THE PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
THE MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
AMAR TELIDJI UNIVERSITY OF LAGHOUAT
FACULTY OF TECHNOLOGY
DEPARTMENT OF ELECTROTECHNIC

Master's dessertation

Domain : Science and Technology
Field : Automatic
Option : Automatic and systems

Theme

Synergetic Sensorless Speed Decoupled Control of Induction Motor using an Adaptive Sliding Mode Observer

---

by :

Aissaoui Bouchra

chairman:	*D^r BENMOUIZA Khalil*	M.C.A
Examiner:	*D^r AMEUR Aissa*	Professor
Supervisor:	*M^{me} KOUZI Kattia*	Professor

20/06/2023

Academic year 2022/2023

ملخص

هذا العمل يهدف لتطوير التحكم في محرك الحث من خلال البدء أولاً بنمذجة هذا المحرك ثم نجد أن هناك عدم خطية في معادلاته مما يجعل من الصعب التحكم فيه لذلك ننتقل إلى تحويل المحاور عن طريق PARK. بعد المحاكاة ببرنامج MATLAB، نلاحظ أن هناك اقترانًا بين عزم الدوران والتدفق، لتجنب هذه المشكلة، يتم اقتراح طريقة للتحكم اعتمادا على PI التقليدي و هي التحكم الشعاعي. بعد المحاكاة، نلاحظ أن التحكم ب PI التقليدي ليست مثالية في حالة حدوث اضطرابات خارجية ، لذلك نستخدم المنظم الغامض الذي يمنحنا نتائج مثالية مقارنة بالمنظم التقليدي.

بعد ذلك، نقوم بالتحكم لتحسين نظامنا، ونختتم مع المراقب التكيفي في وضع الانزلاق الذي يمنحنا نتائج مثالية لتحسين متانة مراقبنا الكامل في حالة وجود اختلاف في خاصيات المحرك ولديه تتبع جيد للقيمة الفعلية الحقيقية.

الكلمات الرئيسية: محرك الحث، تحول Park، التحكم الشعاعي، منظم PI، منظم غامض، مراقب، وضع الانزلاق.

Abstract:

This articles proposes for making the development of the control of induction motor in first we start with the modeling of this motor then we find that there is a non-linearity in its model After the simulation which make it difficult to control so we go to the transformation of park. with MATLAB we observe that there is a coupling between the torque and the flux, to avoid this problem a victor control method with conventional PI is proposed. After the simulation we notice that the PI classic is not ideal in the case of disturbances, so we use the fuzzy regulator which gives us perfect results compared to the PI regulator.

After that we do the synergetic control to improve our system, and we conclude by the adaptive observer by sliding mode which gives us ideal results improve the robustness of our full observer where there is a parameter variation and it has a good pursuit to the real parameter.

Key words: induction motor, transformation of park, victor control, PI regulator, fuzzy regulator, observer, sliding mode.

Résume

Cet article propose pour faire le développement du contrôle du moteur à induction en commençant d’abord par la modélisation de ce moteur puis on trouve qu’il y a une non-linéarité dans son modèle qui rend difficile à contrôler donc on passe à la transformation Après la simulation avec MATLAB nous observons qu’il y a un couplage entre de park. le couple et le flux, pour éviter ce problème une méthode de contrôle vectorielle avec PI classique est proposée. Après la simulation, nous remarquons que le contrôleur PI n’est pas idéal en cas de perturbations, nous utilisons donc le régulateur flou qui nous donne des résultats parfaits par rapport au régulateur classique.

Après cela, nous faisons le contrôle synergétique pour améliorer notre système, et nous concluons par l’observateur adaptatif en mode glissant qui nous donne des résultats idéaux amélioré la robustesse de notre observateur complet où il y a une variation de paramètre et il a une bonne poursuite du paramètre réel.

Mots clés : moteur à induction, , transformation de Park, commande vectorielle, régulateur PI, régulateur flou, observateur, mode de glissement.

Acknowledgements

Praise be to the Almighty God who has given me faith, courage, and patience to carry out this work.

Second, i would like to express my appreciation to my dear supervisor Mme. KOUZI Katia from Laghouat university for her patience, guidance and encouragement, she really gave me the support i needed, May Allah bless her,
a special word must go to the members of the jury.

I would like to thank everyone who helps me to improve my work. and who give me any remark that helped me to perfect this manuscript.

Last and not least, i would thank all the teachers and the administrative staff of our department and all my friends from automatic and systems promo of 2018-2023.

Finally, I express my gratitude to all those who have contributed in one way or another to the development of this work.

Aissaoui Bouchra

Dedication

I dedicate my humble effort to my loving father Abdelkader and mother Aisha whose affection, love and pray make me able to achieve such success.

To my dear grandmother Fatma and the souls of my grandparents who have left us.

To my soul mates sister Mamma and brothers Abdeldjalil and Youcef.

To all my extended family uncles and aunts.

To my little dears Lokman , Djoud and Amdjad and especially my lovely niece Aisha Watine.

To the special person who has been my support throught my career, God bless him

Aissaoui BOuchra

Contents

A Appendix A

List of Figures

List of Tables

List of Symbols

- C_e: Electromagnetic torque (N.m)
- C_r: Resistance torque (N.m)
- f: Network frequency (Hz)
- i_{dqs}: Components of stator, direct and quadrature current (A)
- i_{dqr}: Components of rotor, direct and quadrature (A)
- $i_{\alpha\beta s}$: Composantes du courant statorique dans le référentiel du stator (A)
- J: Moment of inertia (Kgm^2)
- k: Discrete moment (t)
- k_1, k_2: Observer gains by sliding modes (without unity)
- K_p, K_i: Classical PI regulator coefficients (without unity)
- $k_e, k\Delta e, k\Delta cem$: Fuzzy PI regulator coefficients (without unity)
- $k_e 1, k\Delta e1, kCem1$: Fixed adaptation gains of the blurred gains regulator adapted fuzzy (without unity)
- L_r: Circular cyclic inductance (H)
- L_s: Statoric cyclic inductance (H)
- f_r: Coefficient of friction (N.s)
- C: Filter capacity (F)
- L: Filter inductance (H)
- L_r: Circular cyclic inductance (H)

- M: Mutual cyclic inductance (H)
- Ω: Rotor mechanical rotation speed (tr/mn)
- ω_g: Sliding pulse (rad/s, tr/mn)
- ω_s: Stator pulsation (rad/s, tr/mn)
- ω_r: Rotor angular speed of rotation (rad/s, tr/mn)
- p: Number of pole pairs (without unity)
- Ψ_{dqs}: Components of stator, direct and quadrature flux (Wb)
- $\Psi_{\alpha\beta s}$: Components of the rotor flux in the stator (Wb)
- R_r: Resistance of a rotor phase (Ω)
- R_s: Resistance of a stator phase (Ω)
- σ: Coefficient of dispersion of Blondel (without unity)
- σ_r: Rotor time inverse constant (s^{-1})
- Tech: Sampling period (s)
- T_r: Rotor time constant (s)
- θ: Rotor mechanical rotation angle (rad)
- θ_s: Electrical position of the referential rotating in relation to the stator (rad)
- $\hat{}$: Sign of an estimated size (without unity)
- ref: Sign of a reference quantity (without unity)
- $\hat{x}$: Estimated state
- v_{dqs}: Components of Stator, Direct and Quadrature Voltage (V)
- v_{dqr}: Components of rotoral, direct and quadrature voltage (V)
- $v_{\alpha\beta s}$: Stator voltage components in the stator reference (V)

GENERAL INTRODUCTION

PROBLEM FORMULATION

Basis on of its structure simplicity, the robustness, its low cost, and does not require a maintenance, Induction Motor (IM) yields technological prospects in several industrial applications. However, the IM is characterized by non-linear model, coupling between the magnetic flux and the electromagnetic torque, which makes its control more complex compared to that of the DC machine. With the availability of low-cost and excellent performance digital signal processors (DSPs) and dedicated chips, makes IM control a practical choice for a large range of applications [27].

Vector control offers good performance during transient and permanent phases. The first controllers used are the PIDs. They have the advantage of simplicity of implementation and ease of synthesis. Nevertheless, they have poor robustness with respect to the machine parameter variations.

Synergetic control has only evolved in recent years, similar in its conceptual approach to sliding mode control; it is seems as a powerful methodology for robust control design. It ensures a minimization of chattering with in addition robustness. The synergistic technique not only reduces the size of system model, but also ensures the stability of the fed system generally. Synergetic control theory has several advantages it is well suited for digital control purpose and it operates at constant switching frequency; which simplifies filtering design; and reduces chattering phenomena, while maintaining the intrinsic robust features of sliding mode control [9].

Moreover, vector control requires good knowledge of mechanical speed and flux. For these reasons, in recent years there has been a growing industrial interest in high-performance drives for IM without sensors due to their many advantages, such as low cost, low maintenance, high reliability. The sensorless control contributes to the costs reduction, and solves many of the implementation problems encountered: lack of space, severe environment. The main objective of the current efforts is to improve the performance of observers at low speed and to develop a robust observer with respect to parametric variations and external disturbances.

In sensorless controls, the speed information must be reconstructed from the electrical quantities. Several strategies can be distinguished: those based on the machine model behavior, which relies in particular on observation techniques from the IM terminal voltages and currents [6][22]. Other strategies that could be called an approach without a model are based on a heuristic approach close to artificial intelligence: neural networks and / or fuzzy [19]. There are also more physical methods, classified without a model, based on the estimation of the position from the information collected on the existing projections in the machine. In the adaptive observers, the speed is estimated by additional equations based on the adaptive control theory. This allows one to find out the analytical conditions for stability. Among these strategies, The sliding mode observers seems an interesting choice, in terms of robustness against parameter variations, external disturbance, and fast convergence [23].

Based on above point, in this work we present robust synergetic adaptive speed- sensorless vector control of IM. The sliding-mode observer detects the rotor flux components in the stationary reference frame, using the motor measurement (current, voltage). The motor speed is estimated by addition of Lyapunov function.

OUTLINE OF THE THESIS

The thesis is constructed by three chapters given as follows:

The first chapter of thesis is dedicated to modeling of IM according to d.q frame, and its power supply composed by voltage inverter with PWM control. Besides, the application of indirect of vector control to IM will well explained. At the end of chapter, the performances of vector control will be given by simulation results.

The second chapter is dedicated to design of different robust controllers of IM speed regulation. We will use two kind of regulators such as: Fuzzy PI and synergetic controller (SC). Different digital simulation will be given to confirm this assertion.

The last chapter deal with the conception of an adaptive sliding-mode observer for speed-sensorless control of IM. The suggested observer estimate the rotor flux components in the stationary reference frame from IM. The speed is estimated by adding a Lyapunov function. Several tests were carried out under various dynamic operating conditions, such as sudden changes in command speed, to determine the efficacy of the proposed observer and to verify the stability of system.

To close this work, a general conclusion will be given, in regard to the continuation of this work, different perspectives will be suggested.

Chapter 1

Induction motor modeling and vector control

1.1 Introduction

Induction motor is a hesitant current machine without contact between the stator and the rotor.The term asynchronous comes from the fact that the speed of these machines does not necessarily correspond to the frequency of the currents they cross the asynchronous machine has always been very competitive by the simultaneous machine in high power areas, until the advent of energy electronics. Today we find the induction motor located in most of the industrial application because it is robust, available with low cost and high standard. Without forgetting the maintenance of this type of motors is easy to do. These features are currently the most used machine to achieve speed variations [10].

1.2 induction motor model

The mathematical model of an electric machine is a model of the real machine that allows to render an image of what can be observed experimentally, it provides an appreciable help in solving technical problems in this part to make the modelling of the induction motor.

1.2.1 IM modelling in the three-phase plan abc

Let a three-phase induction machine with stator and rotor represented schematically by the following figure:

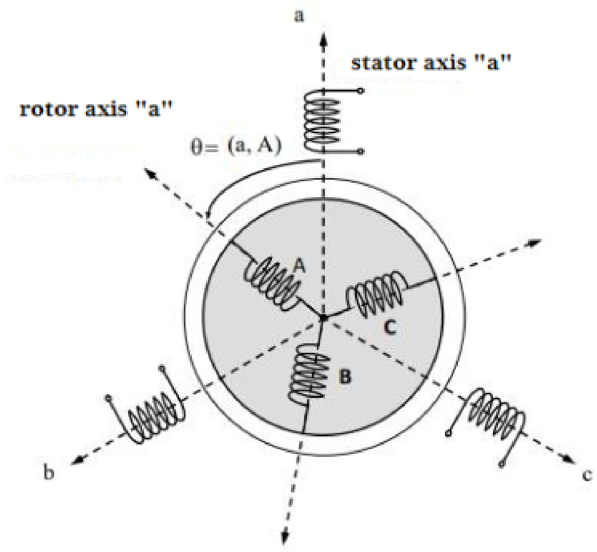

Figure 1.1: Schematic representation of a three-phase induction motor

The voltage equations

For the stator

$$[U_{sabc}] = R_s[i_{sabc}] + [L_s]\frac{d}{dt}[i_{sabc}] + \frac{d}{dt}\{[L_s][i_{rABC}]\} \tag{1.1}$$

For the rotor

$$[U_{rABC}] = R_r[i_{rABC}] + [L_r]\frac{d}{dt}[i_{rABC}] + \frac{d}{dt}\{[L_{sr}][i_{sabc}]\} \tag{1.2}$$

Through these equations we can observe the existence of a relationship between variables and this is what we call non-linearity which makes the IM difficult to control and to avoid this problem we will go to the transformation of Park.

1.3 Application of the park transformation on three-phase induction motor

The transformation of Park is a transformation of the axes, made corresponding to the two windings of the original machine followed by a rotation, equivalent windings from the electric and magnetic point of view.for the purpose of making the mutual inductances of the model independent of the angle of rotation[21]. The transformation that reflects this transition from the three-phase system to the two-phase system (d, q) is called Park, and given by:

$$[U_{dqo}] = [A][U_{abs}] \tag{1.3}$$

$$[i_{dqo}] = [A][i_{abs}] \tag{1.4}$$

$$[\psi_{dqo}] = [A][\psi_{abs}] \tag{1.5}$$

With [A]:is the park matrix

$$[A] = \begin{bmatrix} \cos\theta & \cos(\theta - 2\frac{\pi}{3}) & \cos(\theta + 2\frac{\pi}{3}) \\ -\sin\theta & -\sin(\theta - 2\frac{\pi}{3}) & -\sin(\theta + 2\frac{\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

1.3.1 State form of the induction motor model in the mark (d, q) Linked to the rotating field

Under the assumptions of magnetic circuits linearity, and assuming sinusoidal distributed air-gap flux density, the equivalent two-phase model of induction motor, represented in a synchronous frame (d,q) and expressed in state-space form, is a fourth-order model [16]:

$$\dot{x} = Ax + Bv_s \tag{1.6}$$

where

$$x = [i_s^T \psi_r^T]^T, i_s = [i_{ds} i_{qs}]^T, \psi_r = [\psi_{dr} \psi_{qr}]^T, V_s = [V_{ds} V_{qs}]^T$$

The system matrices are given by:

$$A = \begin{bmatrix} -\frac{1}{\sigma L_s}(R_s + \frac{M^2}{L_r}\sigma_r) & \omega_s & \frac{M}{\sigma L_s L_r}\sigma_r & \frac{PM\Omega_r}{\sigma L_s L_r} \\ -\omega_s & -\frac{1}{\sigma L_s}(R_s + \frac{M^2}{L_r}\sigma_r) & -\frac{PM\Omega_r}{\sigma L_s L_r} & \frac{M}{\sigma L_s L_r}\sigma_r \\ M\sigma_r & 0 & -\sigma_r & (\omega_s - P\Omega_r) \\ 0 & M\sigma_r & -(\omega_s - P\Omega_r) & -\sigma_r \end{bmatrix}$$

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

where

$\sigma = 1 - \frac{M^2}{L_s L_r} \quad and \quad \sigma_r = \frac{R_r}{L_r}$.

The mechanical modeling part of the system is given by:

$$J\frac{d\Omega_r}{dt} = C_{em} - T_l - K_f\Omega_r \tag{1.7}$$

$$C_{em} = \frac{3}{2}P\frac{M}{Lr}(\psi_{dr}i_{qs} - \psi_{qr}i_{ds}) \tag{1.8}$$

1.3.2 Model of induction motor in mark linked to the stator

$$\frac{d}{dt}\begin{bmatrix}\hat{i_s}\\ \bar{\psi}\end{bmatrix} = \begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix}\begin{bmatrix}\hat{i_s}\\ \bar{\psi}\end{bmatrix} + \begin{bmatrix}b\\ 0\end{bmatrix}\bar{V_s}$$

Or in vector

$$\frac{dx}{dt} = Ax + Bv_s \qquad State \quad equation. \tag{1.9}$$

$$y = \bar{i_s} = Cx \qquad Output \quad equation. \tag{1.10}$$

$$\bar{x} = \begin{bmatrix}\bar{i_s}\\ \bar{\psi}\end{bmatrix} \qquad State \quad vector.$$

with

$\bar{i_s} = \begin{bmatrix}i_{s\alpha}\\ i_{s\beta}\end{bmatrix}$ Stator current vector.

$\bar{\psi}r = \begin{bmatrix}\psi_{r\alpha}\\ \psi_{r\beta}\end{bmatrix}$ Rotor current vector.

$\bar{v_s} = v_s = \begin{bmatrix}v_{s\alpha}\\ v_{s\beta}\end{bmatrix}$ State voltage vector.

$a_{r11} = -(\frac{R_s}{\sigma L_s} + \frac{M^2\sigma_r}{\sigma L_s L_r})$

$A_{11} = a_{11}I$

$A_{12} = \frac{M}{\sigma L_s L_r}(\sigma_r I - \omega_r J) = a_{r12}I - a_{i12}J$

$A_{21} = a_{r21}I, a_{r21} = \sigma_r M,$

$A_{22} - \sigma I + \omega_r J = a_{r22}I + a_{i22}J, I = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, J = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$

$$b = b1I, \begin{bmatrix} b_1 \\ 0 \end{bmatrix}, b_1 = \frac{1}{\sigma L_s}$$

$\begin{bmatrix} I & 0 \end{bmatrix}$ Output Matrix; I and 0: Identity and dim zero matrices 2*2.

1.3.3 Modeling of the induction motor -voltage inverter association

Generally the asynchronous machine is powered by two cascade converters, The machine side converter is a voltage inverter at MLI, and the side converter network is a dual-phase three-phase diode rectifier separated by a low-pass filter (LC) as follows:

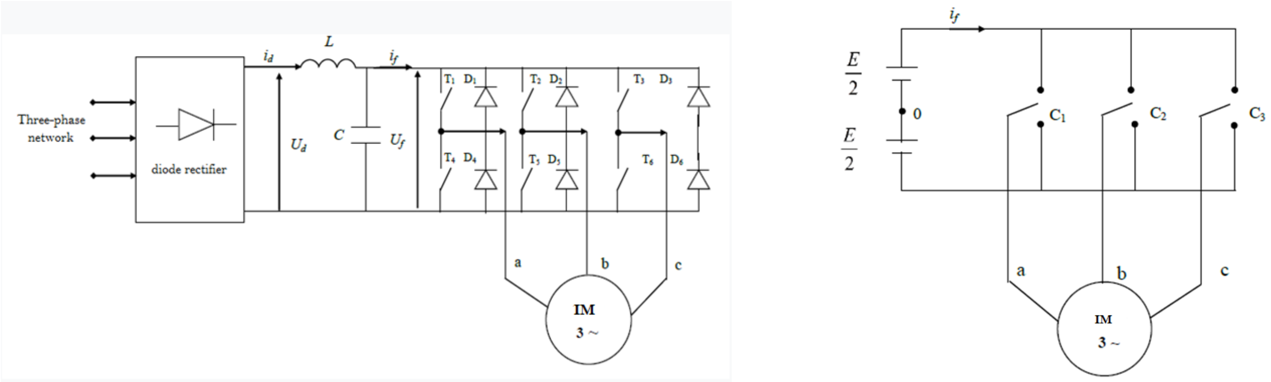

Figure 1.2: Diagram of the induction motor- voltage inverter by switches association

Each switch C is associated with a logic function F_i with (i=1.3), such as: If F_1 = 1 then phase a is connected to the positive terminal of the DC source E. And F_1 = -1 then phase a is connected to negative terminal of DC source E.
Then

$$U_{ab} = \frac{1}{2}(F_1 - F_2)E$$
$$U_{bc} = \frac{1}{2}(F_2 - F_3)E$$
$$U_{ca} = \frac{1}{2}(F_3 - F_1)E$$

The current at the input of the inverter has the expression:

$$i_f = F_1 i_a + F_2 i_b + F_3 i_c \tag{1.11}$$

1.3.4 Hysteresis MLI control

The hysteresis MLI control forces the phase current to continue the reference current. The imposition of sinusoidal currents on the asynchronous machine guarantees constant electromagnetic torque. 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 that produces pulses impulses triggering and blocking of the inverter switches in order to limit the current of the phase in a hysteresis band $2\Delta i$ around the reference current[20]. Switching conditions of the three static switches Fi (i=1,3) of The inverter is defined in terms of corresponding logical states as follows:

$$Fi = -1 \ \ if \ \ i_i \geq i_{ref} + \Delta i \tag{1.12}$$

$$Fi = 1 \ \ if \ \ i_i \leq i_{ref} - \Delta i \tag{1.13}$$

$$Fi = F_{(i-1)} \ \ i_i = i_{ref} \tag{1.14}$$

With i (i=1, 3): are the currents of the stator phases (ia,ib,ic).
i_{ref} (i=1, 3): are the reference currents from the three inverter arms.
Δi is the band of hysteresis, it is chosen so as not to exceed the permissible switching frequency of controlled semiconductor, and Sufficiently minimize harmonics of currents.

1.3.5 Simulation results and discussion

The numerical resolution of the differential equations (state space) and the dynamic equation was solved by using the MATLAB software. IM parameters used in the simulation are given in the appendix (A). two tests were presented :

1.3.6 Operating without load

Figure (1.3) shows the evolution of the characteristics of the IM without load operation (Tr=0) :

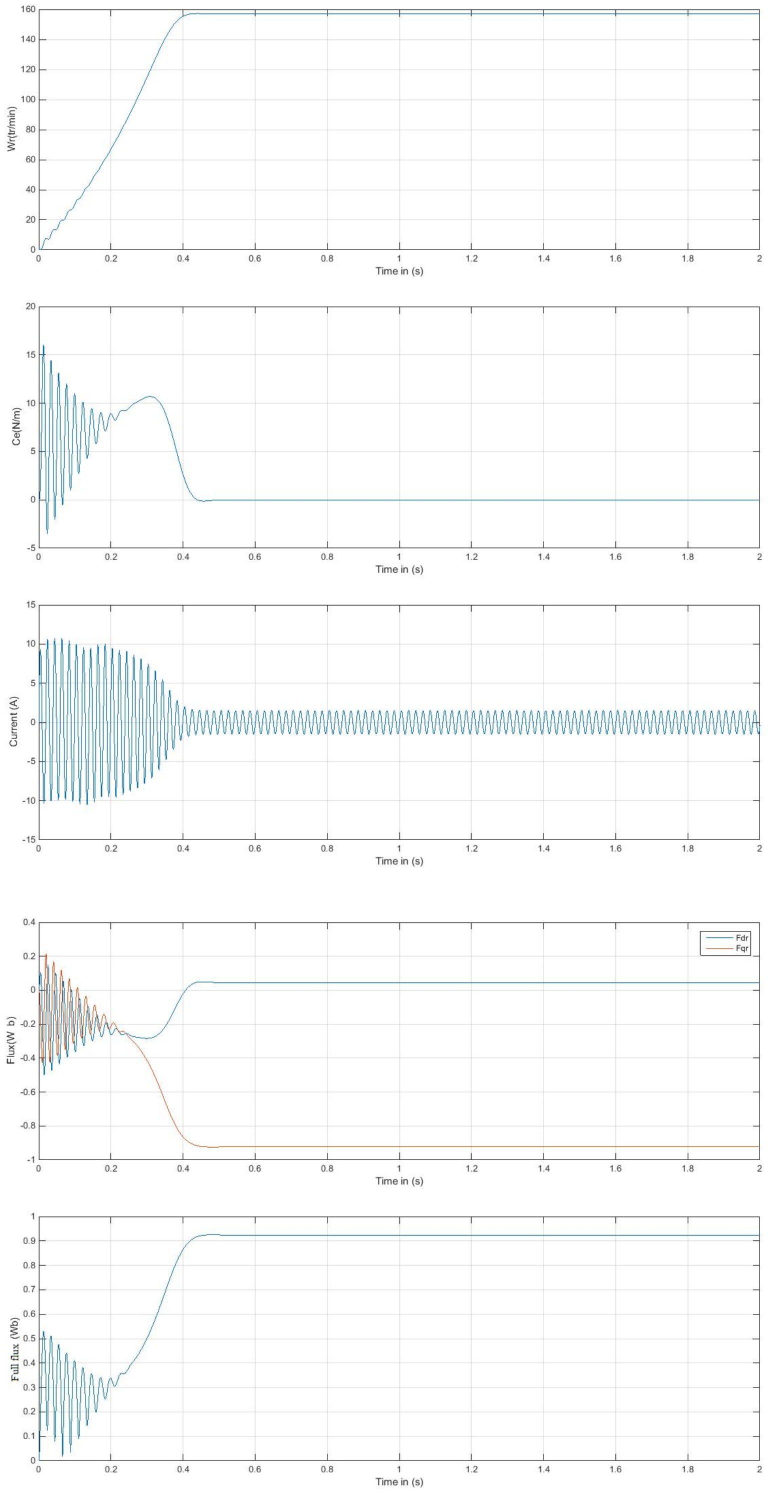

Figure 1.3: Dynamic and static Characteristic of IM without load torque

1.3.7 Operating with load Tr=5 N.m

In this test, we introduce load torque $T_r = 5$ N.m at t = [0.8,1.2]s

Simulation results and discussion of induction motor modelling with load

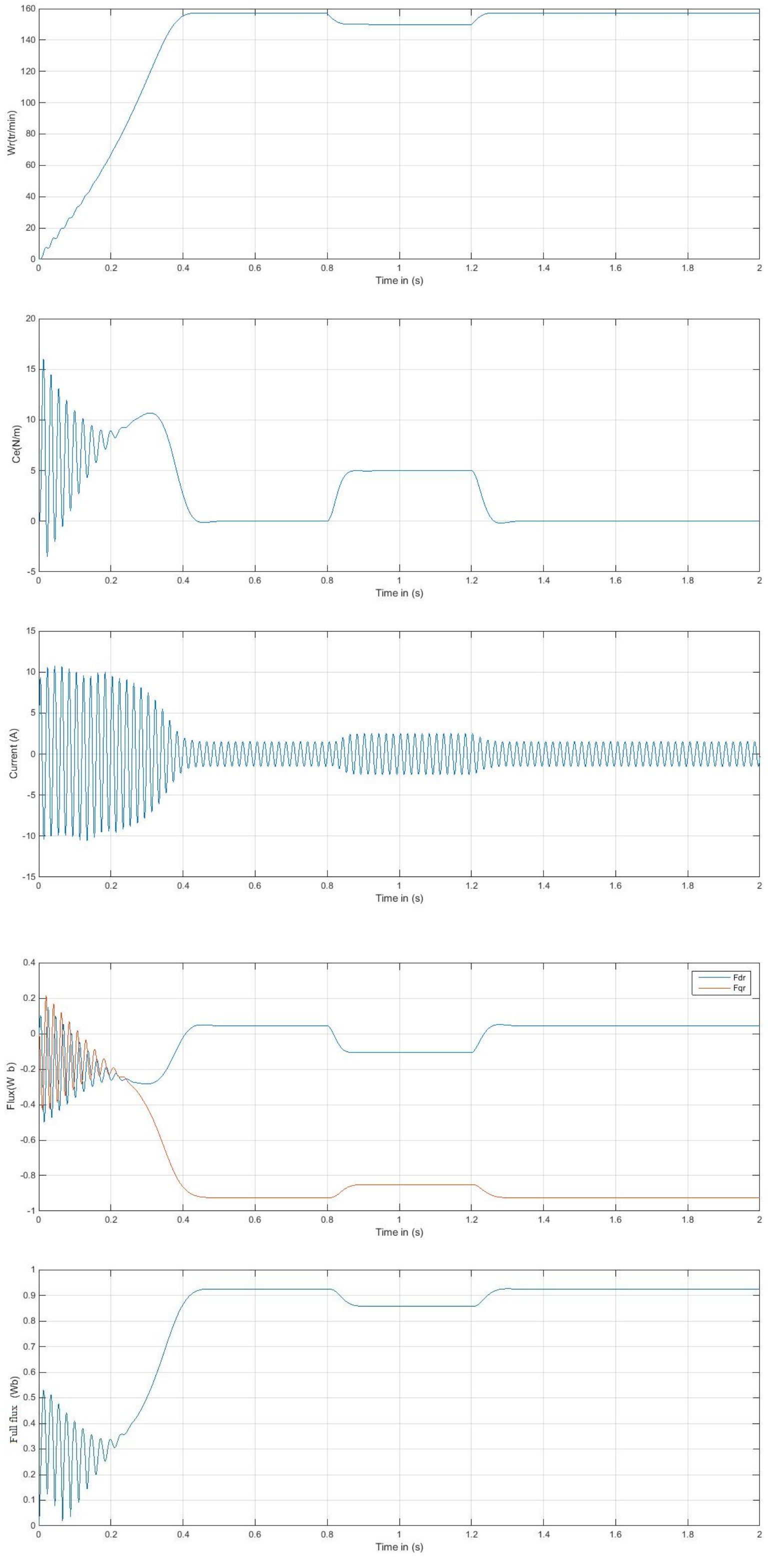

Figure 1.4: IM characteristic during load application Tr= 5N.m at t = [0.8-1. 2]s

Discussion

From these figures we can observe that there is a relationship between the torque and flux and this is the reason of the non-linear of our motor. so we go to work with the vector control to make a decoupling between the torque and flux which mean avoid the problem of non-linearity.

1.4 IM Control technique

1.4.1 Introduction

The control of the induction motor has paid much attention in the past few decades. One of the most popularly developments in this area has been the Vector Control (VC),where partial feedback linearization, together with a proportional integral (PI) controller is used to regulate the motor state. The following section will deal with principal aspects of vector control, and its application to IM.

1.4.2 Principle of flux orientation control (F.O.C)

Examination of the expression of asynchronous machine torque shows that it results from a product difference of two quadrature components, rotor flux and stator currents which has a complex coupling between machine quantities. The objective of flux orientation control is to decouple the quantities responsible for the magnetization of the machine, And the production of torque. Mathematically, the law of the control consists in establishing all the transformations to pass from a system possessing a structural double nonlinearity to a linear system that ensures the independence between the creation of the flux and the production of the torque as in a separate excitation direct current machine. Flux orientation control consists of adjusting the flux by one component of the current and the couple by the other component. To do this, you must choose a «d, q» axis system. A judicious choice of the angle of orientation of the «d, q» marker leads to the alignment of the «d» axis on the result of the flux, this alignment allows the cancellation of the transversal component of the flux. It is possible to choose the reference axes according to one of the machine flux, at know the stator flux, rotor flux or air flux From which the conditions of the orientation of the:

Stator flux

$$\phi_{ds} = \phi_s and \phi_{qs} = 0 \tag{1.15}$$

Air gap flux

$$\phi_{dr} = \phi_r and \phi_{qm} = 0 \tag{1.16}$$

Rotor flux

$$\phi_{dr} = \phi_r and \phi_{qr} = 0 \tag{1.17}$$

In the three reference systems, the torque is proportional to the flux product by the current component iqs but only the choice of rotoric flux allows a decoupling characterized by an independence of flux and current component in quadrature with flux, Moreover, this choice makes it possible to have a high starting torque which justifies the use of this type of flux orientation[17].

1.4.3 Vector control types

There are two main types of vector control -The direct vector control. - The indirect vector control.

The direct vector control

This control method was proposed by Blaschke. In this case, the knowledge of the flux module and its phase is required to ensure decoupling between torque and flux regardless of the point of operation in order to access information concerning the amplitude and phase of the flux, it is possible to use sensors. The disadvantage of this method is that the sensors are mechanically fragile and cannot work under severe conditions such as vibration and excessive heating.

The indirect vector control

The principle of this method consists in not measuring (or estimating) the amplitude of flux but only its position, the idea is proposed by Hasse. It consists in estimating the position of the flux vector. This method has been favoured by the development of microprocessors, it is very sensitive to the parametric variations of the machine. It is important to note that the indirect method is the simplest and most used than the direct method, but the choice between the two methods varies from application to application[20].

1.4.4 Induction Motor Current Model

When the presence of the frequency converter is unknown, assuming it is ideal, and the effect of the stator dynamic, we obtain the model of the induction motor current: This phenomenon put the AC machine as the perfectly compounded separate excitation content current machine or there is a natural decoupling between torque and flux.

1.4.5 Speed regulation of the IM controlled vector by a conventional PI

The block diagram of the speed control of a drive based on the asynchronous flUX machine oriented by a conventional PI controller is represented by the following figure:

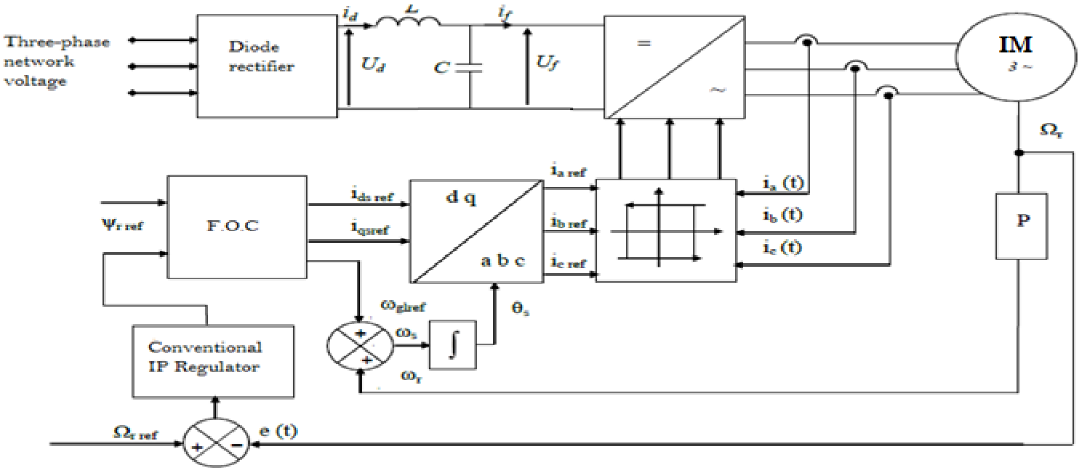

Figure 1.5: Indirect vector control of IM

1.4.6 Simulation results and discussion

In order to show how the overall dynamics of the control system can be improved, several tests were performed to evaluate the performance of the presented control. So we set the values of PI regulator as follow: kp =0.5, ki = 3.06 . From t=0 to t=0.8 we don't have any charge, in t=0.8 to t=1.2 we apply a charge Cr=5 N/m, Right now we can observe that there is a disturbance in the system caused by this load. Cr also has effect on rotation speed so we make speed variation in t=4 to t=6 cheeking the robustness of the control .in t=8 we push our system to go to 0 which mean stopping the motor in t=8 we restart the machine with speed rotation equal to 10 tr/min.

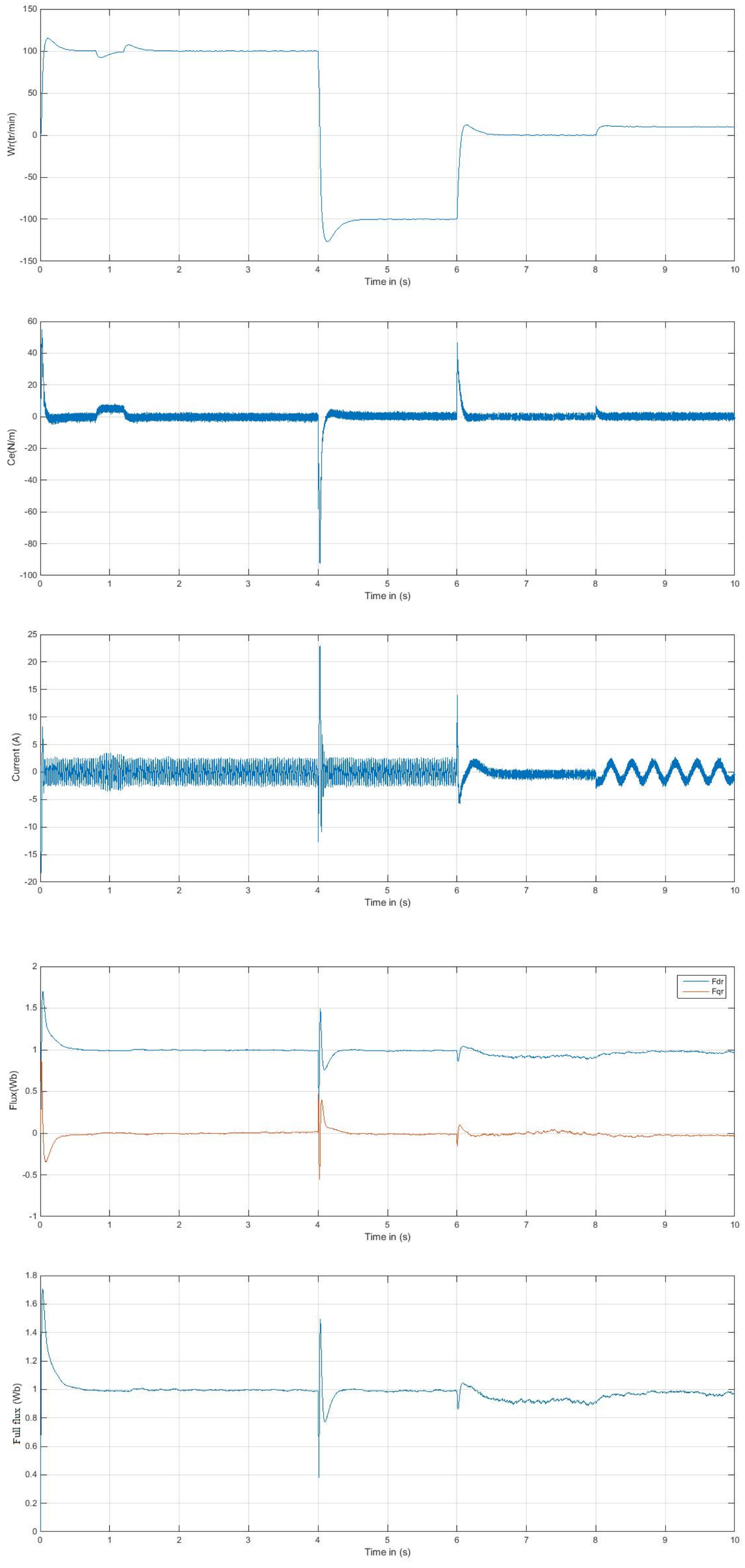

Figure 1.6: Performances IM vector control with classical PI of 1.2.

Discussion

From these figures we can observe the effect of the charge in our system we can say that PI regulator does not has a good reaction of disturbances so we go to work with the fuzzy regulator for evaluate the performances of our system.

1.5 Conclusion

In this chapter the modeling of IM and it's power supply was presented. Then the concept of vector control for induction machine has been introduced. From simulation results, one can notice that the vector control of IM with PI classical, provide acceptable performances.

In order to enhance the robustness of IM vector control, the next chapter will deal with robust controllers such as fuzzy logic control, and synergetic control

Chapter 2

Fuzzy and Synergetic Vector Control of Induction Motor

2.1 Introduction

Fuzzy logic is a mathematical approach that deals with uncertainty and imprecision in decision-making processes. Unlike traditional logic, which operates on crisp, binary values (0 or 1).

The application of fuzzy logic in the control of induction motors has gained significant attention due to its ability to handle the nonlinear and uncertain nature of these systems.

To date, all fuzzy controllers are based on the traditional PI–fuzzy controller. This one could result in an inability to fully address certain uncertainties and disruptions of the system to be controlled. To solve this problem, the a fuzzy adaptation approach to IP gains, the mechanism for which is developed from the very concept of fuzzy logic in contrast to conventional mechanisms derived from mathematical models. The interest of this fuzzy adaptation lies in its ability to compensate in real time for any parametric change taking place.

After vector control and their results in progress to a new approach to controlling non-linear systems is the synergistic approach, work on the application of the synergistic controller, has shown that it offers a better robustness in terms of possible parametric variations as well as the level of efficiency high simplicity of design and flexibility of the synergistic controllers.

In this chapter start with the fuzzy command and make comparison results with the conventional command.Then proceed to the synergetic command and do a robustness test of this method.

2.2 History and principle of fuzzy logic

Fuzzy logic is a technique of artificial intelligence, just like neural networks and genetic algorithms, has been the subject of a significant amount of scientific research in recent years. In 1965, Professor L. Zadeh proposed for the first time, the theoretical basis of this logic in a celebrated article entitled (Fuzzy set)[3][25][26].

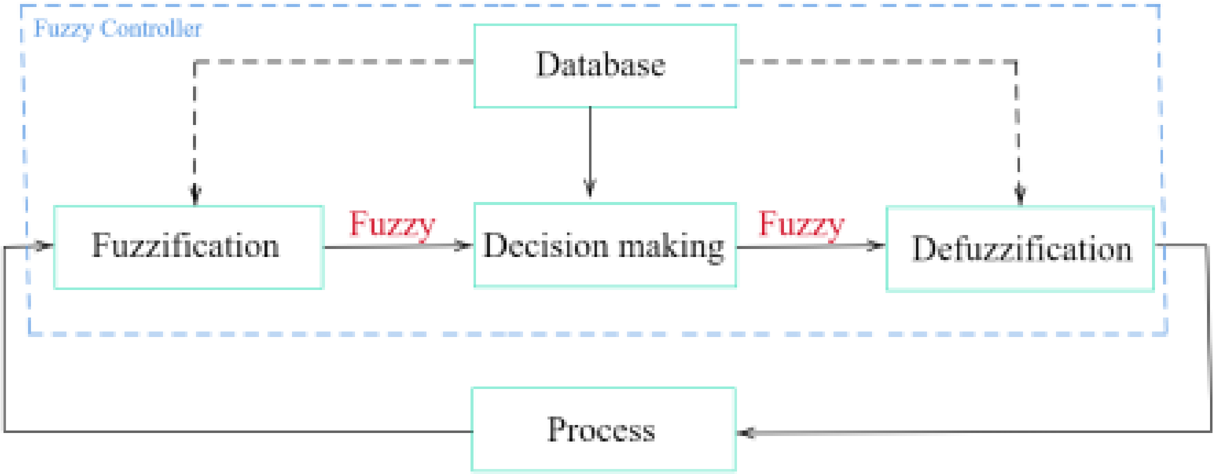

Figure 2.1: General block diagram of a fuzzy controller

Fuzzification

It consists of transforming real quantities into linguistic variables that are associated with a database with sets characterizing them. The basic rules: those are the rules that make it possible to link fuzzy input and output variables, they have the form: if-then.

The inference method

It calculates the fuzzy set associated with the command and is done by the fuzzy inference operations and the aggregation of the rules. Fuzzy inference relies on the use of a fuzzy implication operator for each rule to be analyzed. Two approaches are commonly used, Mamdani and Larsen.

The defuzzification

This stage consists of transforming the fuzzy information decided by the inference mechanism into a numerical or physical magnitude to realize the control law of the system.

2.3 The design of a fuzzy controller

The design of a fuzzy controller requires careful consideration of the system dynamics, defining appropriate linguistic variables, formulating effective fuzzy rules, and selecting suitable membership functions. It often involves a combination of domain expertise and knowledge, along with experimentation and tuning to achieve desired control performance.

For the fuzzy regulator thus designed, we use:

- An integral proportional structure with error and variation of speed relative to its reference.
- Output representing electromagnetic torque variation[20][12][11].

Hence the input-output variables can be normalized as follows:

$$e_n = \frac{e}{k_e}; \Delta e_n = \frac{\Delta e}{k_{\Delta e}}; \Delta C_{em} = \frac{\Delta C_{em}}{k_{\Delta Cem}}$$

with , $e = \Omega_{ref} - \Omega$:speed error; $\Delta e = e_k - e_{k1}$error variation. $k_e, k_{\Delta en}, k_{\Delta Cem}$: are normalization gains that can be constant (or even variables).

In our work we choose symmetrical triangular belonging functions are used on a universe of standardized speech in the range [-1 1] for each variable as shown in next figure for the error, variation error:

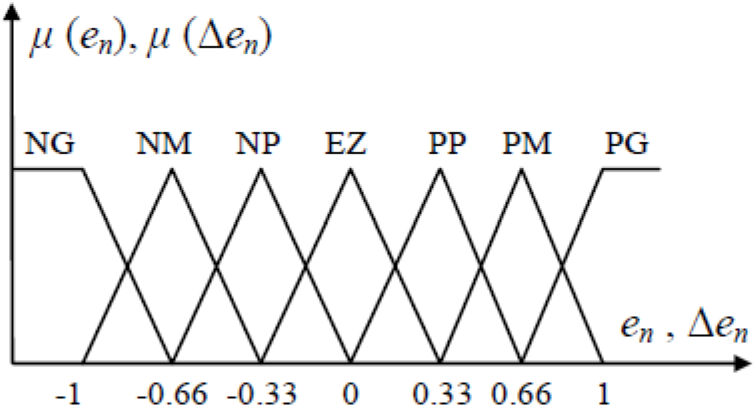

Figure 2.2: Functions of belonging the output variable(e_n, Δ_{en}).

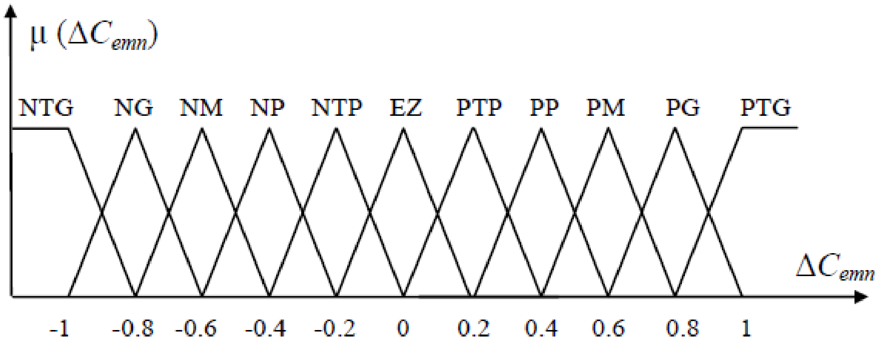

Figure 2.3: Functions of belonging the output variable (Δ_{Cemn}).

With :
NTG: Negative Very Large.
NG:Large Negative.
NM:Medium Negative.
NP:Negative Small.
NTP: Very Small Negative EZ:Equal to zero.
PTP: Very Small Positive.
PP:Positive Small.
PM:Positive Medium.
PG: Positive Large.
PTG: Positive Very Large.

The fuzzy rules, allowing to determine the output variable of the regulator according to input variables are deduced from the Mac-Vicar Inference table. This brings together, in this case, 49 rules as the following table shows:

Δen	NG	NM	NP	EZ	PP	PM
NG	NTG	NTG	NG	NM	NP	NTP
NM	NTG	NG	NM	NP	NTP	EZ
NP	NG	NM	NP	NTP	EZ	PTP
EZ	NM	NP	NTP	EZ	PTP	PP
PP	NP	NTP	EZ	PTP	PP	PM
PM	NTP	EZ	PTP	PP	PM	PG
PG	EZ	PTP	PP	PM	PG	PTG

Table 2.1: Inference matrix.

This inference matrix is based on a perfect knowledge of the behaviour of system to be adjusted, We take as a criterion for deflecting the centre of gravity method(for more information see Annexe), including the action of the command generated is expressed as follows:

2.3.1 Simulation results of IM vector control with fuzzy regulator

We make the same steps of the PI regulator and we find these results:

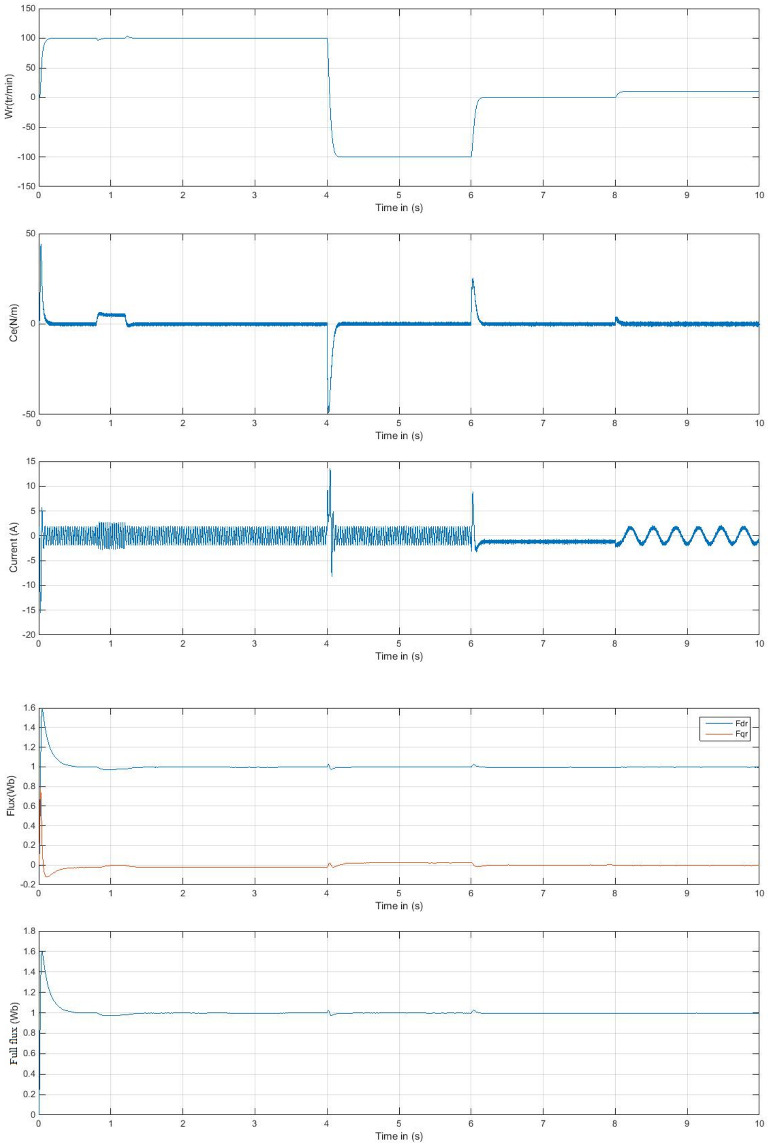

Figure 2.4: Fuzzy regulator with $k_i = 3.06$ and $k_p = 0.5$with charge of 5Nm between 0.8 and 1.2.

2.3.2 Discussion

From these results we can say that the fuzzy regulator has a good reaction to the disturbance better than the PI, also has a good dynamic response, now we move to another type of control to evaluate our work which is the synergetic control.

2.4 The synergetic control of induction motor

The synergetic control is a control technique quite close to the SMC in the sense that it forces the system to evolve with a dynamic pre-chosen by the designer. This approach explicitly uses a nonlinear model for the synthesis of the command[13]. Suppose that the system to be ordered is described by a set of nonlinear equations of the following form:

$$\dot{x} = f(x, u, t) \tag{2.1}$$

where
$x = (x_1, x_2, ...x_n)$:state vector.
$u = (u_1, u_2, ...u_n)$:state vector of input control .

$f\ :\ anonlinear functionandcon-tinuousintime.$ The first step in designing a synergetic control is the formation of macro-variables defined in terms of system state variables. The macro-variable.
The command will make the system to operate on the manifold = 0, the dynamic evolution of the macro- variables according to the equation is defined by:

$$T\dot{\Psi} + \Psi = 0 \tag{2.2}$$

with T positive. where the function must satisfy, the following conditions to ensure the stability of this functional equation: $\Psi(0) = 0, \psi(\Psi)\Psi$ biggest then 0 for allΨ different to 0
Solution

$$\Psi(t) = \Psi_0 e^{t/T} \tag{2.3}$$

The parameter T defines the speed of convergence of macro-variables to the intersection of manifolds $\Psi = 0$.

2.4.1 Synergetic speed controller design

In first chapter is well known used a classical PI controller in the external speed to make the reference torque. In this work, we proposed a new robust controller design basing on the synergetic control[14]. The speed controller generates the reference torque Tref. The speed error is defined by:

$$e(t) = \Omega_{ref} - \Omega_r = 0 \tag{2.4}$$

Consider the macro-variable given by:

$$\Psi = k_p\dot{e}(t) + k_i \tag{2.5}$$

where Kp and KI are the proportional and integral parameters of the speed macro-variable

$$\dot{Psi} = k_p\dot{e}(t) + k_I e(t) \tag{2.6}$$

Basing on the synergetic theory, we can write:

$$T(k_p(\dot{\omega}_{ref} - \dot{\omega}_r) + k_I(\dot{\omega}_{ref} - \dot{\omega}_r)) + k_p(\omega_{ref} - \omega_r) + k_I(\omega_{ref} - \omega_r) = 0 \tag{2.7}$$

$$T^*_{e\,m} = T_r - f_r\Omega - J(\dot{\Omega_{ref}} + \frac{1}{k_p}(\frac{\Psi}{T} + k_I(\Omega_{ref} - \Omega)) \tag{2.8}$$

The synergetic control law must ensure the stability of the closed loop speed control. One can use the following Lyapunov function:

$$V = \frac{1}{2}\Psi(e)^2 \tag{2.9}$$

after differentiation one gets

$$\dot{V} = \Psi(e)\dot{\Phi}(e) \tag{2.10}$$

Thus, the lest equation will ensure the stability of closed speed control loop.

2.4.2 Simulation results of the synergetic control

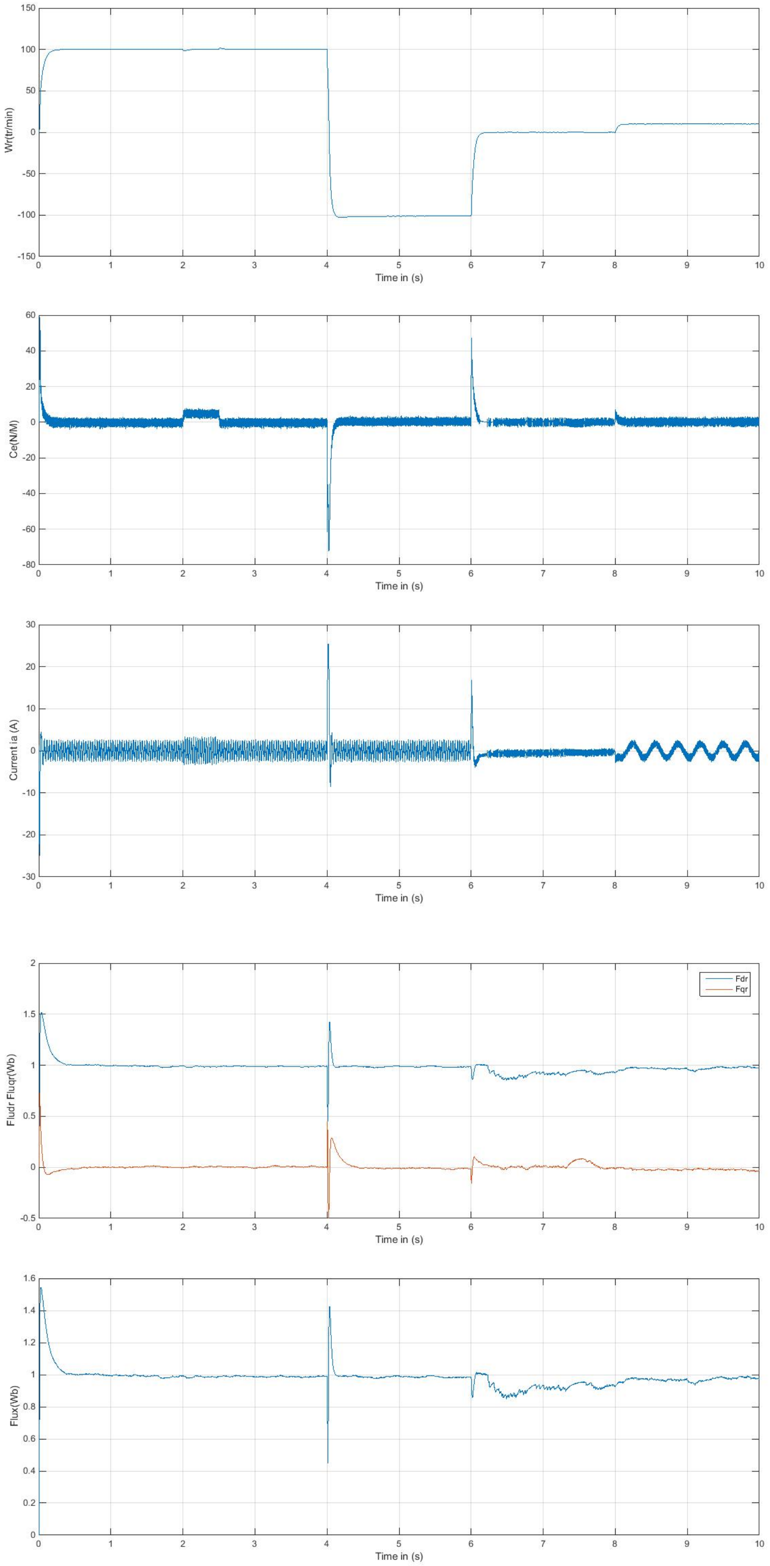

Figure 2.5: Synergetic control of induction motor

Discussion

One can notice that the application of the synergetic control to the IM has made it possible to demonstrate its simplicity of design and the superiority of the performances obtained, relative to those obtained with the conventional regulation, or a fuzzy logic regulator. In fact, it is observed that the orientation condition of the flux of the proposed synergetic control is demonstrated by the cancellation of the quadrature flux and by similar performances to those of the separately excited DC machine. Besides; the synergetic control gives satisfactory results even with sudden reversal of the speed reference, and rejection of load torque.

2.4.3 Conclusion

In this chapter we have presented the aspects of the design of a fuzzy PI regulator for the speed control of IM controlled by vector control. From the simulation results obtained, we see that the PI fuzzy regulator provides a good dynamic speed response and a good rejection of the disturbance compared to the classic PI.

Moreover, to enhance the features of vector control scheme of IM a synergetic control was proposed. The main advantage of synergetic control is that it supports all parametric and nonparametric uncertainties, which is not the case in several control strategies from the obtained results, it can be say that synergetic control can increase the robustness of the drive speed control.

In fact, the synergistic controller demonstrates best performance time response and in the load torque rejection.In order to increase the robustness and reduce the cost of vector control scheme, the follow chapter, we will introduce the conception of Sensorless Vector Control of Induction Motor based on an adaptive sliding mode observer.

Chapter 3

Design of Sensorless Vector Control of Induction Motor based on an adaptive sliding mode observer

3.1 Introduction

It is assumed that high efficiency controls for the induction machine can be implemented through speed/flux controllers based on field orientation concepts. Mechanical sensors such as incremental encoders and resolvers are usually used to measure the speed of the induction machine. It is also known that the use of these sensors can reduce the robustness and reliability of the induction motor drive by increasing the cost and makes the system difficult to maintain. Based on this problem, we go to work with sensorless by using the nonlinear observer by adaptive sliding mode with techniques of estimating or observing the speed of the induction motor. The sliding mode observer is a technique used in the field of control and observation of dynamic systems. It is a non-linear observer type that is designed to estimate the internal state of a system using only available measurements of its outputs[20].

3.2 Nonlinear observer

A non-linear observer, also known as a "estimator" or "state observer", is an algorithm or mathematical system used to estimate the internal states of a non-linear dynamic system based on available measures of its outputs.

The purpose of a non-linear observer is to provide accurate, real-time estimates of unmeasured or inaccessible states of a non-linear system. Non-linear observers are widely used in various fields such as control systems, robotics, aerospace engineering and many other applications where accurate estimation of system states is essential for control, effective monitoring or decision-making.

3.2.1 Types of nonlinear observer

There are many types of nonlinear observer here are some types of commonly used:

- Kalman Filter.
- High-Gain Observer.
- Nonlinear Moving Horizon Observer.
- Backstepping Observer.
- Luenberger Observer.
- Sliding Mode Observer which is the subject of this chapter.

3.3 sliding mode control

sliding mode control is a robust control technique that creates a sliding surface and uses a switching control law to drive the system's state trajectories to the surface, ensuring accurate and reliable control even in the presence of uncertainties and disturbances.

3.3.1 Theory of sliding Modes

Systems with a variable structure are characterised by the choice of a function and a appropriate switching logic. This choice ensures the switching between these structures. By combining the properties of each of these structures, the desired behaviour in the global system[7].

3.3.2 Sliding surface

The sliding surface in sliding mode control is a mathematical construct that represents the desired system behavior. It is designed to be stable, robust to uncertainties and disturbances, and guides the control input to keep the system's state trajectories on the surface, achieving accurate and reliable control[8].

3.3.3 Choice of sliding surface

This control method mainly requires to:

- Determine a sliding surface on which the error of the output estimate is zero.

- Establish the sliding conditions (calculation of the observer gains for which all system trajectories move towards and remain on the sliding surface (attractiveness) (invariance).

3.4 Nonlinear observer by sliding mode

The sliding mode observer works by creating a "sliding surface" in the system state space which the error of the output estimation is equal to 0 . The main principle of the sliding mode observer is to use a discontinuous mode of operation, where the estimation of the state of the system is updated abruptly and not continuously according to the position of the sliding surface. This makes the observer robust to disturbances and model variations, as it quickly adapts to sudden changes and maintains an accurate estimate of the state of the system[4]. The observer dynamics by sliding modes refer to the state observation error

$$e = x - \hat{x} \tag{3.1}$$

Their evolution is imposed on a variety of surface, on which the error of estimation of the output

$$e = y - \hat{y} \tag{3.2}$$

Tending towards zero. Thus, the dynamics on this surface variety will be stabilized, or assigned, so as to limit or cancel the estimation error. A sliding mode observer is written in the form:

$$\dot{\hat{\epsilon}} = f(\hat{\epsilon}, u) + \Delta sign(y - \hat{y}) \tag{3.3}$$

$$\hat{y} = h(\hat{\epsilon}) \tag{3.4}$$

With
$\hat{\epsilon}$: Estimated state, size n*1.
u = Observer input or command.
y and y : $MeasuredandEstimatedOutputs, Dimension$ p*1 $respectively.$
$where sign(y - \hat{y}) = [sign(y_1 - \hat{y}_1) \quad sign(y_2 - \hat{y}_2).....sign(y_p - \hat{y}_p)]$(3.5) V: observer gain matrix.
f(.) : Nonlinear state evolution function dimension n*1.
h(.) : Nonlinear output function dimension n*p.
The interesting properties in this type of observer are those related to the convergence in finite time towards the sliding surface or surfaces and the reduction of the total dynamics from n to n-p (n: system order, p: order of measurable outputs) conditions on the sliding surface.
The robustness vis-à-vis internal (parametric) and external disturbances (load, noise, etc.) will

be conferred to the optimal settings of the sign function gains where a chattering–performance compromise (chattering) should be observed.

3.5 The adaptive slide observer

It consists of two blocks, the first concerning the machine model for state estimation (flux-rotor , current-stator) and the second the mechanism for adjusting the speed estimate[5].

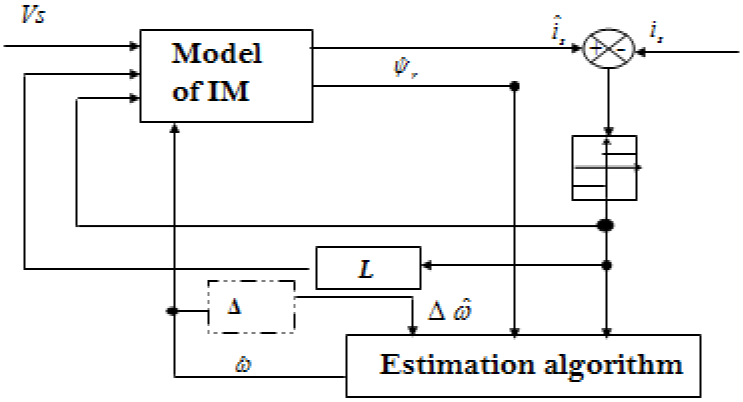

Figure 3.1: Structure of an observer by adaptive sliding modes.

3.5.1 Conception of sliding mode observer

The sliding-mode observer consists of stabilizing the error dynamics of the states to estimate which amounts to :

- Determine a sliding surface on which the error of the output estimate is zero.
- Establish the sliding conditions (calculation of the observer gains for which all system trajectories move towards and remain on the sliding surface (attractiveness) (invariance).

The observer is designed from the model of the stator-bound induction motor so the sliding surfaces are defined by:

$$[s] = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} \hat{i}_{s\alpha} - i_{s\alpha=} \\ \hat{i}_{s\beta} - i_{s\beta} \end{bmatrix}$$

The formulation of the motor condition model given by:

$$\frac{dx}{dt} = Ax + Bv_s \tag{3.6}$$

$$\frac{d\hat{x}}{dt} = \hat{A}\hat{x} + Bv_s + ksign(\hat{i}_s - i_s) \tag{3.7}$$

with $\hat{x}$:is the estimated state of the x state (assumed true). $\hat{x} = [\hat{i_s}\hat{\psi_r}]^T$; $\hat{i_s} = [\hat{i_{s\alpha}}\hat{i_{s\beta}}]^T$; $\hat{\psi_r} = [\hat{\psi_{r\alpha}}\hat{\psi_{r\beta}}]^T$; $v_s = [v_{s\alpha}v_{s\beta}]^T$

$$[K] = \begin{bmatrix} k_1 \\ -Lk_1 \end{bmatrix} : Gain \quad matrix$$

where

$$[K] = \begin{bmatrix} -k_1 & 0 \\ 0 & -k_2 \end{bmatrix}$$

$$[L] = \begin{bmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \end{bmatrix}$$

then the error status model is given as follows:

$$\frac{de}{dt} = A_e + \Delta A\hat{X} + Ksign(\hat{i_s} - i_s) \tag{3.8}$$

with

$e = \hat{x} - x = [e_i e_\phi]^T$: stat error
$\Delta A = \hat{(}A) - A$:modelling error
$e_i = \hat{i_s} - i_s$: current error
$e\psi = \hat{\psi} - \psi_r$: flux error
Δ A $= \begin{bmatrix} \Delta A_{11} & \Delta A_{12} \\ \Delta A_{21} & \Delta A_{22} \end{bmatrix}$: matrix block.

The conditions of the slide mode, in terms of convergence to the surface and invariance on the same surface, allow to write:

$e_i = 0, \frac{de_i}{dt} = 0$

And so the state equation (2.7) becomes:

$$0 = A_{12}e_\psi + \Delta A_{11}\hat{i}_s + \Delta A_{12}\hat{\psi}_r - z \tag{3.9}$$

$$\frac{d}{dt}e_\psi = A_{22}e_\psi + \Delta A_{21}\hat{i}_s + \Delta A_{22}\hat{\psi}_r + Lz \tag{3.10}$$

with
$z = -k_1 sign(\hat{i_s} - i_s)$:switching function.

The modeling error, or A variation, is considered to be due to the variation of the parameter alone ω, hence the recovery of the same formulations:

$\Delta A = \begin{bmatrix} o & \frac{\Delta\omega}{\epsilon}J \\ 0 & \Delta\omega J \end{bmatrix}$:$\Delta\omega = \hat{\omega} - \omega$; J= $\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ then

$$0 = A_{12}e_\psi - \frac{\Delta\omega}{\epsilon}J\hat{\Psi}_r - z \tag{3.11}$$

$$\frac{d}{dt}e_\psi = A_{22}e_\psi - \Delta\omega J\hat{\psi}_r + Lz \tag{3.12}$$

$$e_\Psi = \frac{\Delta\omega}{\epsilon}{A_1}_2^{-1}J\hat{\psi}_r + {A_1}_2^{-1}z \tag{3.13}$$

$$\frac{d}{dt}e_\psi = A_{22}(\frac{\Delta\omega}{\epsilon}J\hat{\psi}_r{A_1}_2^{-1} + {A_1}_2^{-1}z) + \Delta\omega_r J\hat{\psi}_r + Lz \tag{3.14}$$

we have

$A_{22} = -\epsilon A_1 2$

$$\frac{e\psi}{dt} = Vk_1 sign(e_i) \tag{3.15}$$

with $V = (L - \epsilon I)$ and $\epsilon = \frac{\sigma L_s L_r}{M}$ For the determination of k_1 and k_2 the Popov condition $S * \dot{S}$ must be checked to ensure the stability of the flow observer. Therefore it is necessary to explain first of all the equation of the current error in the following form[2][18]:

$$\frac{d}{dt}\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} -\gamma_1 & 0 \\ 0 & -\gamma_1 \end{bmatrix}\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} + \begin{bmatrix} \gamma_2 & \gamma_3 \\ -\gamma_3 & \gamma_2 \end{bmatrix}\begin{bmatrix} e_3 \\ e_4 \end{bmatrix} + \begin{bmatrix} -k_1 sign(e_1) \\ -k_2 sign(e_2) \end{bmatrix}$$

with

$\gamma_1 = \frac{R_s}{\sigma L_s} + \frac{M^2}{\sigma L_s L_r}\sigma_r$ $\gamma_2 = \frac{M}{\sigma L_s L_r}\sigma_r$ $\gamma_3 = \frac{pM}{\sigma L_s L_r}\Omega$

3.5.2 Determining the gains matrix L

$$|\psi_{r\alpha}| < \eta_1 \quad and \quad |\psi_{r\beta}| < \eta_2 \tag{3.16}$$

$$\rho_1 > (\frac{R_s}{\sigma L_s} + \frac{M^2\sigma_r}{\sigma L_s L_r})|e_1| + \frac{M\sigma_r}{\sigma L_s L_r}(\eta_1 + |\hat{\psi}_{r\alpha}|) + \frac{PM}{\sigma L_s L_r}|\Omega_r|(\eta_2 + |\hat{\psi}_{r\beta}|) \tag{3.17}$$

$$\rho_2 > (\frac{R_s}{\sigma L_s} + \frac{M^2\sigma_r}{\sigma L_s L_r})|e_2| + \frac{M\sigma_r}{\sigma L_s L_r}|\Omega_r|(\eta_2 + |\hat{\psi}_{r\beta}|) + \frac{PM}{\sigma L_s L_r}|\Omega_r|(\eta_1 + |\hat{\psi}_{r\alpha}|) \tag{3.18}$$

$$L = -\gamma {A_1}_2^T + \epsilon I \tag{3.19}$$

The development of this relationship leads to:

$$L = \begin{bmatrix} -\epsilon - \frac{\gamma\sigma_r}{\epsilon} & \frac{\gamma\omega_r}{\epsilon} \\ -\frac{\gamma\omega_r}{\epsilon} & -\epsilon - \frac{\gamma\sigma_r}{\epsilon} \end{bmatrix}$$

In order to achieve the targeted dynamic performance of rotoric flux estimation, the L matrix could be transcribed as follows:

$$L = \begin{bmatrix} -(q-1)\epsilon - \frac{\gamma\sigma_r}{\epsilon} & \frac{\gamma\omega_r}{\epsilon} \\ -\frac{\gamma\omega_r}{\epsilon} & -(q-1)\epsilon - \frac{\gamma\sigma_r}{\epsilon} \end{bmatrix}$$

q: is a positive constant chosen to ensure convergence and achieve the desired performance (dynamic and static) for the estimated rotoric flux[1][24][15].

3.5.3 Simulation results and discussion

To investigate the effectiveness of the proposed system, and to check the closed-loop stability of the complete system, several tests were performed at different dynamic operating conditions such as sudden change in command speed, and step change in load

Simulation results of adaptive sliding mode observer

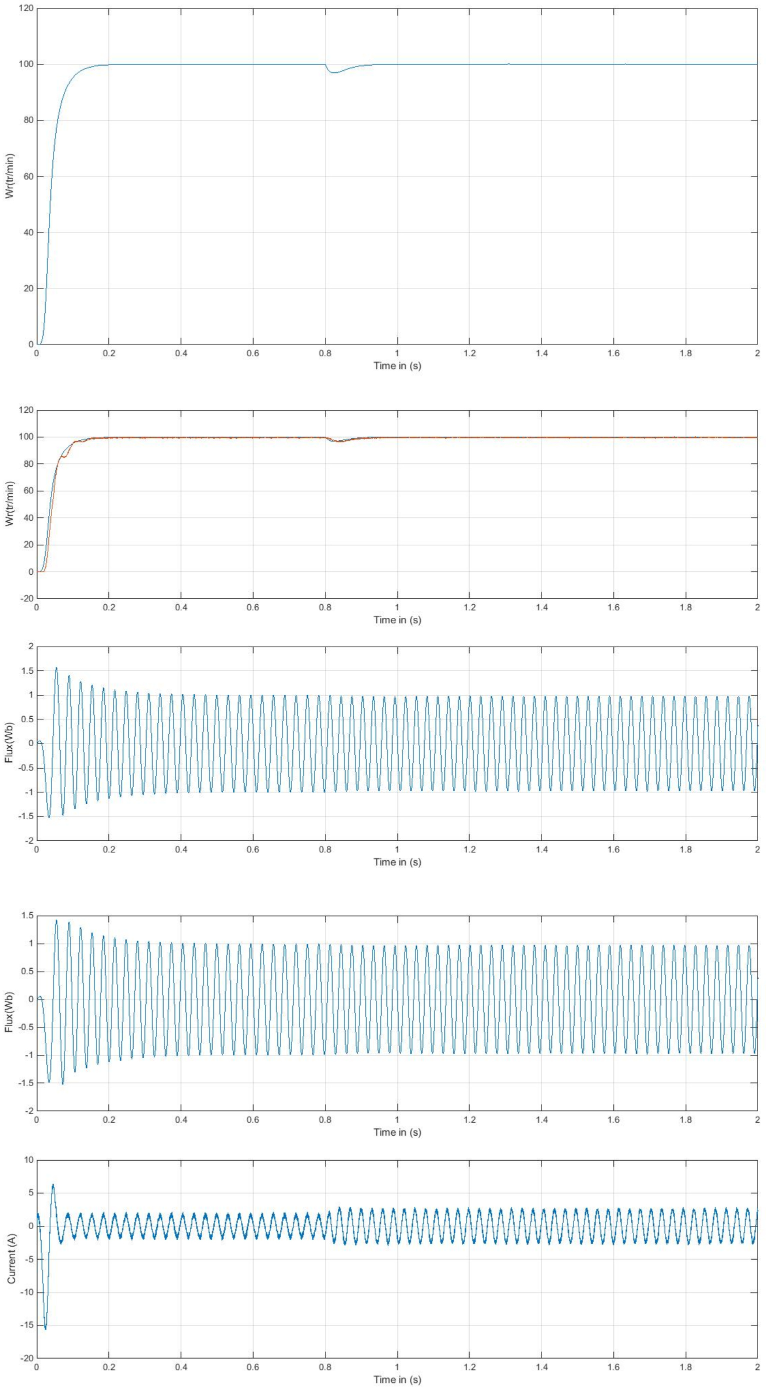

Figure 3.2: Adaptive sliging observer with $c_r = 5N/m$ at t=0.8

3.5.4 Discussions

We can say that our observer is perfect and robust when there is a parameter variation (apply a charge), and also when the estimed speed its equal to the real speed without any overrun or delay. We note also the perfect pursuit of the estimed rotor flux with its real one.

To test if our control is robust we make a change of input in t=0.6 $W_r = -100tr/min$ The simulation results:

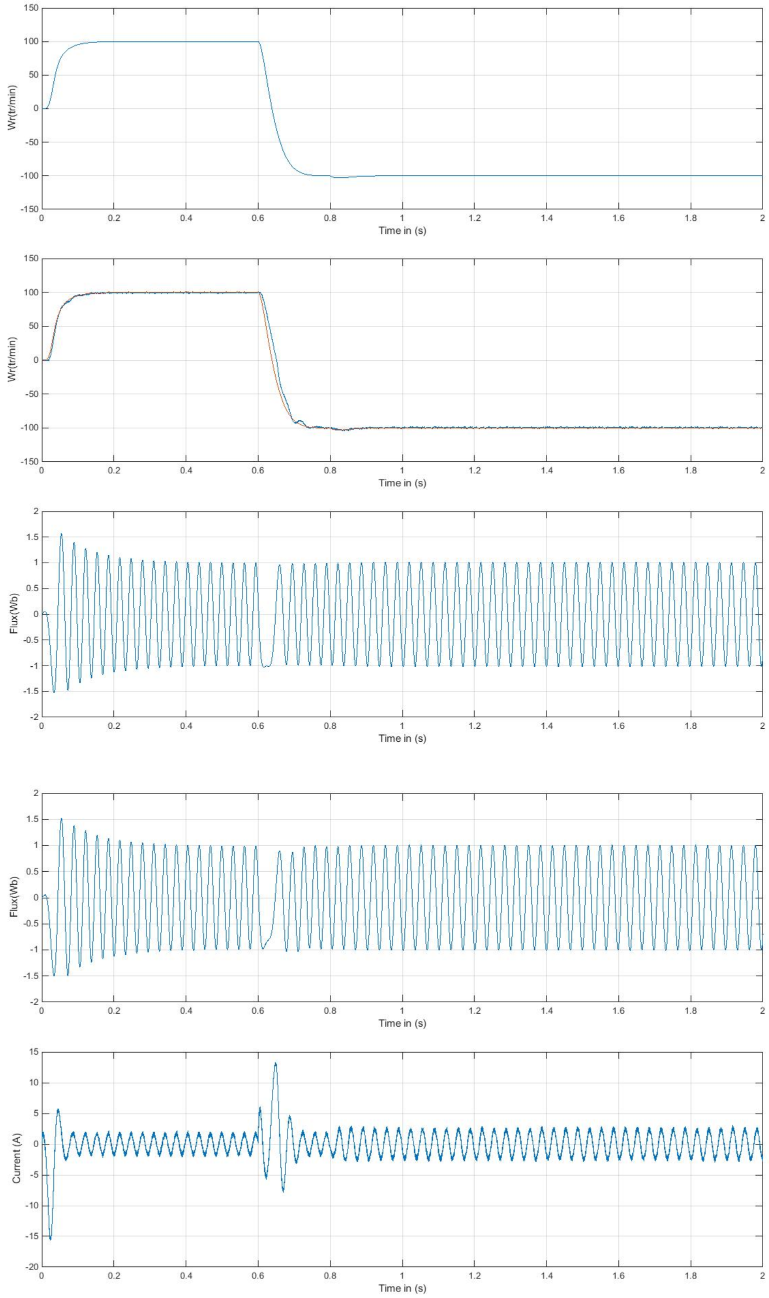

Figure 3.3: Adaptive sliging observer with $c_r = 5N/m$ at t=0.8 with speed variation at t=0.6 $w_r = -100$

3.5.5 Speed Maximum Dynamic Error

The effectiveness of the sensorless scheme in terms of the speed estimation accuracy are also tested. Figure. 3.4 show the maximum of the speed dynamic error versus the speed reference. It can be noted that the speed estimation is sufficiently accurate, in fact the dynamic error is 2.1 purcent at a very low speed of (5rad/s) and doesn't exceed 0. 3 purcent at the rated speed (100 rad/s).

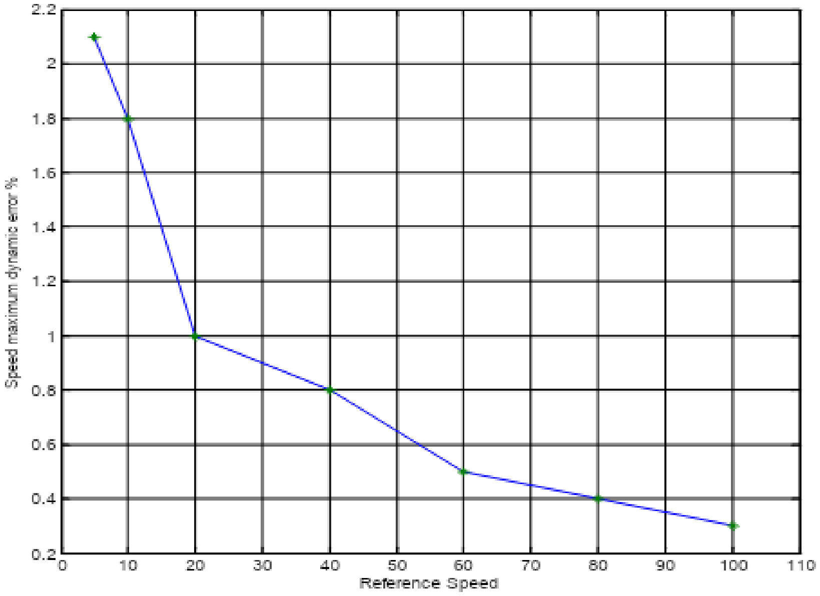

Figure 3.4: Speed Maximum Dynamic Error

The outcome of the adaptation mechanism is presented in the following form:

3.5.6 Conclusion

In this chapter, robust speed sensorless vector control of IM based on an adaptive sliding mode observer was well explained. The observer estimates both the rotor flux and mechanical speed by using the IM measurement (current, voltage).

The effectiveness of the developed observer is verified by simulation testing in the low speed region. From these simulation results, one can conclude that the proposed scheme shows good convergence and closed-loop stability over a wide speed range at rated load operation

GENERAL CONCLUSION

The study carried out during this thesis work focused on design of robust synergetic sensorless vector control of induction motor based on an adaptive sliding mode observer. The effectiveness of the sensorless scheme in terms of the speed estimation accuracy has been examined particularly for low speed operations, and for speed consign variation.

The use of vector controlled IM drives yields various advantages over DC motors in terms of low cost, size, robustness, no maintenance. However, the vector control of IM needs the employ of an accurate shaft encoder for good operating. Hence the sensorless control seems good solution for costs reduction, and solving several of the implementation problems encountered: lack of space, severe environment.

In this context, firstly, we have modeled IM using Park's model, then we have defined a vector control method that allows obtaining decoupled model of IM. The modeling of IM by state equations in reference frame (d, q) has been very beneficial to us; as long as it leads us to conclude that the IM can be controlled using the Park transformation. The performance of classical vector control was illustrated by the simulation results.

In the second chapter, we have presented the theory of fuzzy logic, and synergetic control applied to IM, which allowed to obtain a good performance in terms of tracking and regulation. The presented control approaches were justified by the numeral results.

In order to reduce the cost of the control by eliminating the speed sensor, an adaptive sliding-mode observer for speed-sensorless control of IM. The presented observer estimate the rotor flux components in the stationary reference frame from IM. The speed is detected by adding a Lyapunov function. The performance of this observer was illustrated by simulation results.

Regarding the continuation of this work, different perspectives open up:

-Development of vector control of IM associated with an algebraic observer.

-Design of sensorless tolerant control of IM

- Practical realization of the proposed control strategy.

Bibliography

[1] I. Al-Rouh. *Contribution à la commande sans capteur de la machine asynchrone.* PhD thesis, Henri Poincaré University, Nancy-I, France, 2004.

[2] Ahmed Aoufi. Utilisation d'observateurs à modes glissants pour le contrôle direct de couple et le contrôle vectoriel d'une machine asynchrone à cage. Magister thesis.

[3] W. Ayrir, M. Ourahou, B. E. Hassouni, and A. Haddi. Direct torque control improvement of a variable. *Journal of Electrical Engineering*, Year.

[4] Hanane Bouchareb. Observateur non linéaire mode glissant. Magister thesis.

[5] T. Boukhobza. *Contribution aux formes d'observabilité pour les observateurs à modes glissants et Etude des commandes par ordres supérieurs.* PhD thesis, University of South Paris, Orsay, 1997.

[6] B. Boumegouas, K. Kouzi, and M. Birame. Robust synergetic control of electric vehicle equipped with an improved load torque observer. *International Journal of Emerging Electric Power Systems*, 2023.

[7] C. Carlos. *Optimisation, discrétisation et observateurs, commande des moteurs asynchrones.* Edition Hermes Science Europe Ltd, 2000.

[8] J. Faucher. *Les plans d'expériences pour Le Réglage de Commandes à Base de Logique Floue.* PhD thesis, Institut National Polytechnique de Toulouse : Electrical Engineering and Automation, Septembre 2006.

[9] H. Guermit, K. Kouzi, and S. A. Bessedik. Novel design of an optimized synergetic control for dual stator induction motor. *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, 38(6):1828–1845, October 2019.

[10] MEKKI Hemza and ABDELKEBIR Anis. Commande vectorielle d'une machine asynchrone (mas). Master's thesis, University of Mohamed Boudiaf, M'ssila, Algeria.

[11] S. Himavathi and B. Umamaheswari. New membership functions for effective design and implementation of fuzzy systems. *Fuzzy Sets and Systems*, 31:717–723, 2001.

[12] L. P. Holmblad and J.-J. Østergaard. The application of fuzzy logic. *Control Engineering Practice*, 70:135–146, 1995.

[13] A. A. Kolesnikov. Introduction of synergetic control. 2014.

[14] I. Kondratiev and R. Dougal. General synergetic control strategies for arbitrary number of paralleled buck converters feeding constant power load: Implementation of dynamic current sharing. 2006.

[15] K. Kouzi, L. Mokrani, and M-S. Naït-Saïd. Adaptive sliding-mode observer for speed-sensorless control of induction motors. *IEEE Transactions on Industrial Applications*, 36(5):1380–1387, 2000.

[16] K. Kouzi, L. Mokrani, and M.-S. Naït-Saïd. A new design of fuzzy logic controller with fuzzy adapted gains based on indirect vector control for induction motor drive. In *IEEE-SSST Annual Meeting*, West Virginia, USA, March 2003.

[17] K. Kouzi, L. Mokrani, and M.-S. Naït-Saïd. High performances of fuzzy self-tuning scaling factor of pi fuzzy logic controller based on direct vector control for induction motor drive without flux measurements. In *Proceedings of the IEEE International Conference on Industrial Technology (ICIT)*, December 2004.

[18] K. Kouzi, L. Mokrani, and M-S. Naït-Saïd. A rotor flux sliding-mode observer for a fuzzy logic control of direct field oriented induction motor. In *International Conference on Electrical and Electronics Engineering*, Sétif, October 2004.

[19] K. Kouzi and M-S. Naït-Saïd. Adaptive fuzzy logic speed-sensorless control improvement of induction motor drives for standstill and low-speed operations. *International Journal COMPEL*, 26(1):22–33, 2007.

[20] Kattia Kouzi. Contribution des techniques de la logique floue pour la commande d'une machine à induction sans transducteur rotatif. Master's thesis, University of Elhadj Lakhdar, Batna, Algeria.

[21] Ould Sass Mohamed. Commande synergétique d'un moteur asynchrone. Master's thesis, University of Annaba, Annaba, Algeria.

[22] H. Tajima, G. Guidi, and H. Umida. Consideration about problems and solutions of speed estimation method and parameter tuning for speed-sensorless vector control of induction motor drives. *IEEE Transactions on Industry Applications*, 38(5):1282–1289, Sept./Oct. 2002.

[23] M. Tursini, R. Petrella, and F. Parasiliti. Adaptive sliding-mode observer for speed-sensorless control of induction motors. *IEEE Transactions on Industry Applications*, 36(5):1380–1387, Sep./Oct. 2000.

[24] M. Tursini, R. Petrella, and F. Parasiliti. Adaptive sliding-mode observer for speed-sensorless control of induction motors. In *IEEE International Conference on Systems, Signals and Devices*, 2000.

[25] L. Zadeh. Fuzzy sets. *Information and Control*, 8(3):338–353, 1965.

[26] L. A. Zadeh. Outline of a new approach to the analysis of complex systems. *Journal of the Society for Industrial and Applied Mathematics*, 9(2):286–299, 1963.

[27] A. Zorig, A. Belkheiri, M. Belkheiri, and K. Kouzi. Adrc control of an induction motor with varying parameters. In *19th International Multi-Conference on Systems, Signals & Devices (SSD)*, 2022.

Appendix A

Appendix A

Table A.1: Motor Specifications

Parameter	**Value**
Number of pole pairs	2
Rated power (kW for 50 Hz)	0.75
Nominal speed (tr/min)	1400
Nominal voltage (V)	220/380
Nominal current (A)	3.6/2.1
Nominal torque (Nm)	5
Rs; Rr (Ω)	10; 6.3
Ls; Lr (H)	0.656; 0.653
M (H)	0.612
J (kg.m^2)	0.02
fs (N m.s)	0

- Three phase Network parameter: 220/380 V ; 50Hz.
- Inverter parameter:$\Delta_i = 0.1A$ Hysteresis strip.
- Filter parameter : Capacity C=$6.10^{-3}F, Inductance L = 1.2.10^{-3}H$.