\left(\frac{1}{L_m}\right)}$$

Other expressions for instantaneous torque can be obtained by using and substituting expressions for stator fluxes. (II.25), (II.26), (II.27) in (II.33), we obtain [9][10][7]:

$$C_{em} = pL\left[\left(i_{qs1} + i_{qs2}\right)i_{dr} - \left(i_{ds1} + i_{ds2}\right)i_{qr}\right] \qquad (II.47)$$

Another expression for torque can be derived from the rotor flux in Eq. (II.27). Consider the following rotor currents:

$$
\begin{aligned}
i_{dr} &= \frac{1}{L_m + L_r}\left[\Phi_{dr} - L_m\left(i_{ds1} + i_{ds2}\right)\right] \\
i_{qr} &= \frac{1}{L_m + L_r}\left[\Phi_{qr} - L_m\left(i_{qs1} + i_{qs2}\right)\right]
\end{aligned}
\tag{II.48}
$$

By introducing i_{dr} and i_{qr} into the expression (I.47), we obtain:

$$
C_{em} = p\frac{L_m}{L_m + L_r}\left[\left(i_{qs1} + i_{qs2}\right)\Phi_{dr} - \left(i_{ds1} + i_{ds2}\right)\Phi_{qr}\right]
\tag{II.49}
$$

By replacing and simplifying the expression for magnetizing flux in (II.45), we obtain the following new system of equations:

$$
\begin{aligned}
\frac{d}{dt}\Phi_{ds1} &= V_{ds1} + w_s\Phi_{qs1}\frac{L_a - L_{s1}}{T_{s1}L_{s1}}\Phi_{ds1} + \frac{L_a}{T_{s1}L_{s2}}\Phi_{ds2}) + \frac{L_a}{T_{s1}L_r}\Phi_{dr} \\
\frac{d}{dt}\Phi_{qs1} &= V_{qs1} - w_s\Phi_{ds1}\frac{L_a - L_{s1}}{T_{s1}L_{s1}}\Phi_{qs1} + \frac{L_a}{T_{s1}L_{s2}}\Phi_{qs2}) + \frac{L_a}{T_{s1}L_r}\Phi_{qr} \\
\frac{d}{dt}\Phi_{ds2} &= V_{ds2} + \frac{L_a - L_{s1}}{T_{s2}L_{s1}}\Phi_{ds1} + \frac{L_a - L_{s2}}{T_{s1}L_{s2}}\Phi_{ds2} + w_s\Phi_{qs2} + \frac{L_a}{T_{s2}L_r}\Phi_{dr} \\
\frac{d}{dt}\Phi_{qs2} &= V_{qs2} + \frac{L_a}{T_{s2}L_{s1}}\Phi_{qs1} - w_s\Phi_{ds2} + \frac{L_a - L_{s2}}{T_{s2}L_{s2}}\Phi_{dr} + \frac{L_a}{T_{s2}L_r}\Phi_{qr} \\
\frac{d}{dt}\Phi_{dr} &= \frac{L_a}{T_rL_{s1}}\Phi_{ds1} + \frac{L_a}{T_rL_{s2}}\Phi_{ds2} + \frac{L_a - L_r}{T_rL_r}\Phi_{dr} + w_{gl}\Phi_{qr} \\
\frac{d}{dt}\Phi_{qr} &= \frac{L_a}{T_rL_{s1}}\Phi_{qs1} + \frac{L_a}{T_rL_{s2}}\Phi_{qs2} - w_{gl}\Phi_{dr} + \frac{L_a - L_r}{T_rL_r}\Phi_{qr}
\end{aligned}
\tag{II. 50}
$$

By putting the system of equations (II.50) in the form of equations of state, we will have:

$$
\dot{X} = AX + BU \tag{II.51}
$$

Such as:

$X = \left[\Phi_{ds1} \quad \Phi_{qs1} \quad \Phi_{ds2} \quad \Phi_{qs2} \quad \Phi_{dr} \quad \Phi_{qr}\right]^T$: State vector.

$U = \left[V_{ds1} \quad V_{qs1} \quad V_{ds2} \quad V_{qs2} \quad V_{dr} \quad V_{qr}\right]^T$: Control vector (input vector).

Based on matrix calculation, the following matrices are obtained: [2][10]:

$$A=\begin{bmatrix} \frac{L_a-L_{s1}}{T_{s1}L_{s1}} & w_s & \frac{L_a}{T_{s1}L_{s2}} & 0 & \frac{L_a}{T_{s1}L_r} & 0 \\ -w_s & \frac{L_a-L_{s1}}{T_{s1}L_{s1}} & 0 & \frac{L_a}{T_{s2}L_{s1}} & 0 & \frac{L_a}{T_{s1}L_r} \\ \frac{L_a}{T_{s2}L_{s1}} & 0 & \frac{L_a-L_{s1}}{T_{s1}L_{s1}} & w_s & \frac{L_a}{T_{s2}L_r} & 0 \\ 0 & \frac{L_a}{T_{s2}L_{s1}} & -w_s & \frac{L_a-L_{s1}}{T_{s1}L_{s1}} & 0 & \frac{L_a}{T_{s2}L_r} \\ \frac{L_a}{T_rL_{s1}} & 0 & \frac{L_a}{T_rL_{s2}} & 0 & \frac{L_a-L_{s1}}{T_{s1}L_{s1}} & w_{gl} \\ 0 & \frac{L_a}{T_rL_{s1}} & 0 & \frac{L_a}{T_rL_{s2}} & -w_{gl} & \frac{L_a-L_{s1}}{T_{s1}L_{s1}} \end{bmatrix}$$

$$B=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

OR:

$T_{S1}=\frac{L_{S1}}{R_{S1}}$: Satiric time constant of the first star.

$T_{S2}=\frac{L_{S2}}{R_{S2}}$: Static time constant of the second star.

$T_r=\frac{L_r}{R_r}$: Rotor time constant.

II.6 NUMERICAL SIMULATION

To illustrate the usual characteristics of DSIM, the behaviour of motors supplied directly by the three-phase network was simulated for two cases: no-load and on-load starting.

Differential equations (II.51) were solved using MATLAB programming.

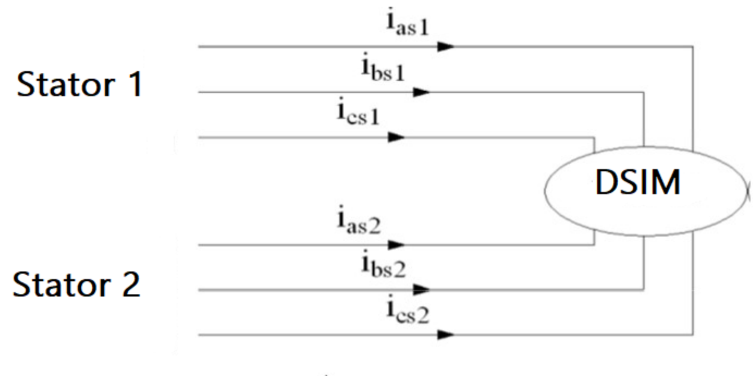
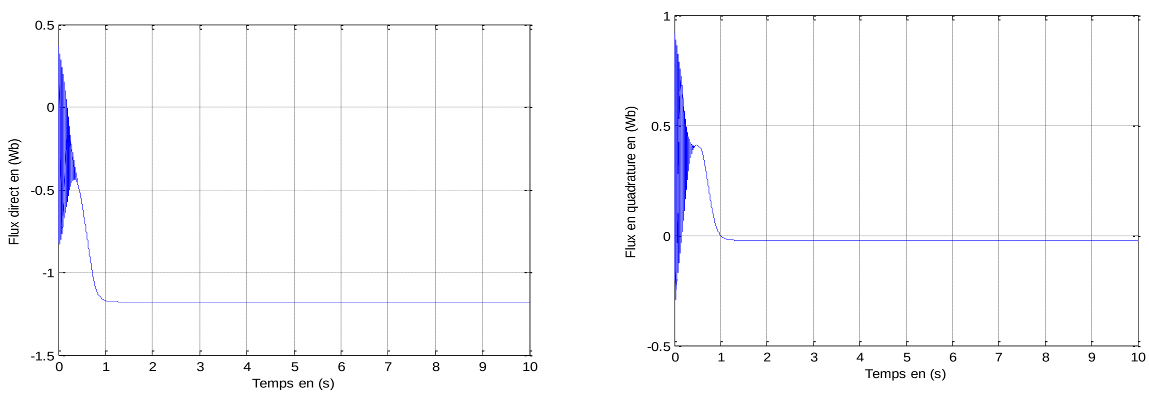


Fig. II. 2.Direct power supply of the DSIM.

- II.6.1 Empty operation

Figures The following represents the performance of the DSIM during no-load operation



Cr = 0.

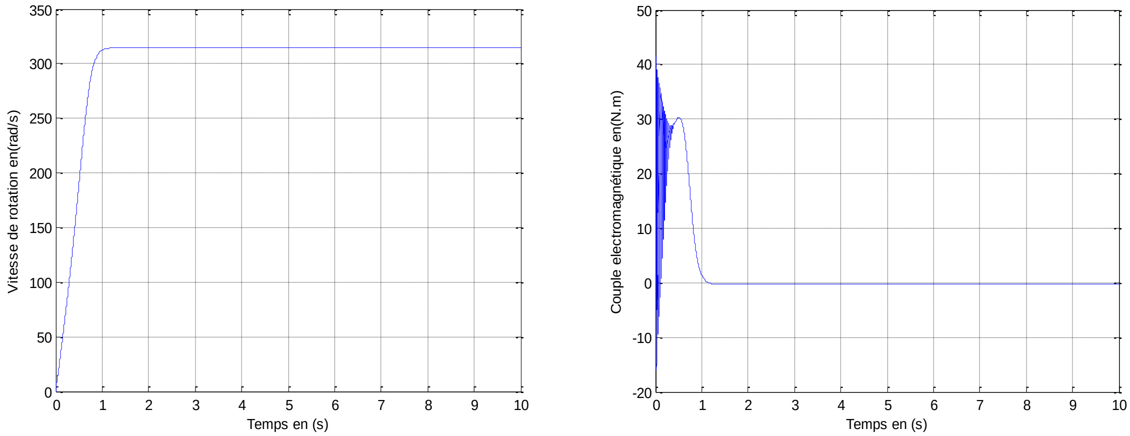


Fig. II. 3.Characteristics of the DSIM when empty.

- II.6.2 Operation under load

The effect of introducing a load torque of (14 Nm) at the instant (t=2s) after a no-load start on the dynamics of the DSIM is illustrated in the following figures:

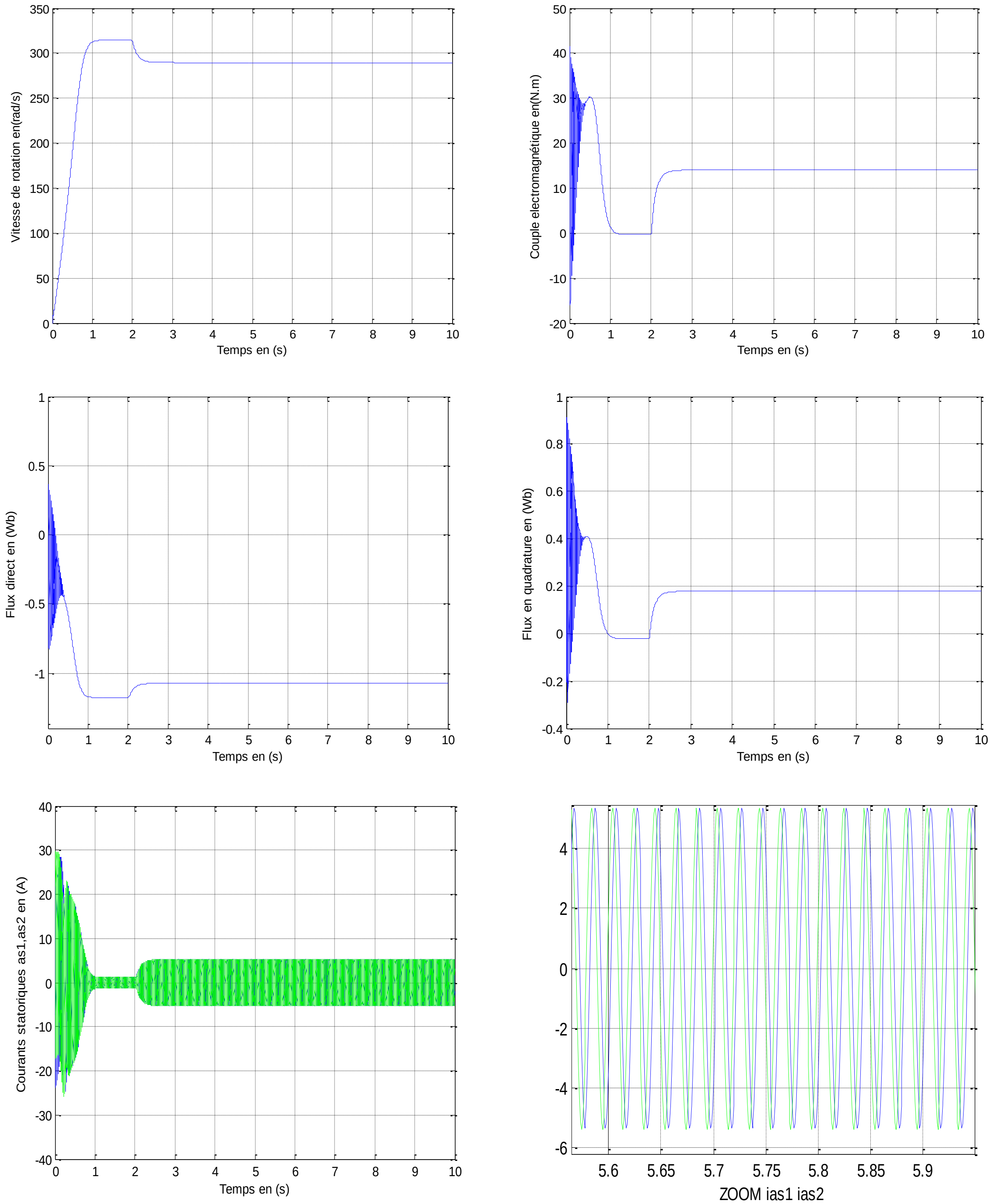


Fig. II. 4.Characteristics of the DSIM when empty.

II.7 INTERPRETATION OF SIMULATION RESULTS

II.7.2 Empty operation

- The rotation speed stabilizes at around 315 rad/s after a transient period of around 1.4s.
- At start-up, the electromagnetic torque reaches its maximum at 41.4 N.m and oscillates. After this speed, the electromagnetic torque compensates for friction losses. The machine generates a torque of 0.1 N.m.
- The stator current « i_{as1} » is sinusoidal. During transient conditions, the machine draws a very high current, reaching a magnitude of 28 A. After the transient state, the current decreases to a peak value of 1.3 A.

The same is true for the two q-axis currents, except that the steady-state current value is zero.

II.7.2Under load

When a charge of 14 N.m is applied to the moment t=2s: the following observations can be made:

- The speed of rotation drops to 289 (rad/s).
- The torque compensates for the load torque and friction losses. The torque reaches a constant value of 14 N.m.
- The current « i_{as1} » fluxing in the first star has the same value at start-up as when there is no load, but this current increase when a load is inserted, reaching a peak value of 5.35A.

It should also be noted that the introduction of load torque reduces the rotational speed as well as the rotor flux. Therefore, the introduction of a speed control loop is necessary to improve the dynamic response of the machine.

II.8 MODELING OF THE ASSOCIATION (RECTIFIER + LC LOW-PASS FILTER + CURRENT-CONTROLLED VOLTAGE INVERTER USING HYSTERESIS TECHNIQUE)

Developments in the field of power electronics, either at the level of semiconductor elements or at the level of static converters, allow the production of control elements with high and easily controllable output powers [11].

II.8.1 Modelling of a three-phase double diode alternator

The rectifier which is a device used to convert alternating current (AC) into direct current (DC). Rectifiers are essential components in many electronic circuits and power systems [10]. The following diagram shows a three-phase full-wave rectifier using diodes:

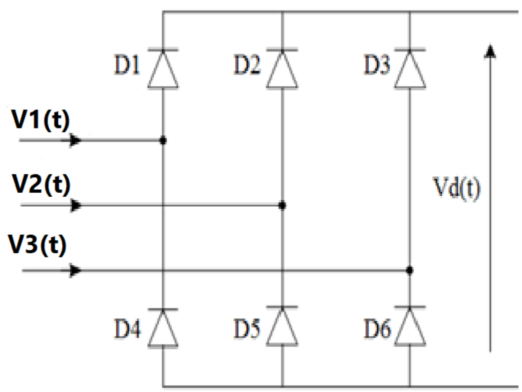


Fig. II. 5.Representation of a three-phase double alternating diode adjuster.

We assume that the rectifier is powered by a balanced three-phase voltage network:

$$
\begin{aligned}
V_1(t) &= \sin(wt)\\
V_2(t) &= \sin\left(wt - \frac{2\pi}{3}\right)\\
V_3(t) &= \sin\left(wt + \frac{2\pi}{3}\right)
\end{aligned}
\quad \text{(II.52)}
$$

If the overlap effect is eliminated, the output voltage of the fixer is expressed as follows:

$$V_d(t) = Max[V_1(t), V_2(t), V_3(t)] - Min[V_1(t), V_2(t), V_3(t)] \quad \text{(II.53)}$$

The output voltage is not truly DC and contains a slight ripple, but this is minimized by the addition of a low pass filter.

II.8.2 Modelling of the filter circuit

To minimize voltage ripples and relatively smooth the current, a filter circuit containing a capacitor and an inductor is inserted. Capacitance "C" suppresses sudden voltage fluctuations during the switching interval and absorbs negative currents collected by the load, while inductance "L" smoothes the current to a near constant state. This filter is shown in the diagram of the following [4].

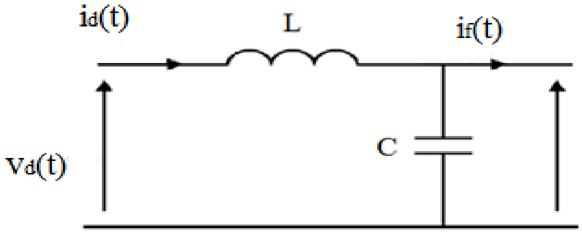


Fig. II. 6.Representation of a low pass filter

We can write:

$$\frac{di_d(t)}{dt} = \frac{1}{L}(v_d(t) + U_f(t))$$
$$\frac{dU_f(t)}{dt} = \frac{1}{C}(i_d(t) + i_f(t)) \qquad (II.54)$$

Where U_f is the voltage of the inverter input $V_d(t)$, is the rectified voltage.

The transfer function of the previous filter in the Laplace plan is written as follows:

$$F(p) = \frac{U_f(p)}{V_d(p)} = \frac{1}{1+(\sqrt{(LCp)^2}} \qquad (II.55)$$

with:

$$f_C = \frac{1}{2\pi\sqrt{LC}} \qquad (II.56)$$

OR: f_C : Cut-off frequency.

II.8.3 Modelling of PMW commissioned inverter

Inverters are of crucial importance in the field of power electronics. Voltage converters are static converters made up of switching cells. For high power, GTO transistors or thyristors are used, especially in the field of variable-speed electric drives, while for low power, switching transits are used. (IGBT or MOSFET). [4].

To power the DSIM, two symmetrical PWM (Pulse Width Modulation) controlled three-phase inverters are used.

To model the two inverters, we start with the modelling of the three-phase inverter:

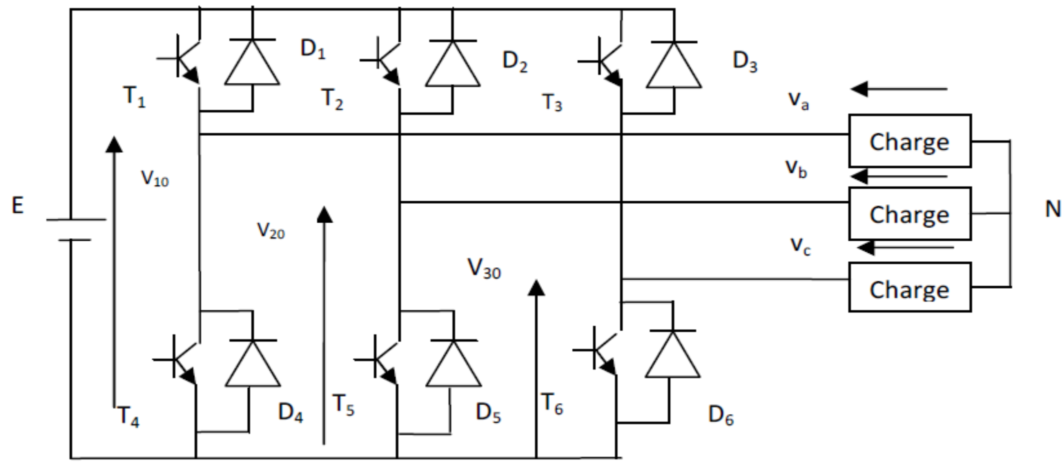


Fig. II. 7.Schematic diagram of a three-phase inverter.

According to figure (II.7), v_a , v_b *and* v_c are the phase voltages measured relative to the neutral N of the symmetrical three-phase load.

Each switch (transistor + diode) assumed ideal, (K_{ij} $i=1,2$ or 3, j=1 or 2), we can establish the following relationships:

$$v_{10} - v_a + v_b - v_{20} = 0 \quad \text{(II.56)}$$

$$v_{10} - v_a + v_c - v_{30} = 0 \quad \text{(II.57)}$$

By adding the equation (I.56) to the equations (I.57), we obtain:

$$2v_{10} - 2v_a + v_b + v_c - v_{20} - v_{30} = 0 \quad \text{(II.58)}$$

The sum of the currents i_a, i_b *or* i_c or and must be zero because the load has an isolated and symmetrical neutral. Same thing for the phase voltages $(v_a + v_b + v_c = 0)$So, in equation (I.58), we can replace $(v_a + v_c)$ by $(-v_c)$.

$$\begin{aligned} v_a &= \frac{1}{3}\left(2v_{10} - v_{20} - v_{30}\right) \\ v_b &= \frac{1}{3}\left(-v_{10} + 2v_{20} - v_{30}\right) \\ v_c &= \frac{1}{3}\left(-v_{10} - v_{20} + 2v_{30}\right) \end{aligned} \quad \text{(II.59)}$$

Depending on the state of the switch K_{ij}, the voltage of the branch v_{jo} is either E or 0. Three switching functions $F_1, F_2\ et F_3$ are defined, which take the value 1 if the switch K_{i1} is closed and the value -1 if It is open. Equation (II.60) can be rewritten as follows.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{E}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} \tag{II.60}$$

The power supply of the DSIM consisting of two three-phase voltage inverters thus:

For the inverter N°1:

$$\begin{bmatrix} v_{as1} \\ v_{bs1} \\ v_{cs1} \end{bmatrix} = \frac{E}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \end{bmatrix} \tag{II.61}$$

For the inverter N°2:

$$\begin{bmatrix} v_{as2} \\ v_{bs2} \\ v_{cs2} \end{bmatrix} = \frac{E}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} F_{12} \\ F_{22} \\ F_{32} \end{bmatrix} \tag{II.62}$$

Sinusoidal PWM (voltage inverter) technology or current control with hysteresis PWM (current inverter) is used to determine the closing and opening times of the switch. The control technique used in this study is hysteresis PWM current control. [4].

II.8.4 Control by hysteresis PWM

The hysteresis PWM (Pulse Width Modulation) command forces the phase currents to follow a reference current. By applying a sinusoidal current to the machine, a constant electromagnetic torque is guaranteed. The simplest approach used for this purpose is a control strategy that compares the measured phase current to the reference current using a hysteresis comparator (see Figure II.11). This generates switching and interruption pulses in the inverter switch to limit the phase currents within a hysteresis band 2Δi centered around the reference current. [4].

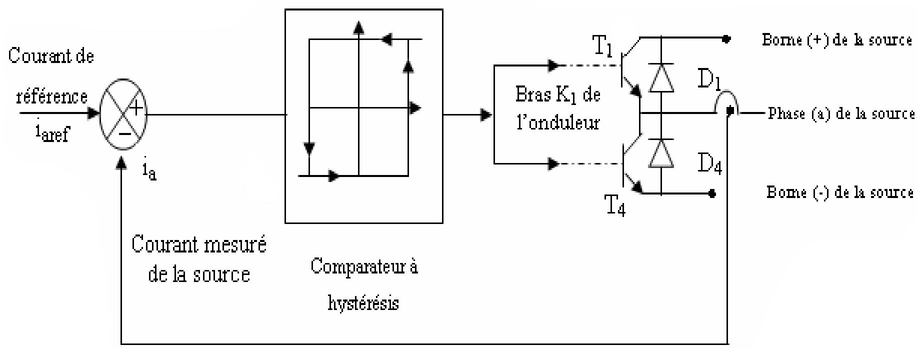


Fig. II. 8.Schematic diagram of hysteresis control of an inverter arm

The switching conditions of the static switches of the two inverters are defined in terms of the corresponding logical states as follows:

$$si \qquad i_{ksj} \geq i_{ksjref} + \Delta i; \qquad F_{kj} = 1 \tag{II.63}$$

$$si \qquad i_{ksj} \leq i_{ksjref} - \Delta i; \qquad F_{kj} = 1 \tag{II.64}$$

$$si \qquad i_{ksj} = i_{ksjref} \ ; \quad F_{kj} = F_{kj-1} \tag{II.65}$$

with:

i_{ksj} (K=1, 2,3/ j=1,2): are the stator phase currents $\left(i_{as1}, i_{bs1}, i_{cs1}, i_{as2}, i_{bs2}, i_{cs2}\right)$, respectively.

Δi : The hysteresis band is selected so as not to exceed the permissible switching frequency of the semiconductor and to minimize current harmonics.

II.9 CONCLUSION

In the first part of this chapter, the current state of the art of multi-phase machines is presented, the DSIM is modelled according to the Park benchmark and the usual characteristics of the DSIM are presented in the simulation results.

The second part of this chapter presented the modelling of a DSIM power supply, which mainly consists of two voltage inverters whose current is controlled by a PWM with hysteresis.
The following chapter describes the vector control of the DSIM.

Chapter III

Direct Torque Control of DSIM

III.1 INTRODUCTION

Direct torque control (DTC) of asynchronous machines proposed by Takachachi and Depenbrok appeared in the second half of the 1980s as competitive with traditional methods. In a frame linked to the stator, the instantaneous values of the stator flux of the electromagnetic torque are estimated from the stator quantities. Using hysteresis comparators, flux and torque are controlled directly and independently with appropriate selection of the voltage vector imposed by the inverter [8][12][13]

DTC, or Direct Torque Control, is the regulation of the torque of an asynchronous machine by applying a relative voltage vector from the inverter, which determines its state. The control variables are the stator flux and the electromagnetic torque, which are generally controlled by hysteresis regulators. The output of these regulators determines the voltage vector of the inverter applied at each switching instant. [9][14].

III.2 DIRECT TORQUE CONTROL

Direct torque control (DTC), also known as direct torque and flux control (DTCF), is a method of controlling asynchronous induction motors (MAS). It allows direct control of motor torque and flux, which offers several advantages over traditional control methods, such as flux steering control (FOC).

In this innovative control technique, flux steering is achieved without a feedback loop, using motor modelling to directly calculate torque.

The control variables are magnetic flux and motor torque, DTC does not require modulators, tachometers or position encoders for speed or position feedback.

III.2.1 PRINCIPLE OF DTC CONTROL

In (DTC), the torque and stator flux of the asynchronous motor are controlled directly. This is achieved by determining the direction of the stator flux vector using the instantaneous value of the voltage vector [15-19].

A three-phase inverter can generate eight low voltage current vectors, represented as vectors in the complex plane. Two of these vectors have a zero value, while the other six represent six possible directions for the inverter currents.

The appropriate voltage vector to apply is determined from a switching table. This table depends on the flux and torque errors, as well as the position of the stator flux vector. Flux and torque errors are continually updated based on instantaneous current and voltage measurements. The position of the stator flux vector is determined by a mathematical model of the motor.

Based on continuous voltage measurements at the input path of the inverter and the stator phases, the model displays the following for each position [20]:

- The actual stator flux of the machine.
- Actual torque generated.
- The speed of rotation.

Measuring the shaft speed is not necessary, which is a major advantage of these methods. The flux and torque thus calculated are compared to reference values to determine the switching control time.

III.3 FUNCTION AND SEQUENCES OF A THREE-PHASE VOLTAGE INVERTER

The voltage inverter switches must be controlled to maintain machine flux and torque. The stator voltage vector V_s can be written as follows:

$$\overrightarrow{(V_s)} = \sqrt{\left(\frac{2}{3}\, U_c \left[S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}}\right)\right.} \tag{III.1}$$

Where S_a, S_b *and* S_c represent the logical state of the three switches, and Si=1 means that the upper switch is closed and the lower switch is open $V_i = +\frac{U_0}{2}, and\ S_i = 0$ means that the upper switch is open and the lower switch is closed $V_i = -\frac{U_0}{2}$ So we will try to control the flux and torque by selecting the voltage vector that will be done by configuring the switches. Since we have three keys, then there are 2^3=8 probabilities for the vector Vs. There are two vectors that correspond to the zero vector: $S_a, S_b, S_c = 0{,}0{,}0\ and\ S_a, S_b, S_c = 1{,}1{,}1$.

In each modulation period, the arm is not switched twice. The diagram shows the six non-zero voltage vectors that can be generated by a three-phase two-level voltage inverter on the complex plane [21].

This is how it works:

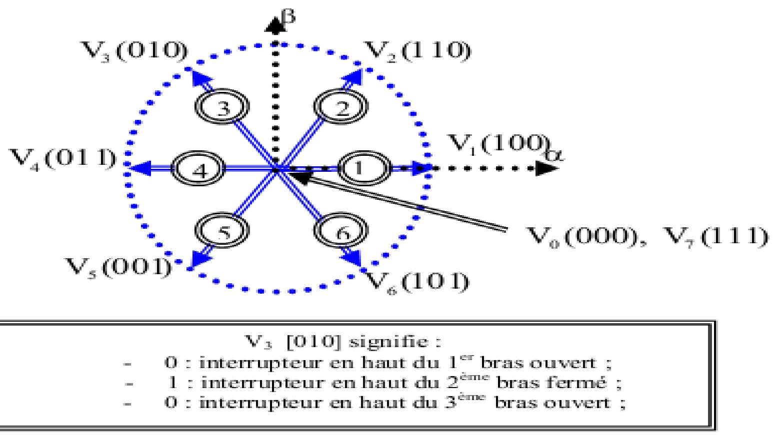


Fig. III. 1.Operating Sequences of a Two-Level Voltage Inverter

III.4 CONTROL OF STATORIC FLUX AND ELECTROMAGNETIC TORQUE

III.4.1 Stator Flux Control Principle

Starting from the stator voltage equation with the asynchronous machine model with stator-related reference:

$$V_s = R_s I_s + \frac{d\phi_s}{dt} \qquad (III.2)$$

The stator flux is estimated from the following relation:

$$\phi_s(t) = \int (V_s - R_s I_s)dt \qquad (III.3)$$

$$\phi_s(t) = \phi_{s0} + V_s(t) - R_s \int_0^t I_s dt \qquad (III.4)$$

Assuming that R_s remains constant and that the term $R_s I_s$ is negligible in relation to the voltage V_s.

On a periodic control interval [0, Te] corresponding to a sampling period Te the commands are fixed, so we can write:

$$\phi_s(t) \approx \phi_{s0} + V_s T_e \qquad (III.5)$$

OR

ϕ_{s0}: is the flux vector at time t = 0.

In the time interval T_e, the end of the vector ϕ_s moves along a given line of direction Vs.

Figure (IV.3) illustrates this principle, when we choose the vector $V_s = V_2$, for example.

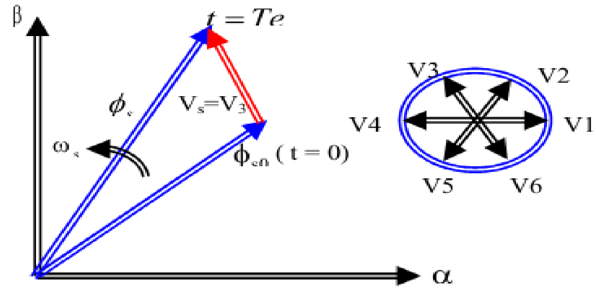


Fig. III. 2.Evolution of the end of the vector ϕ_s

If the control period "Te" is too small compared to the rotation period of the stator flux vector. Therefore, by selecting the appropriate sequence of inverter voltage vectors at successive time intervals of duration Te, the ϕs end of the flux vector can be made to follow the desired path[22].

The vector ϕs is maintained between two values $\phi_{s\,max}$ *and* $\phi_{s\,min}$ the passage from one to the other being controlled by V_s, If the control vector is one of the non-zero vectors, ϕ_s evolves with a constant speed proportional to the control voltage [23].

When the voltage vector Vs is non-zero, the direction of the end-of-flux displacement ϕ_s given by its derivative $\frac{d\phi_s}{dt}$ practically corresponds to the vector Vs.

With regard to the rotary flux, it can be assumed that, given the high time constant of the asynchronous machine's rotor, its amplitude does not vary during a transitional regime.[24], so the variation of the rotor flux is negligible compared to that of the statoric flux.

III.4.2 PRINCIPLE OF CONTROL OF ELECTROMAGNETIC TORQUE

The electromagnetic torque is proportional to the vector product between the stator and rotor flux vectors according to the following expression [25-29]:

$$Ce = k\left(\overrightarrow{\phi_s} * \overrightarrow{\phi_r}\right) = k\left|\overrightarrow{\phi_s}\right|\left|\overrightarrow{\phi_r}\right|\sin(\gamma) \quad \text{(III.6)}$$

Such as $k = \frac{P}{lq}$

With:

- $\overrightarrow{\phi_s}$: The stator flux vector.
- $\overrightarrow{\phi_r}$: The rotor flux vector referred to the stator.
- γ : the angle between the vectors of the stator and rotor fluxes.

According to this expression, the torque depends on the amplitude of the vectors $\overrightarrow{\phi_S}$ and $\overrightarrow{\phi_r}$ of their relative positions.

III.5 CHOICE OF VOLTAGE VECTOR

It is possible to control variations in the electromagnetic torque by modifying the rotation speed of the magnetic flux vector (ϕ_s). Using four specific vectors ($V_{i+1}, V_{i+2}, V_{i-1}, V_{i-2}$)in a given operating area (Zi).

Table (1) shows the evolution of the flux and the torque for each vector.

When the flux $\overrightarrow{(\phi_s)}$ is in region i, the control of the flux and torque can be ensured by choosing one of the following eight voltage vectors [24 -26]:

if V_{i+1} is selected, the amplitude of the du flux ϕ_s increases and the torque Cem increase

if V_{i+2} is selected, the amplitude of the flux ϕ_s decreases and the torque Cem increase

If V_{i-1} is selected, the amplitude of the flux ϕ_s increases and the torque Cem decreases.

if V_{i-2} is selected, the amplitude of the flux ϕ_s decreases and the torque Cem decreases.

If V_0 or V_7 is selected, the flux rotation will be stopped, resulting in a decrease in torque while the flux coefficient ϕ_s remains unchanged.

The voltage vectors to be applied depend on the area where the flux vector is located. The parameters Z_1, Z_2, Z_3, Z_4, Z_5, Z_6 (figure III. 3) represent the six possible zones of operation.

Vecteur V_k	V_{i+1}	V_{i+2}	V_{i-1}	V_{i-2}
ϕ_s	↗	↘	↗	↘
C_{em}	↗	↗	↘	↘

TAB. III .1 EVOLUTION OF FLUX AND TORQUE QUANTITIES AS A FUNCTION OF THE VECTOR $\boldsymbol{Vs}$APPLIED IN THE ZONE $\boldsymbol{Zi}$ K= (I-1, I-2, I+1, I+2)

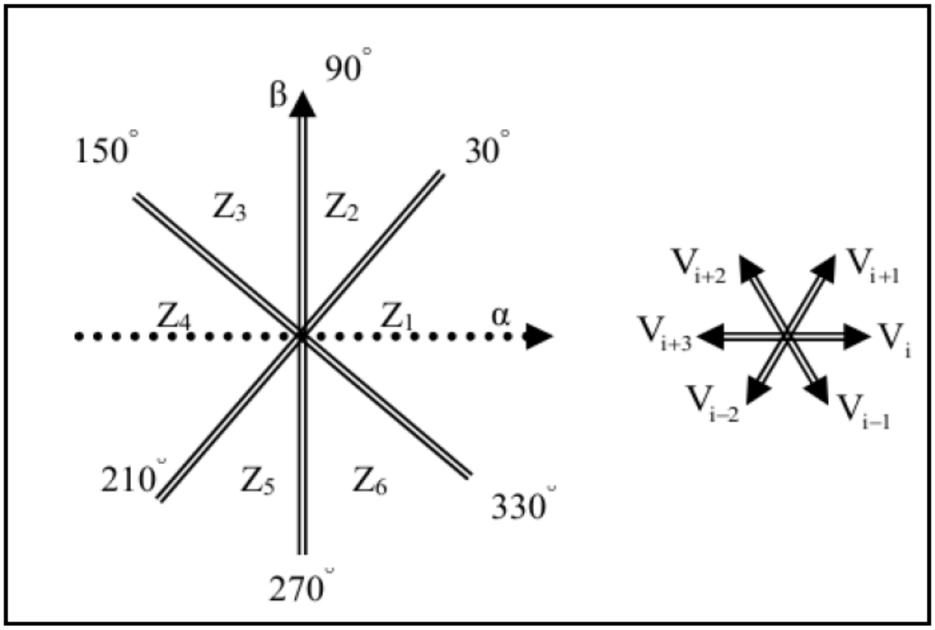


Fig. III. 3.Distribution of zones

The level of efficiency of the applied voltage vectors also depends on the position of the flux vector in zone i.

The voltage vector at the output of the inverter is determined from the torque and flux deviations relative to their references, as well as the position of the vector $\overrightarrow{(\phi_s)}$.

An estimator of the magnitude and position of the vector $\overrightarrow{(\phi_s)}$, as well as a torque estimator, are therefore necessary.

III.6 ESTIMATEURS

III.6.1 ESTIMATION OF STATORIC FLUX

The magnetic flux can be estimated from the measured statoric currents and tensions of the machine.

From the equation:

$$\phi_s(t) = \int (V_s - R_s i_s)dt \tag{III.7}$$

The components α and β of the vector are obtained $\overrightarrow{\phi s}$:

$$\begin{cases} \phi_{s\alpha} = \int_0^t (V_{s\alpha} - R_s i_{s\alpha})dt \\ \phi_{s\beta} = \int_0^t \left(V_{s\beta} - R_s i_{s\beta}\right)dt \end{cases} \tag{III.8}$$

These equations represent the computational steps necessary to estimate the amplitude of the stator flux.

We obtain the components $V_{s\alpha}$ et $V_{s\beta}$ after applying the CONCORDIA transform to the measured input voltages V_{an}, V_{bn}, V_{cn}.

These voltages are expressed from the inverter input voltage U_0 and the control states S_a, S_b, S_c, i.e.:[29]

$$\begin{cases} V_{s\alpha} = \sqrt{\frac{2}{3}}U_0\left(S_\alpha - \frac{1}{2}(S_b + S_c)\right) \\ V_{s\beta} = \sqrt{\frac{1}{2}}U_0(S_b - S_c) \end{cases} \tag{III.9}$$

The currents $Is\alpha$ and $Is\beta$ are also obtained from the real currents $Is\alpha$, $Is\alpha$ and $Is\alpha$ ($Is\alpha$ +$Is\alpha$ +$Is\alpha$ = 0) and by application of the CONCORDIA transformation:

$$\begin{cases} i_{s\alpha} = \sqrt{\frac{2}{3}}(i_{s\alpha} \\ i_{s\alpha} = \sqrt{\frac{2}{3}}(i_{sb} - i_{sc}) \end{cases} \tag{III.10}$$

The estimation of the amplitude of the statoric flux is made on the basis of its components $\phi_{s\alpha}$ and $\phi_{s\beta}$ by:

$$\Phi_s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \tag{III.11}$$

The angle αs between the stator reference frame and the flux vector ϕs is: [17,19]

$$\alpha_s = arctg\frac{\Phi_{s\beta}}{\Phi_{s\alpha}} \tag{III.12}$$

III.6.2 Estimation of electromagnetic torque

The electromechanical torque can be estimated from the estimated magnetic flux and the measured statoric current and can be expressed as follows:

$$C_{em} = p\left(\phi_{s\alpha}i_{s\beta} - \phi_{s\beta}i_{s\alpha}\right) \tag{III.13}$$

The equation shows that the accuracy of the latter depends on the quality of the flux estimate and the precision of the measurement of the current of the stator.

III.7 DEVELOPMENT OF THE CONTROL VECTOR

III.7.1 THE FLUX CORRECTOR

The goal is to keep the endpoints of vector ϕ_s circular, as shown in the figure (III.4).

The output of the compensator must indicate the direction of evolution of the elastic modulus ϕ_s in order to select the corresponding voltage vector. A simple two- level hysteresis corrector is ideal for this purpose and also offers very good dynamic performance [31-33].

The output of the corrector, represented by a Boolean variable $cflx$ directly indicates whether the amplitude of the flux must be increased ($cflx$ = 1) or decreased ($cflx$ = 0) in order to maintain [19]:

$$\left|(\phi_s)_{ref} - \phi_s\right| \leq \Delta\phi_s \qquad \text{(III.14)}$$

with:

$(\phi_s)_{ref}$: The flux instruction

$\Delta\phi_s$: The hysteresis width of the corrector.

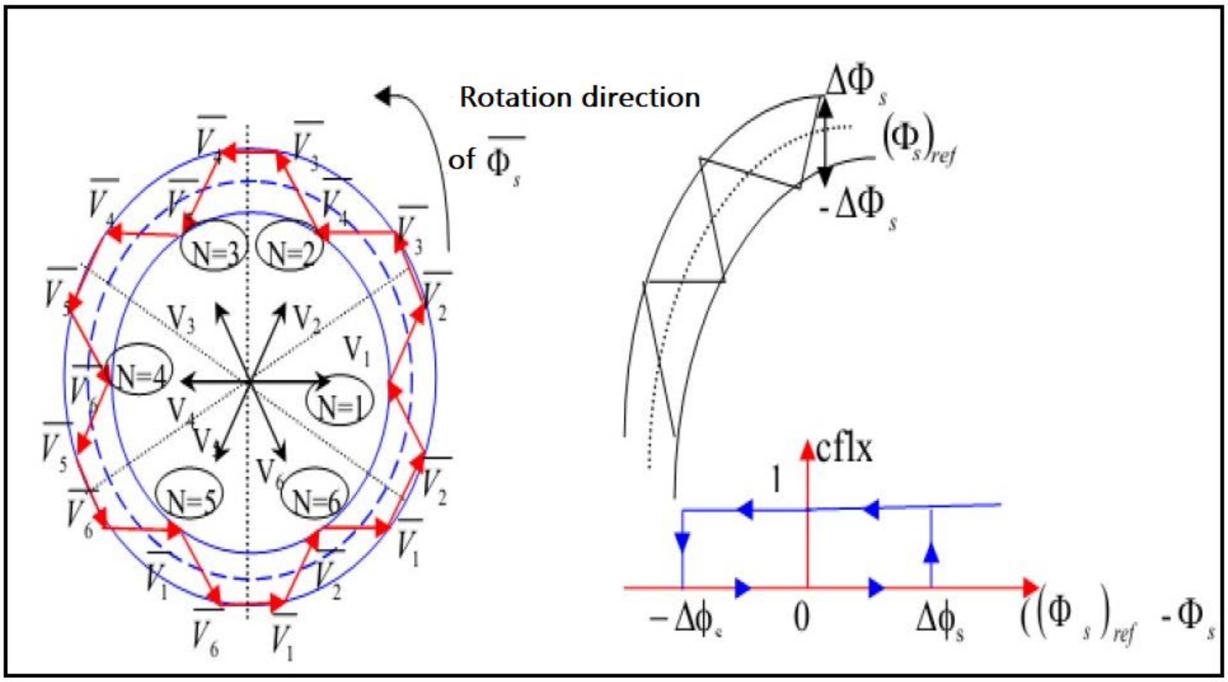


Fig. III. 4.Selection of voltages corresponding to stator flux amplitude controls

III.7.2 THE TORQUE CORRECTOR

The purpose of the torque corrector is to maintain the torque within the admissible limits specified as follows [31-34]:

$$\left|C_{ref} - C_{em}\right| \leq \Delta C \qquad \text{(III.15)}$$

with:

C_{ref} : Reference torque

ΔC : the torque hysteresis band

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

III.7.2.2 THE THREE-LEVEL CORRECTOR

These devices allow the motor to be controlled in both directions of rotation, whether for positive or negative torque. The output of the regulator, represented by the Boolean variable, directly indicates whether to increase in absolute value the torque amplitude ($ccpl$ =1 for a positive command and $ccpl$ = −1 for a negative command) or to decrease it ($ccpl$ = 0). Figure (III.5) illustrates this type of regulator [32-34].

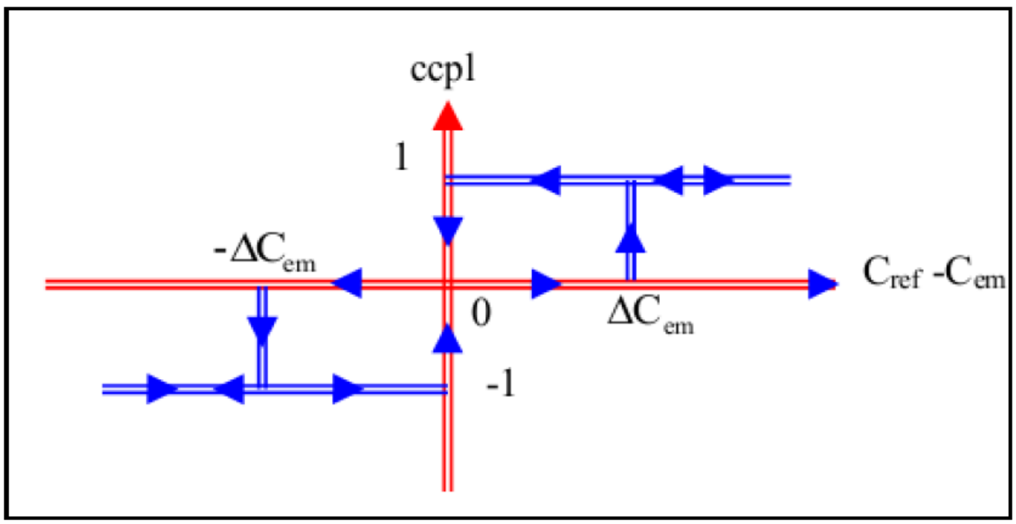


Fig. III. 5.Three-level torque corrector

III.8 DESIGN OF THE CONTROL TABLE

The command table is created based on the condition of the cflx and ccpl variables for the Ni region of the position $(\overrightarrow{\phi_s})$ and is as follows:

Flux	couple	N=1	N=2	N =3	N =4	N =5	N=6	Correcteur
cflx=0	ccpl=1	V_3	V_4	V_5	V_6	V_1	V_2	Deux niveaux
	ccpl=0	V_4	V_5	V_6	V_1	V_2	V_3	
	ccpl=-1	V_5	V_6	V_1	V_2	V_3	V_4	trios niveaux
cflx =1	ccpl=1	V_2	V_3	V_4	V_5	V_6	V_1	Deux niveaux
	ccpl=0	V_1	V_2	V_3	V_4	V_5	V_6	
	ccpl=-1	V_6	V_1	V_2	V_3	V_4	V_5	trois niveaux

TAB III.2 Control strategy using a three-level hysteresis comparator (With non-zero voltage vectors).

III.9 GENERAL STRUCTURE OF DIRECT TORQUE CONTROL

The basic elements of a direct torque control system for an asynchronous double star machine (DSIM) are illustrated in the diagram. This is a sampling command where the T_e sample period is very small relative to the machine's time constant: The Vs vector is selected at each T_e Sampling period and a filtering is applied to the current amounts of the stator. To reduce noise and sampling effects in the calculated flux signal [34].

One of the essential elements of this structure is the switching table, which allows the selection of the vector Vs to be set independently of the rotor position, which usually requires a speed sensor. Combined with a hysteresis comparator, the switching table replaces the PWM generator in conventional PWM voltage inverter control structures. The classic sequence table proposed by Takahashi is used [34]. Typically, a DTC consists of two main blocks: a speed control block and a torque control block.

III.10 TORQUE CONTROL LOOP

This part of the diagram includes:

III.10.1 Current sensors and switch status

The inverter's DC supply voltage, stator phase currents, and inverter switch status are transmitted to the motor model.

III.10.2 The engine model

By injecting the measurements and parameters into the motor model, one can process this data to obtain the motor's current flux and torque, as well as its current speed.

III.10.3 The torque and flux comparator

The role of the comparator is to compare the flux and torque signals to the values imposed on hysteresis and send a comparison signal which is processed by the optimal switch selector module.

III.10.4 THE OPTIMAL COMMUTATION SELECTOR

In this module there is a table containing the switching logic of the switch.

III.11 SPEED CONTROL LOOP

This part of the scheme includes a speed regulator, which consists of a comparator between the standard speed and the actual speed. This comparator injects the error into a PI regulator which, in turn, sends a reference to the torque regulator. The latter has the role of eliminating static error and reducing response time whitening the stability of the system.

III.11.1 Summary of PI regulators

The objective of using regulators is to guarantee an efficient dynamic response and greater resistance to internal or external disturbances. The functional current regulation diagram is illustrated in (Fig.III.6) and is applicable to both axes d and q.

III.11.2 Calculation of PI regulator parameters

Writing the closed loop transfer function of the is as follows:

$$\frac{i_{dsl}}{i^{*}{}_{dsl}} = \frac{k_{idl}+k_{p}S}{L_{s1}S^{2}+(R_{s1}+k_{pd1})S+k_{id1}}$$

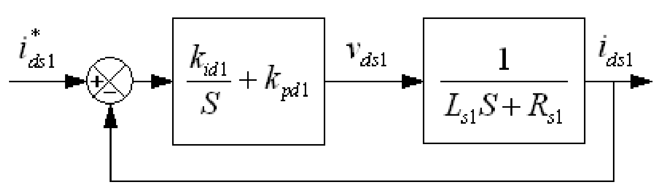


Fig. III. 1. Reduced current control scheme.

By imposing a pair of complex conjugate poles $S_{1,2}=\rho_{d1}\pm j\rho_{d1}$, The desired closed-loop characteristic polynomial is written as follows:

$$\mathrm{P(S)} = S^{2}+2_{\rho d1}S+2\rho^{2}{}_{d1} \qquad \text{(III.16)}$$

By identification, we obtain the parameters of the PI controller:

$$k_{pd1} = 2\rho_{d1}L_{s1}-R_{s1} \qquad \text{(III.17)}$$

$$\mathrm{k}_{\mathrm{id1}} = 2\rho^{2}{}_{\mathrm{d1}}\mathrm{L}_{\mathrm{s1}} \qquad \text{(III.18)}$$

Same procedure for calculating the parameters of the regulators of the current regulators i_{qs1}, i_{ds2} *and* i_{qs2}.

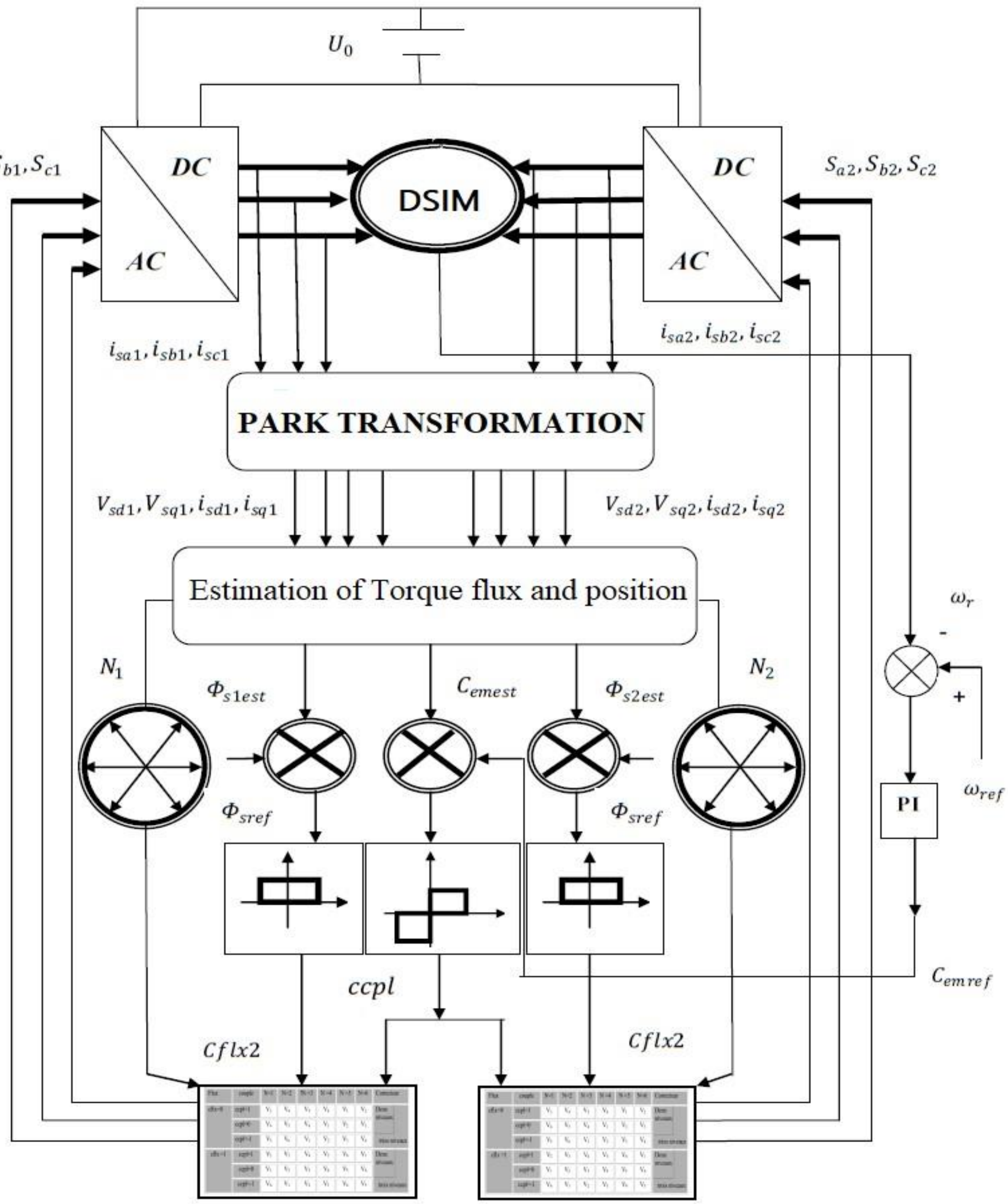


Fig. III. 6.General structure of the DSIM 'DTC'

III.12 Advantages and Disadvantages of DTC [20]

III.12.1 Advantages of DTC

- It is not necessary to perform the coordinate transformation because the currents and voltages are in a stator-related frame.
- Uses a simplified model of the induction motor.
- There is no block that calculates the voltage modulation (PWM).

- It is not necessary to decouple the currents from the control voltages, as in the case of vector control.
- The dynamic response of the torque is very fast.

III.12.1 Disadvantage 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 (using hysteresis controllers), which leads to a rich harmonic content that increases losses and results in acoustic noise and torque oscillations that can excite mechanical resonances.

III.13 SIMULATION RESULTS OF THE "DSIM", "DTC" CONTROL

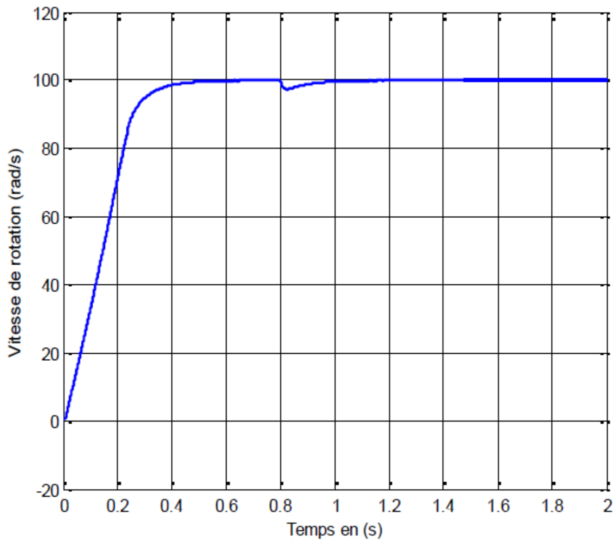
Below we present the simulation results of DSIM speed regulation.

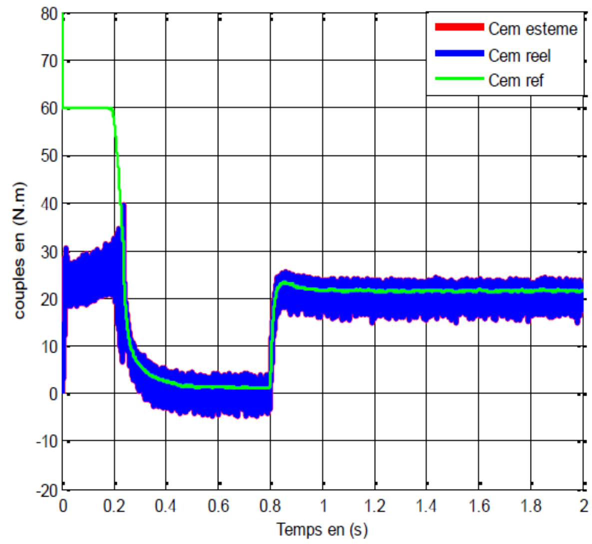
DTC control is implemented on a DSIM model. The two stator windings are individually powered by two inverters, controlled by the DTC technique in the presence of a speed regulation loop with a PI corrector, and using a three-level hysteresis comparator with non-zero voltage vectors.

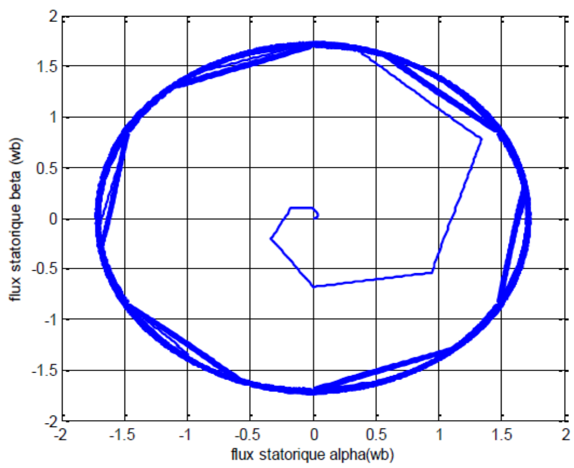
The figure illustrates the responses of the systems at a speed of 100 rad/sec in the presence of a disturbing load Cr = 20 from 0.8 seconds.

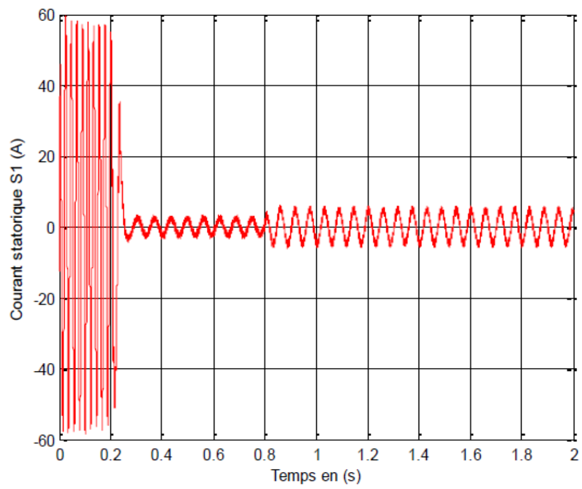
It shows that the command has good dynamic performance. Response time is 0.4 sec. Applying the disturbance does not affect the flux value in any way. The Cem engine torque at start-up reached (40 N.m).

We notice that the trajectory of the stator flux is practically a circle and the value reached (1.7 Wb).


Vitesse de rotation (rad/s)
Temps en (s)


Cem esteme
Cem reel
Cem ref
couples en (N.m)
Temps en (s)


flux statorique beta (wb)
flux statorique alpha(wb)


Courant statorique S1 (A)
Temps en (s)

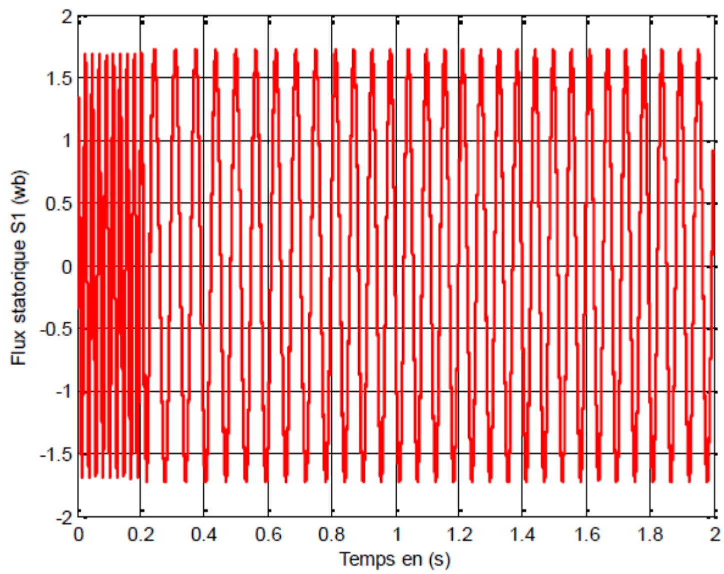


Fig. III. 7.Speed regulation, followed by the application of a load Cr = 20 N.m at t = 0.8 sec

III.13.1 ROBUSTNESS TEST

To adequately evaluate this command, several tests are performed. (Variation of speed, variation of load, variation of stator resistance of the machine).

III.13.1.1 First test

Speed variation

The figure below shows the evolution of the characteristics of the DSIM following a speed variation from 100 rad/sec to 120 rad/sec at t = 1 second.

The simulation results clearly indicate that:

The speed perfectly follows its setpoint and stabilizes within 0.4 seconds. This variation has an influence on the currents and torque. The torque and current experience a peak when transitioning from one mode to another, then return to their reference value.

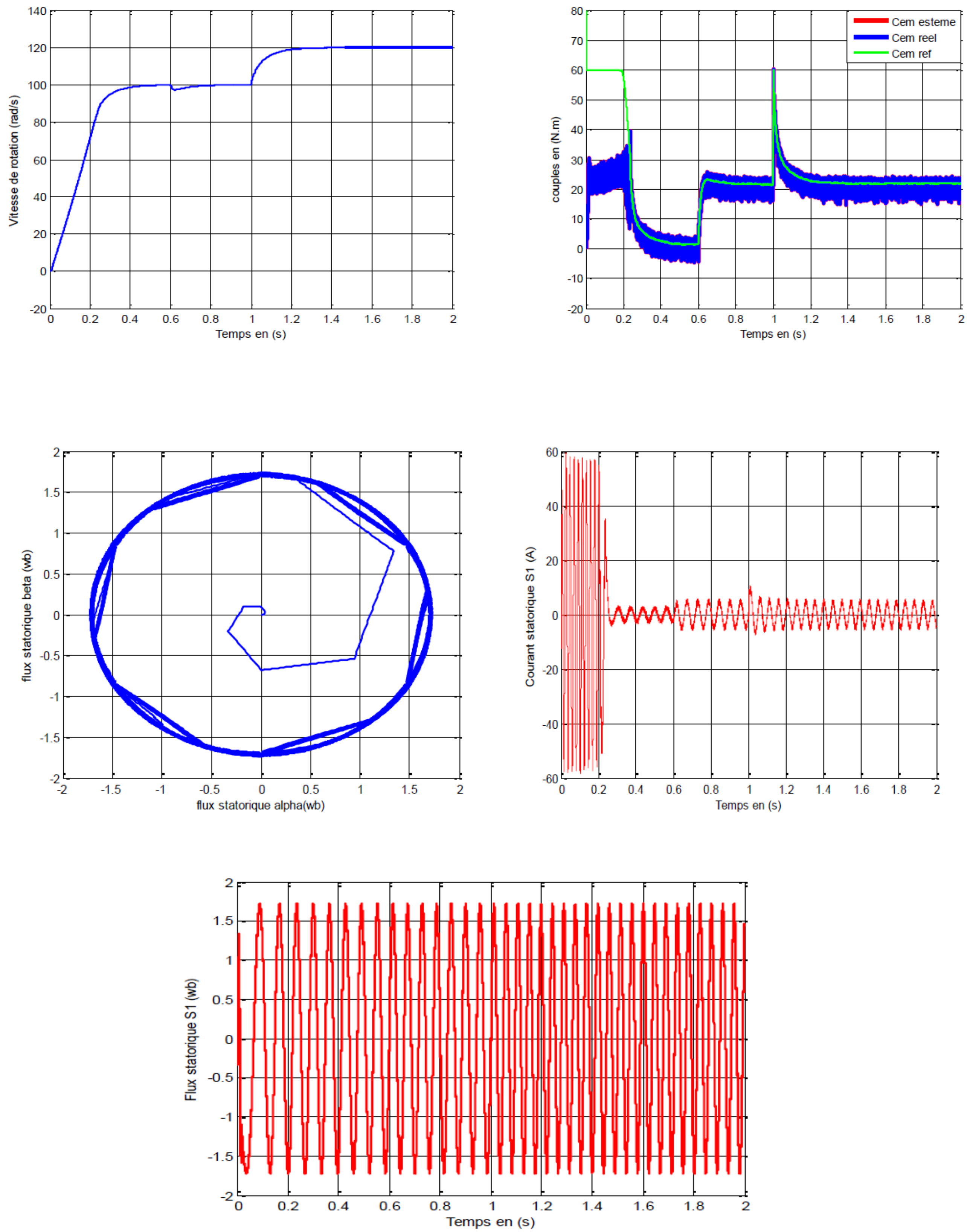
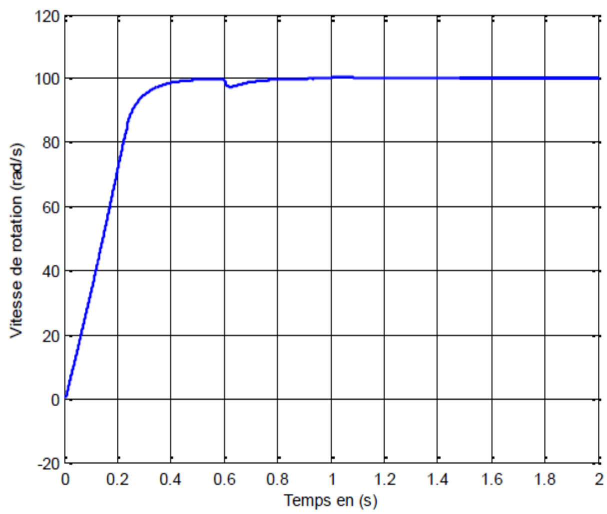


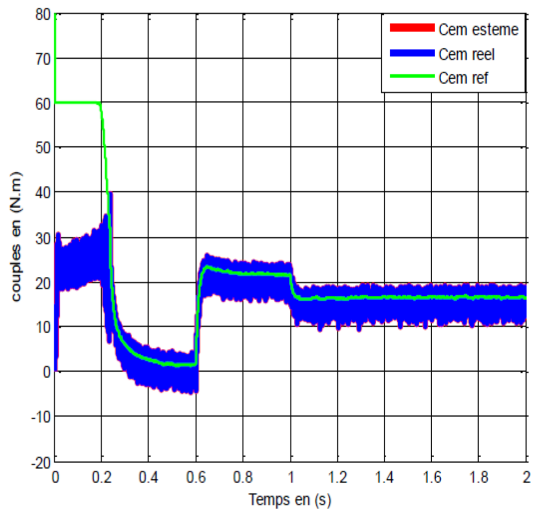
Fig. III. 8.Speed regulation, followed by speed variation

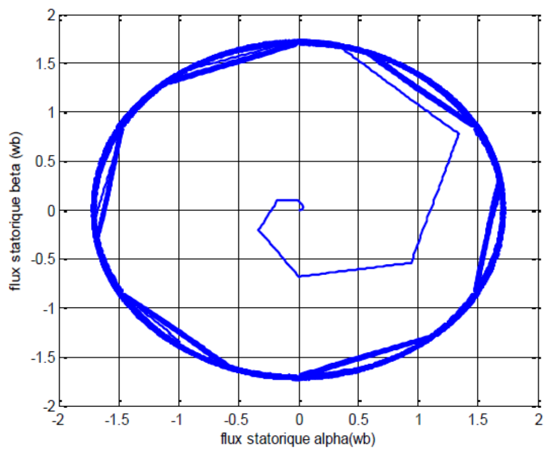
III.13.1.2 SECOND TEST

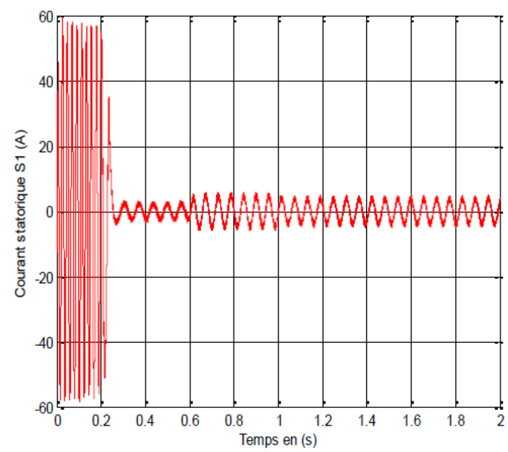
LOAD VARIATION

The simulation results obtained for the variation of the load (Cr= 20Nm to 15 N.m) represented by the following figures:









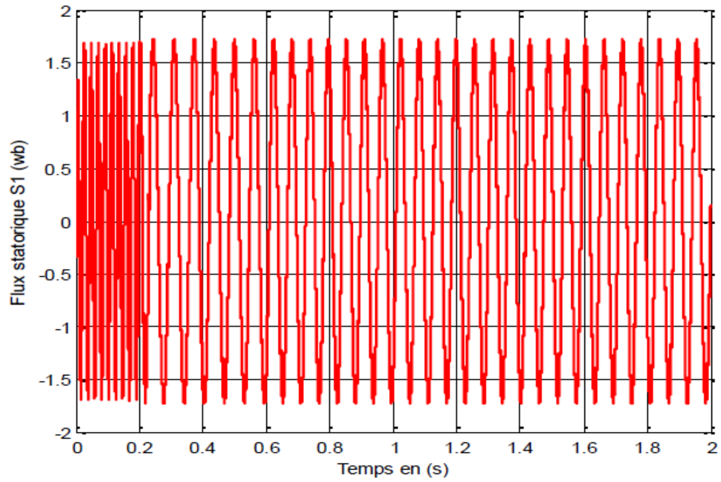


Fig. III. 9.Speed regulation, followed by load variation

Torque, speed, flux and current values show better accuracy and are less sensitive to load variations.

III.14 CONCLUSION

DTC is a control technique exploiting the possibility of imposing torque and flux on alternating current machines in a decoupled manner.

In this chapter, we presented the basic concepts of direct torque control and the application of this method to DSIM. It was concluded that insertion or removal of load causes peaks and oscillations in current and torque, but does not affect flux. Which shows the effectiveness of decoupling torque and flux controls in the case of DTC.

On the other hand, the performance of the DTC is linked to the accuracy in the estimation of the electromagnetic torque which essentially depends on the precision of the estimation of the stator flux, the selection tables of optimal voltage vectors and the correctors to hysteresis. These correctors, despite their simplicity, produce oscillations of the controlled quantities (flux and torque).

General Conclusion

General conclusion

The work presented in this memory is based on the exposition of the fundamental principles of direct torque control for a Dual Star Induction Machine (DSIM). Indeed, this strategy is based on the direct determination of the control sequence, applied to the inverter using pulse width modulation (PWM), and uses a torque and flux corrector by hysteresis whose function is to control the amplitude of the stator flux, torque and speed.

In the first part, we presented a general introduction and a complete definition of the advantages and disadvantages of multi-phase machines and the representation of the double-star asynchronous machine, as well as some examples of its fields of application which justify its effectiveness.

In the second part, we discussed the asynchronous machine and its modelling, highlighting the complexity and non-linearity of the model. Then, based on certain assumptions, we established the model of the asynchronous machine in Park's reference framework in order to linearize the system and facilitate the study. Then, we dealt with the modelling of the frequency converter. We presented the principle of operation and control of the three-phase inverter by giving the principles of (PWM) techniques.

In the third part, we presented the principle of direct torque control (DTC). Indeed, this strategy is based on the direct determination of the control sequence applied to the inverter through the use of hysteresis regulators and an optimal table whose function is to control the amplitude of the stator flux and the torque.

Can Developing Direct Torque Control (DTC) technology for Dual Star Induction Motors using artificial intelligence and deep learning can significantly improve the accuracy and efficiency of these systems. Deep neural networks enable better estimation of torque and flux, reducing torque and speed ripples and enhancing system stability. Additionally, reinforcement learning can develop adaptive control strategies that learn from errors and improve performance over time. Integrating these technologies opens new horizons for DTC applications in industrial and technological fields.

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