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**Domain :** Sciences and Technologies  
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## *Theme*

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# **Design of Robust Fuzzy Mutual MRAS Estimator for Induction Motor**

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## الملخص:

تتعلق هذه الدراسة بتصميم مقدر MRAS القوي الضبابي المتبادل للمحرك التعري (IM). يقدر المقدر المقدم كلا من السرعة الميكانيكية و مقاومة الجزء الثابت و الجزء المتحرك للقيام بذلك, في الخطوة الأولى , تم تقديم النمذجة و التحكم في ناقل الحركة للمحرك التعريفي. في الخطوة الثانية، تم شرح تصميم وحدة التحكم المنطقية الضبابية PI لتنظيم السرعة IM بشكل جيد. تم توضيح أداء التحكم في الخوارزمية المقترحة من خلال بعض نتائج المحاكاة. في الخطوة الأخيرة اقترحنا التحكم في متجه السرعة Fuzzy Sensorless IM بناء على مقدر Mutul-MRAS الذي يكتشف السرعة وبعض المعلومات الرئيسية ل IM مثل مقاومة الجزء الثابت والدوار. تم عرض ميزة وكفاءة السرعة غير المستشعرة من خلال نتائج المحاكاة.

## الكلمات المفتاحية:

مقدر MRAS، مكافحة ناقلات، للمحرك التعريفي (IM)، منظم Fuzzy PI، نموذج مرجعي، نموذج قابل للتعديل، مقاومة الجزء الثابت، المتانة Mutul-MRAS

## Abstract :

This study concerns the design of Robust Fuzzy Mutual MRAS Estimator for Induction Motor (IM). The presented estimator estimates both the mechanical speed, stator and rotor resistance. To do this, in a first step, the modeling and vector control of induction Motor were presented. In the second step, the design of PI fuzzy logic controller for speed IM regulation was well explained. The performance of suggested algorithm control was illustrated by some simulation results. In the last step, we have proposed Fuzzy Sensorless speed vector control of IM based on Mutuel –MRAS estimator which detects the speed and some key parameter of IM such as stator and rotor resistance. The feature and efficiency of Sensorless speed were shown by simulation results.

**Keywords-** Induction Motor (IM); Vector Control; PI regulator; PI Fuzzy, Fuzzy Mutual MRAS , Reference Model, Adjustable Model, Stator resistance, Robustness.

## **Résumé :**

Cette étude concerne la conception d'un estimateur MRAS-Mutuel flou robuste d'un Moteur à Induction. L'estimateur présenté estime à la fois la vitesse mécanique, et les résistances statorique et rotorique. Pour cela, dans une première étape, la modélisation du moteur à induction et sa commande vectorielle ont été présentés. Dans une deuxième étape, la conception d'un régulateur PI flou pour la régulation de vitesse du MI a été bien expliquée. Les performances du contrôle proposé ont été montrées par des résultats de simulation. Dans la dernière étape, on a proposé une commande vectorielle floue sans capteur de vitesse du MI associée à un MRAS-Mutuel flou qui détecte la vitesse rotorique et les paramètres clés du MI à savoir les résistances statoriques et rotoriques. Les performances et l'efficacité de la commande sans capteur ont été illustrées par des résultats de simulation.

**Mots clés :** Moteur à Induction triphasé , Commande vectorielle, Régulateur PI classique, PI flou, Mutuel MRAS flou, Modèle de référence, Modèle ajustable, Résistance statorique, Robustesse.

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# Dedication

First, I would like to thank **Allah** Almighty for giving me patience and strength to finish this work.

I dedicate this modest work to:

To my dear father, to my dear mother for their help and support throughout my studies, and who have made me what I am today and I hope that one day I will be able to give them at least the minimum because no matter what we do, we will never be able to give them everything back.

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**Mihoub SAIHI**

# Dedication

First of all, this work would not be possible without the help of all mighty god, and He who does not thank people, does not thank **Allah**.

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To my dear brothers Hamouda, Omar and Rafik To my all family. To my friends YACINE, MOHAMED and my partner Mihoub SAIHI and his family.

Every student, classmate and teacher that i have had the honour of working with or learning under, Thank you.

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**Ahmed NOUAI**

# Acronyms

## Abridged Words

MAS : Asynchronous Motor

*PWM*: Pulse Width Modulation

MRAS : Adaptive System With A Reference Model

FOC : Field Oriented Control

FLC : Fuzzy Logic Controller

PI : Proportional Integral

## List of abbreviations

### Model Parameters

$R_s$ : Stator Resistor ( $\Omega$ )

$R_r$ : Rotor Resistor ( $\Omega$ )

$L_s$ : The self-inductance of a stator phase (H)

$L_r$ : The self-inductance of a rotor phase (H)

$M_{sr}$ : Mutual inductance between stator and rotor phase (H)

$J$ : Rotor moment of inertia ( $\text{Kgm}^2$ )

$P$ : Number of pole pairs (Without unity)

### Machine Electrical and Mechanical Variables

$V_s$ : Stator voltage (V)

$V_r$ : Rotor voltage (V)

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$I_s$ : The stator current (A)  
 $I_r$ : The rotor current (A)  
 $\psi_r$  The rotor flux (Wb)  
 $\psi_s$  The stator flux (Wb)  
 $\omega_s$ : The stator pulse (rad/s, tr/min)  
 $\omega$ : The mechanical pulse (rad/s, tr/min)  
 $\omega_r$ : The sliding pulse (rad/s, tr/min)  
 $\theta$ : The electrical angle between the rotor and the stator (rad)  
 $\sigma = 1 - \frac{L_m^2}{L_s L_r}$  : Blondel dispersion coefficient (Without unity)  
 $T_s = \frac{L_s}{R_s}$ : The stator time constant (s)  
 $T_r = \frac{L_r}{R_r}$ : The rotor time constant (s)  
 $C_{em}$ : Electromagnetic Torque (N.m)  
 $f$  : Network frequency (Hz)  
 $\psi_{dr}$  : Rotor Flux In Axe d (Wb)  
 $\psi_{qr}$  : Rotor Flux In Axe q (Wb)  
 $\Omega_r$  : Mecanical Speed Of The Rotor (tr/min)  
 $e$  : Error  
 $\hat{\cdot}$  : Sign Of Estimated Size

## Clues

$a, b, c$  : Variables expressed in the three-phase fixed benchmark

$d, q$  : Variables expressed in the fixed frame ( $d, q$ ) rotating at synchronous speed

$\alpha, \beta$  : Variables expressed in the two-phase fixed frame ( $\alpha, \beta$ )

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# General Introduction

## 1.1 PROBLEM FORMULATION

Generally, induction motor drives (IM) used in industrial and process applications requiring high dynamic performances are based on field-oriented control.

However, the speed controller design of such systems plays crucial role on these performances, and the decoupling characteristics of vector controlled induction motor are adversely affected by some key parameters changing [1].

Recently, because of their success, intelligent controllers such as Artificial Neural Network intelligent (ANN) and Fuzzy Logic Controller (FLC) have become one of the most favorable areas of research for controlling nonlinear systems.

Fuzzy logic control (FLC) allows the formalization of inaccuracies due to global knowledge of a very complex system, and the expression of system behavior by words. Fuzzy approach uses linguistic descriptions of dynamic characteristics of a system provided by human expertise to generate a control law.

Hence, FLC is seemed an ultimate solution in term of high dynamic response and best disturbance rejection [2].

Moreover, in high performance vector control, rotor time constant is a critical parameter for indirect field-oriented control induction motor drives. The deviation of rotor time constant affect directly the features and robustness of vector control . In fact, when motor is operating, the temperature and magnetic saturation provide a large variation of key parameters motor such as stator resistance and rotor resistance; this variation can deteriorates the performance of vector control. To solve this problem, in this present work we propose fuzzy mutual MRAS estimator based on rotor flux linkage.

Mutual Model Reference Adaptive Control System (MMRACS) contains two models to implement Sensorless vector control of IM. For the mechanical speed estimation, one model is used as a reference model and another is the adjustable model. Pure integration and stator leakage inductance are removed from the reference model, resulting in robust performance in low and high-speed ranges. For the stator resistance identification, the two models switch their roles, so the reference model becomes the adjustable model and the adjustable model becomes the reference model. Assuming a brief stable rotor speed interval, the stator resistance can be achieved very well. To enhance the estimation accuracy of rotor speed and stator resistance, a simple online rotor time constant identification is included. This mutual MMRACS scheme is a cost-effective approach for sensorless speed variable implementation [3].

## 1.2 OUTLINE OF THE THESIS

The thesis is organized into three chapters given as follows:

The first chapter of thesis concerns the modeling of induction motor and its fed contains mainly the voltage inverter with PWM current control. In addition, the concepts of vector control for IM will be presented. At the end of chapter, the main features of vector control will be shown by simulation results.

The second chapter presents the design of PI fuzzy regulator for IM speed regulation .We will use two kind of regulators such as: PI conventional and Fuzzy PI. Different digital simulation will be given to confirm this assertion.

The third chapter deal with the design of fuzzy Mutual -MRAS estimator to detects both stator, rotor resistances and mechanical speed adapt for fuzzy vector control of IM. The features of suggested estimator will illustrate by simulation results.

To close this study, general conclusion will be give, and some perspectives will be suggested in regard of continuation of this work.

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# Chapter 1

## Modeling and Vector Control of IM

### 1.1 INTRODUCTION

The asynchronous motor (MAS) or induction motor is currently the most widely used electric motor in industry. Its main advantage lies in the absence of sliding electrical contacts, which leads to a simple and robust structure that is easy to build [4]. Its use in the field of variable speed drive calls upon the control, and to do this, one needs the mathematical model of the process. Thus the modeling of the three-phase induction machine, an essential element in the drive, becomes an essential step for the realization of a variable speed control.

This chapter focuses on the modeling aspects of the three-phase asynchronous machine according to the Park benchmark model. We will present the modeling of the cascade supplying the machine in question, consisting mainly of a voltage inverter with current *PWM*. We end this chapter with a presentation of the technique. vector control of an asynchronous machine. Simulation results will be given in order to highlight the improvement of the dynamic performance of training. Also, the degree of sensitivity of the vector decoupling with respect to vis to the parametric variation.

### 1.2 MODELLING OF INDUCTION MOTOR

In this section, we'll propose a model that may be used to explain both the performance in steady-state conditions as well as in transient states. The induction motor in Figure (1.1), which has three phases and two poles, is an example. Suppose that the stator windings have  $N_s$  effective turns,  $R_s$  resistance,  $L_s$  self-inductance, and  $L_{ls}$  leakage inductance. Similar to this, the comparable rotor windings have an effective turn count of  $N_r$ , resistance  $R_r$ , leakage inductance  $L_{lr}$ , and self-inductance  $L_r$ . The angle that separates the rotor and stator axes is denoted by the symbol  $\theta_r$ . The saturation of the iron core, the influence of slots, and cogging torque are examples of non-ideal properties that will not be taken into account in this context. We shall only take into

consideration the centered coil of each phase despite the fact that these are identical sinusoidal dispersed windings that are separated by 120.

For sake of simplicity, we shall simply take into account the centered coil of each phase. Let's now arrive at the induction motor's voltage equations. An induction motor can be described by six voltage equations because it has six windings.[5]

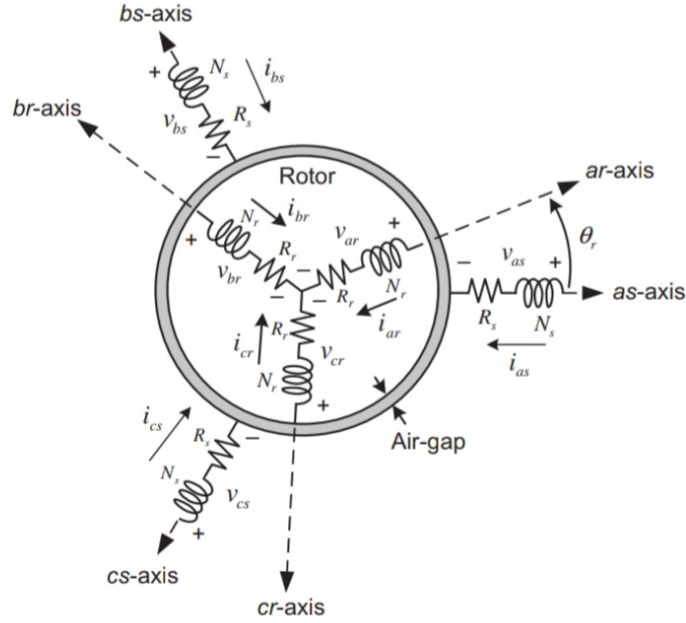


Figure 1.1: Stator and rotor windings of an induction motor

The winding voltage is composed of the voltage drop of the winding resistance and the voltage induced by the flux linkage variation of the winding.

### 1.2.1 Electrical equations

The six windings shown in Figure (1.1) obey the following matrix equations,[6]

$$[V_s] = [R_s] [i_s] + \frac{d}{dt} [\psi_s] \quad (1.1)$$

$$[V_r] = [R_r] [i_r] + \frac{d}{dt} [\psi_r] = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix} T \quad (1.2)$$

With:

$[V_s]$ : Voltage vector

$[i_s]$ : Current vector

$[\psi_s]$ : Stator flux vector

$[R]$ :Matrix resistor

$S, r$  : Stator and rotor indices, respectively

## 1.2.2 Magnetic equations

The simplifying hypotheses cited above lead to linear relations between the fluxes and the currents of the asynchronous machine, these relations are written in matrix form as follows,[7]:

For the stator:

$$[\psi_s] = [L_s] [i_s] + [M_{sr}] [i_r] \quad (1.3)$$

For the rotor:

$$[\psi_r] = [L_r] [i_r] + [M_{rs}] [i_s] \quad (1.4)$$

$[L_s],[L_r]$  : The stator and rotor inductance matrices

$[M_{sr}]$  : corresponds to the matrix of mutual stator-rotor inductances

we denote by :

$$[L_S] = \begin{bmatrix} l_s & M_S & M_S \\ M_S & l_S & M_S \\ M_s & M_S & l_s \end{bmatrix} \quad (1.5)$$

$$[L_r] = \begin{bmatrix} l_r & M_r & M_r \\ M_r & l_r & M_r \\ M_r & M_r & l_r \end{bmatrix} \quad (1.6)$$

$$[L_s] = [M]^T = M \begin{bmatrix} \cos(\theta) & \cos(\theta + 2\frac{\pi}{3}) & \cos(\theta - 2\frac{\pi}{3}) \\ \cos(\theta - 2\frac{\pi}{3}) & \cos(\theta) & \cos(\theta + 2\frac{\pi}{3}) \\ \cos(\theta + 2\frac{\pi}{3}) & \cos(\theta - 2\frac{\pi}{3}) & \cos(\theta) \end{bmatrix} \quad (1.7)$$

$\theta$  : The absolute position between the stator and the rotor

$l_r, l_s$  :Self inductance of rotor and stator, respectively

$M$  :Cyclic mutual inductance between stator-rotor

Finally the voltage equations become:

For the stator:

$$[V_{sabc}] = [R_s] [i_{sabc}] + \frac{d}{dt} \{ [L_s] [i_{sabc}] + [M_{sr}] [i_{rabc}] \} \quad (1.8)$$

For the rotor:

$$[V_{rabc}] = [R_r] [i_{rabc}] + \frac{d}{dt} \{ [L_r] [i_{rabc}] + [M_{rs}] [i_{sabc}] \} \quad (1.9)$$

### 1.2.3 Mechanical equations

The study of the characteristics of the induction machine introduces variation not only of the electrical parameters (voltage, current, flux) but also of the mechanical parameters (torque, speed)[8]

$$C_{em} = p [i_{sabc}]^T \frac{d}{dt} [M_{sr}] [i_{rABC}] \quad (1.10)$$

The equation of motion of the machine is:

$$J \frac{d}{dt} \Omega = C_{em} - C_r - f_r \Omega \quad (1.11)$$

With :

$J$  : moment of inertia of rotating masses

$C_r$  : Resistant torque imposes on the machine shaft

$\Omega$  : rotor speed

$C_{em}$  : Electromagnetic torque

$f_r$  : Viscous coefficient of friction

$f_r \Omega$  : Viscous friction torque term

## 1.3 APPLICATION OF PARK TRANSFORMATION TO THE MACHINE THREE-PHASE ASYNCHRONOUS

### 1.3.1 Principle of Park's transformation :

Park's transformation aims to treat a wide range of machines in a unified way into a unique model. This conversion is often called axis transformation, corresponding fact at the two windings of the original machine followed by a rotation, the equivalent windings from an electrical and magnetic point of view. This transformation thus, for the purpose of making mutual inductances of the model independent of the angle of rotation[9].

Park transformation is often defined by the standard matrix  $[P]$  as follows[10]:

$$|P| = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (1.12)$$

$\sqrt{\frac{2}{3}}$  : The factor ( $\sqrt{\frac{2}{3}}$ ): for the preservation of instant electric power.

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = |M|^T = \begin{bmatrix} X_U \\ X_W \\ X_0 \end{bmatrix} \quad \text{With : } |P|^{-1} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (1.13)$$

### 1.3.2 Model of the three-phase induction machine in the Park marker

La figure(1.2)illustrates the schematization of a three-phase induction machine and its equivalent two-phase machine from the Park transformation :

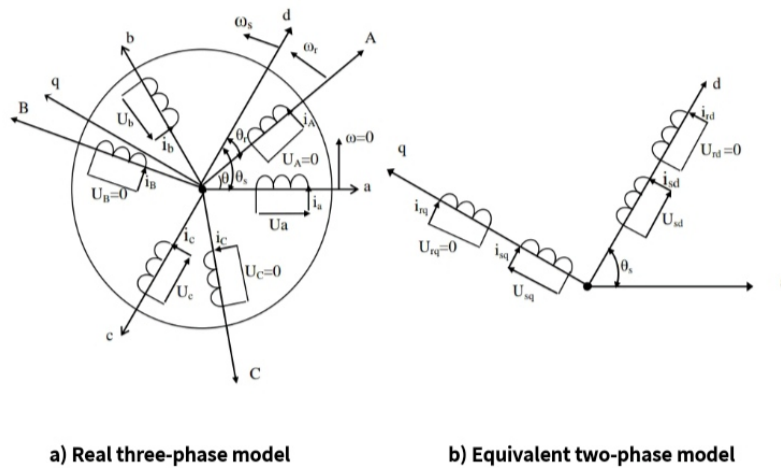


Figure 1.2: Representation of the three-phase induction machine and its two-phase machine

$\theta$  : is the angle between a and A

$\theta_r$  : is the rotor angle between A and d

$\theta_s$  : is the stator angle between a and d

$\omega_a$  : is the angular velocity of the axis system ( $d, q$ )

$\omega_r$  : is the rotor electric angular velocity

### 1.3.3 Application of Park's transformation to the MAS model :

- **Electrical equations:**

$$V_{sd} = R_s i_{sd} + \frac{d}{dt} \psi_{sd} - \omega_s \psi_{sq} \quad (1.14)$$

$$V_{sq} = R_s i_{sq} + \frac{d}{dt} \psi_{sq} + \omega_s \psi_{sd} \quad (1.15)$$

$$0 = R_r i_{rd} + \frac{d}{dt} \psi_{rd} - (\omega_s - \omega_r) \psi_{rq} \quad (1.16)$$

$$0 = R_r i_{rq} + \frac{d}{dt} \psi_{rq} + (\omega_s - \omega_r) \psi_{rd} \quad (1.17)$$

- **Magnetic equations:**

$$\psi_{sd} = L_s i_{sd} + M i_{rd} \quad (1.18)$$

$$\psi_{sq} = L_s i_{sq} + M i_{rq} \quad (1.19)$$

$$\psi_{rd} = L_r i_{rd} + M i_{sd} \quad (1.20)$$

$$\psi_{rq} = L_r i_{rq} + M i_{sq} \quad (1.21)$$

with:  $L_s = l_s - M$  ,  $L_r = l_r - M$  ,  $M = \frac{3}{2} M_0$ .

- **Mechanical equations:**

$$C_{em} = p \frac{M}{L_r} (\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) \quad (1.22)$$

### 1.3.4 Feeding The Induction Machine :

For a voltage-powered induction machine, considering the stator current  $i_s$  and flow  $\psi_r$  as state variables, and pulsation  $\omega_s$  and voltages  $V_{ds}, V_{qs}$ , as magnitude of control and torque  $C_r$  as a disturbance, we will have the following block diagram Figure(1.3)

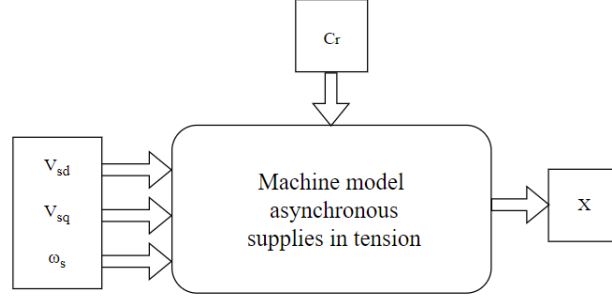


Figure 1.3: block diagram of the induction machine powered by voltage

The output vector  $[X]$ , can have one of the forms of the different expressions:

$$[X] = [ i_{sd} \ i_{sq} \ i_{rd} \ i_{rq} ]^T$$

$$\text{Or } [X] = [ \psi_{sd} \ \psi_{sq} \ \psi_{rd} \ \psi_{rq} ]^T$$

$$\text{Or } [X] = [ \psi_{sd} \ \psi_{sq} \ i_{rd} \ i_{rq} ]^T$$

$$\text{Or } [X] = [ i_{sd} \ i_{sq} \ \psi_{rd} \ \psi_{rq} ]^T$$

So our choice is on the vector :  $[X] = [ i_{sd} \ i_{sq} \ \psi_{rd} \ \psi_{rq} ]^T$

## 1.4 STATE REPRESENTATION OF THE MAS MODEL:

The general form of the state equation is written as follows

$$[\dot{X}] = [A][X] + [B][U] \quad (1.23)$$

With:

$$[X] = [ i_{ds} \ i_{qs} \ \psi_{dr} \ \psi_{qr} ]^T$$

$$[U] = [ V_{ds} \ V_{qs} ]^T$$

Then, the model of the induction machine powered by voltage in a marker ( $d q$ ) turning at the synchronous speed( $\omega_s$ )

$$\begin{aligned} \frac{di_{sd}}{dt} &= - \left( \frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_s} \right) i_{sd} + \omega_s i_{sq} + \frac{1-\sigma}{\sigma M T_r} \Psi_{rd} + \frac{1-\sigma}{\sigma M} \omega_r \Psi_{rq} + \frac{1}{\sigma L_s} v_{sd} \\ \frac{di_{sq}}{dt} &= - \left( \frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_s} \right) i_{sq} + \omega_s i_{sd} + \frac{1-\sigma}{\sigma M T_r} \Psi_{rq} + \frac{1-\sigma}{\sigma M} \omega_r \Psi_{rd} + \frac{1}{\sigma L_s} v_{sq} \\ \frac{d\Psi_{rd}}{dt} &= \frac{M}{T_r} i_{sd} - \frac{1}{T_r} \Psi_{rd} + (\omega_s - \omega_r) \Psi_{rq} \\ \frac{d\Psi_{rq}}{dt} &= \frac{M}{T_r} i_{sq} - \frac{1}{T_r} \Psi_{rq} - (\omega_s - \omega_r) \Psi_{rd} \end{aligned} \quad (1.24)$$

With:  $T_s = \frac{L_r}{R_s}$ ,  $T_r = \frac{L_r}{R_r}$ ,  $\sigma = 1 - \frac{M^2}{L_s L_r}$

In order to obtain the complete model of the machine, the mechanical equation, on the base of the development of the equation of the instantaneous power, we obtain the expression of the torque electromagnetic,[11]

$$C_{em} = P \frac{M}{L_r} (\psi_{dr} i_{qs} - \psi_{qr} i_{ds})$$

On the other hand we have the expression:

$$C_{em} = J \frac{d\Omega}{dt} + f_r \Omega + C_r$$

With:  $\Omega = \frac{\omega_r}{p}$

The following state equation is obtained:

$$\frac{d\omega_r}{dt} = \frac{P^2 M}{J L_r} (\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) - \frac{f_r}{J} \omega_r - \frac{P}{J} C_r \quad (1.25)$$

The following notation can be used:

$$[x] = [x_1 \ x_2 \ x_3 \ x_4 \ x_5]$$

$$\text{And } [x] = [i_{sd} \ i_{sq} \ \psi_{rd} \ \psi_{rq} \ \omega_r]$$

We arrive at the following system of equation

$$\begin{aligned} \frac{dx_1}{dt} &= -a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 x_5 + a_5 V_{sd} \\ \frac{dx_2}{dt} &= -b_2 x_1 - b_1 x_2 + b_3 x_4 - b_4 x_5 x_3 + b_5 V_{sq} \\ \frac{dx_3}{dt} &= c_1 x_1 - c_2 x_3 + c_3 x_4 - x_5 x_4 \\ \frac{dx_4}{dt} &= d_1 x_2 - d_2 x_4 - d_3 x_3 + x_5 x_3 \\ \frac{dx_5}{dt} &= e_1 x_3 x_2 - e_1 x_1 x_4 - e_2 x_5 - e_3 \end{aligned} \quad (1.26)$$

With :

$$\begin{aligned} a_1 &= \left( \frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r} \right), & a_2 &= \omega_s, & a_3 &= \frac{1-\sigma}{\sigma M T_r}, & a_4 &= \frac{1-\sigma}{\sigma M}, & a_5 &= \frac{1}{\sigma L_s} \\ b_1 &= \frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}, & b_2 &= \omega_s, & b_3 &= \frac{1-\sigma}{\sigma M T_r}, & b_4 &= \frac{1-\sigma}{\sigma M}, & b_5 &= \frac{1}{\sigma L_s} \\ c_1 &= \frac{M}{T_r}, & c_2 &= \frac{1}{T_r}, & c_3 &= \omega_s \\ d_1 &= \frac{M}{T_r}, & d_2 &= \frac{1}{T_r}, & d_3 &= \omega_s \\ e_1 &= \frac{p^2 M}{J L_r}, & e_2 &= \frac{f_r}{J}, & e_3 &= \frac{p}{J} C_r \end{aligned}$$

**1.4.1 Induction machine model status form in repository ( $d q$ ):**

$$\frac{d}{dt} \begin{bmatrix} i_{i\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & \omega_s & \frac{M}{\sigma L_s L_r T_r} & \frac{\omega_r M}{\sigma L_s L_r} \\ -\omega_s & -\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & -\frac{\omega_r M}{\sigma L_s L_r} & \frac{M}{\sigma L_s L_r T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & (\omega_s - \omega) \\ 0 & \frac{M}{T_r} & -(\omega_s - \omega) & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \quad (1.27)$$

**1.4.2 Induction machine model state form in repository ( $\alpha \beta$ ):**

$$\frac{d}{dt} \begin{bmatrix} i_{i\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & 0 & \frac{M}{\sigma L_s L_r T_r} & \frac{\omega_r M}{\sigma L_s L_r} \\ 0 & -\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & -\frac{\omega_r M}{\sigma L_s L_r} & \frac{M}{\sigma L_s L_r T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & -\omega_r \\ 0 & \frac{M}{T_r} & \omega_r & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} \quad (1.28)$$

$\sigma = 1 - \frac{M^2}{L_r L_s}$  :Total dispersion coefficient

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

$\omega_r = p\Omega_r$  :Mechanical pulsation of the rotor and ( $p$ ): being the number of pairs of poles.

$$A = \begin{bmatrix} -\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & 0 & \frac{M}{\sigma L_s L_r T_r} & \frac{\omega_r M}{\sigma L_s L_r} \\ 0 & -\frac{1}{\sigma L_s} \left( R_s + \frac{M^2}{L_r T_r} \right) & -\frac{\omega_r M}{\sigma L_s L_r} & \frac{M}{\sigma L_s L_r T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & -\omega_r \\ 0 & \frac{M}{T_r} & \omega_r & -\frac{1}{T_r} \end{bmatrix}; B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

## 1.5 MODELING OF THE ASSOCIATION (RECTIFIER + LOW PASS FILTER $LC$ + VOLTAGE INVERTER)

Inductions motors are usually powered at the stator, and the current is induced in the rotor. It is for this reason that we also speak of "induction motors or machines". The asynchronous machine is mainly used as a motor, but it is sometimes used as a generator.

### 1.5.1 Modeling of a three-phase rectifier

The rectifier is a three-diode Graetz bridge that converts an alternating voltage to the input and a DC voltage at the output, it is represented by the Figure (1.4)[12]:

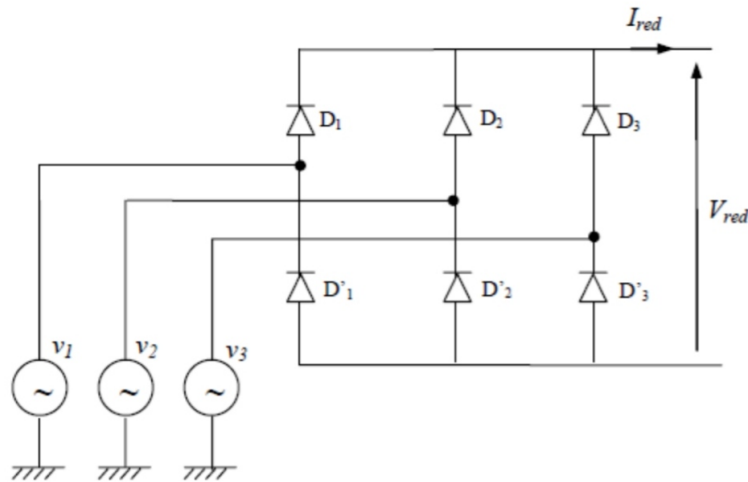


Figure 1.4: Representation Three-phase rectifier

### 1.5.2 Modeling of the filtering circuit

In order to minimize voltage ripples at the input of the inverter, and a rectified current relatively smooth, a filtering circuit is inserted which contains a capacitance and an inductance. The capacitor  $C$  suppresses sudden voltage variations during switching and absorbs the negative currents recovered by the load, and the inductance Allows the smoothing of the current substantially constant.

This filter is shown in the following Figure (1.5):

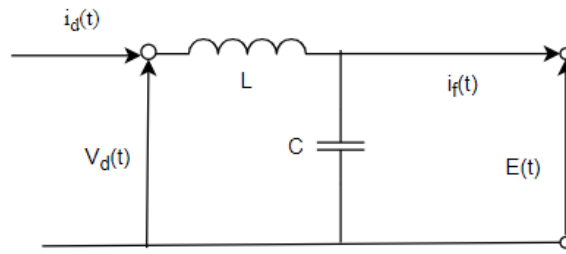


Figure 1.5: Representation of a low-pass filter

### 1.5.3 Modeling of the three-phase inverter

The inverter is a static converter capable of transforming the electrical energy of a source of direct voltage in an alternating type electrical energy, the use of inverters is very extensive in the industry, such as variable speed drives for three-phase motor, induction motor...etc. see Figure(1.6)

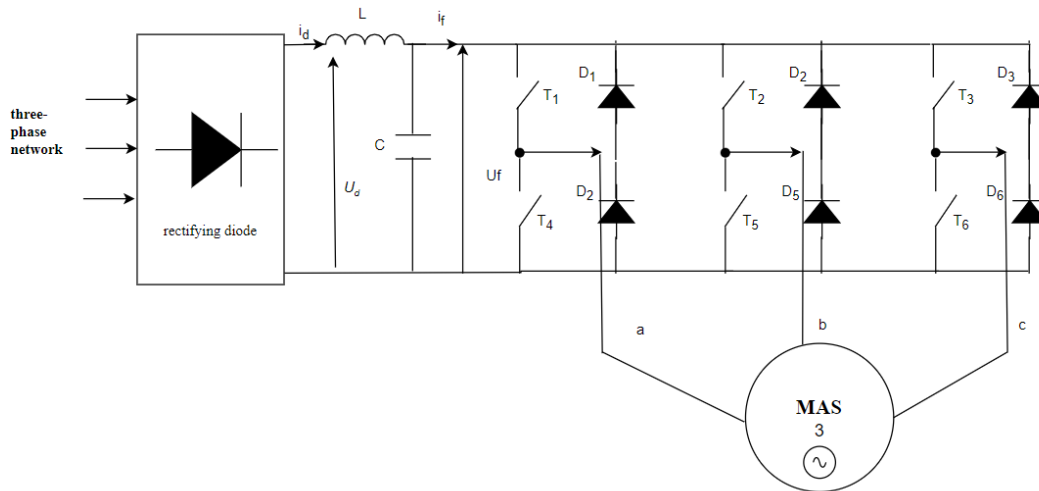


Figure 1.6: Induction machine association diagram-voltage inverter

It follows that :

$$\begin{aligned}
 U_{ab} &= \frac{1}{2}(F_1 - F_2)E \\
 U_{bc} &= \frac{1}{2}(F_2 - F_3)E \\
 U_{ca} &= \frac{1}{2}(F_3 - F_1)E
 \end{aligned}
 \tag{1.29}$$

The simple stator voltages are deduced from (1.29), we obtain:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \frac{E}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} \quad (1.30)$$

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

$$i_f = F_1 i_a + F_2 i_b + F_3 i_c \quad (1.31)$$

### 1.5.4 Control by PWM with hysteresis

The Pulse Width Modulation (*PWM*) approach is used to control the inverter. It entails applying voltages, chopped at a set frequency, evolving in accordance with voltage references acquired from the current regulators, across the terminals of the machine. These voltages are pulse width modulated using a triangle signal known as a carrier to determine the instants of switching and the duration of conduction of each switch of the inverter. One of each arm's two switches is currently conducting while the other is blocked.

The following is the block diagram for the inverter's *PWM* control see Figure (1.7)

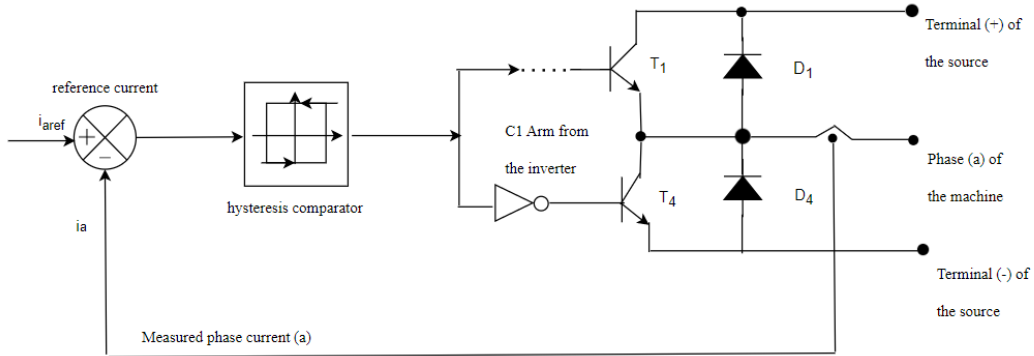


Figure 1.7: Block diagram of control by hysteresis of an arm of the inverter.

The switching conditions of the three static switches  $C_i$  ( $i=1,2,3$ ) of inverter are defined in terms of the corresponding logical states as follows:

$$\begin{aligned} F_i &= -1 \text{ if } i_i \geq i_{refi} + \Delta_i \\ F_i &= 1 \text{ if } i_i \leq i_{refi} - \Delta_i \\ F_i &= F_{(i-1)} \text{ if } i_i = i_{refi} \end{aligned} \quad (1.32)$$

such as :

- $i_i$  ( $i = 1, 2, 3$ ) are the stator phase currents ( $i_a, i_b, i_c$ ).

- $i_{refi}$  ( $i = 1, 2, 3$ ) are the reference currents from the three inverter arms.

- $\Delta_i$  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.

## 1.6 SIMULATION RESULTS AND INTERPRETATION

To illustrate the usual characteristics of IM, the behaviour of the machine powered directly by the three-phase network for two cases: Start on without load, and with load. The resolution of the previous differential equations was done using a programming in the Matlab environment.

- **without load**

In the first test, we will simulate the IM without load  $T_r = 0$  N.m

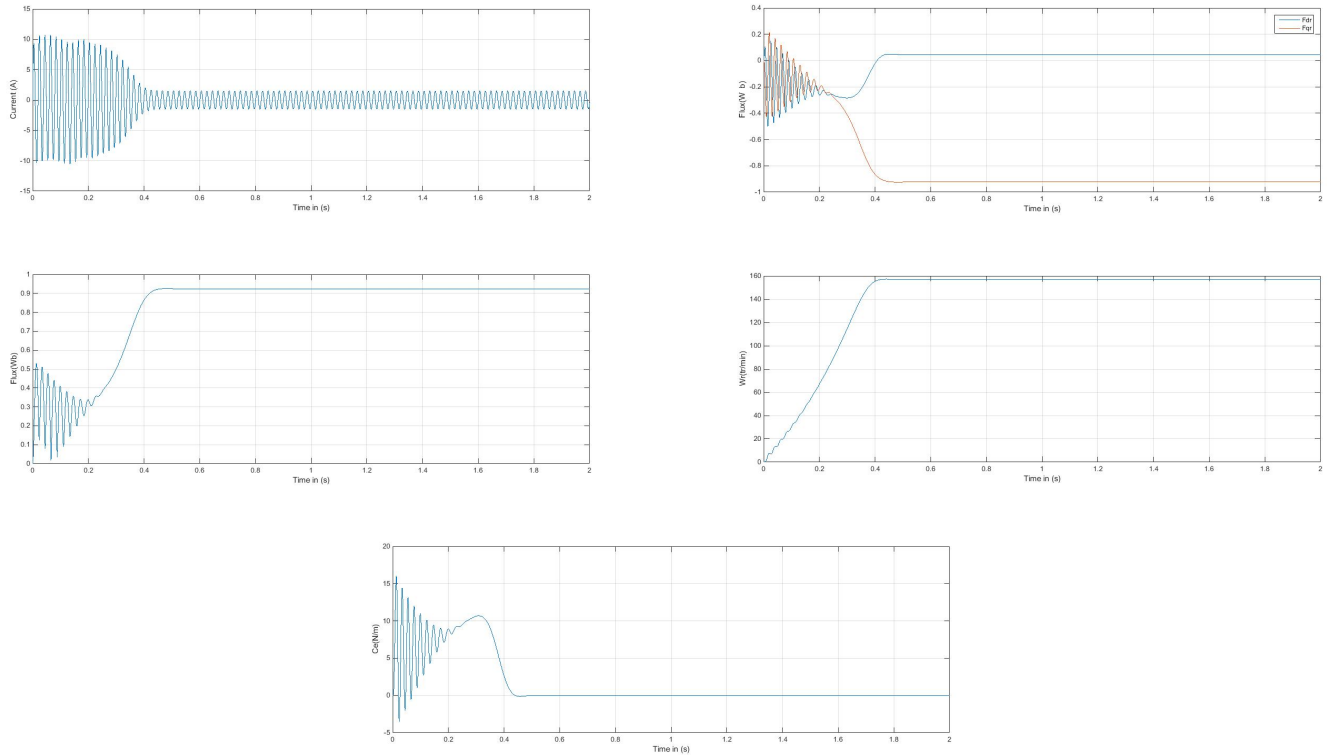


Figure 1.8: Performance of IM with no-load torque

- with load  $T_r=5$  N.m

In this test, we will simulate the IM with load torque  $T_r = 5$  N.m at  $t = [0.8,1.2]$ s

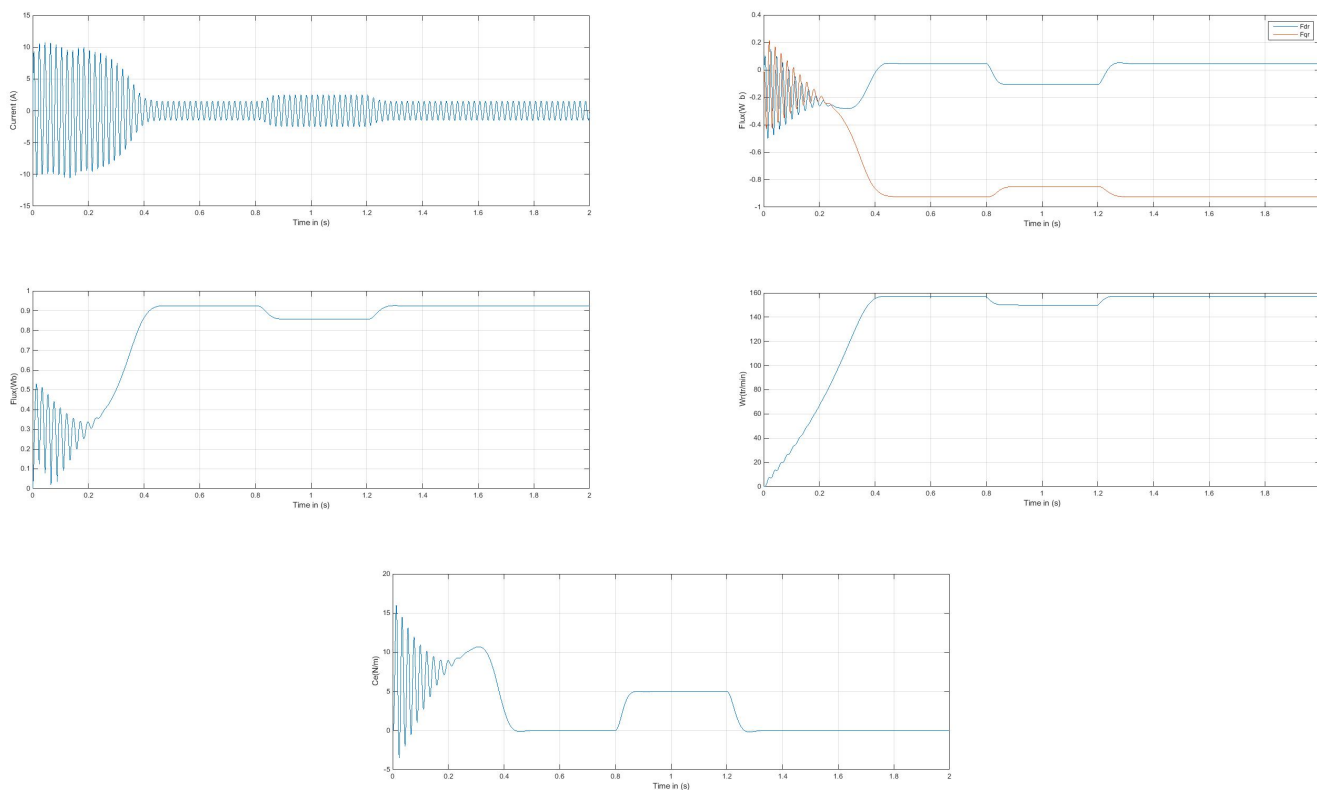


Figure 1.9: Performance of IM with load  $T_r= 5$  N.m between  $t=[0.8-1.2]$ s

### 1.6.1 Interpretation

From these results we can see that there is a relationship between torque and flux. This is why our motors are non-linear. So let's get started with vector control. Provides decoupling between torque and flux, avoiding nonlinear problems.

## 1.7 VECTOR CONTROL OF THE THREE-PHASE INDUCTION MACHINE

### 1.7.1 General :

The induction motors are very common because they are inexpensive and robust, finding use in everything from industrial applications such as pumps, fans, and blowers to home appliances. Traditionally, induction motors have been run at a single speed, which was determined by the frequency of the main voltage and the number of poles in the motor. Controlling the speed of an induction motor is far more difficult than controlling the speed of a DC motor since there is no linear relationship between the motor current and the resulting torque as there is for a DC motor.

The technique called vector control can be used to vary the speed of an induction motor over a wide range. It was initially developed by Blaschke (1971-1973). In the vector control scheme, a complex current is synthesised from two quadrature components, one of which is responsible for the flux level in the motor, and another which controls the torque production in the motor. Essentially, the control problem is reformulated to resemble the control of a DC motor. Vector control offers a number of benefits including speed control over a wide range, precise speed regulation, fast dynamic response, and operation above base speed.

The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents. An induction motor can be modelled most simply (and controlled most simply) using two quadrature currents rather than the familiar three phase currents actually applied to the motor. These two currents called direct ( $I_d$ ) and quadrature ( $I_q$ ) are responsible for producing flux and torque respectively in the motor. By definition, the  $I_q$  current is in phase with the stator flux, and  $I_d$  is at right angles. Of course, the actual voltages applied to the motor and the resulting currents are in the familiar three-phase system. The move between a stationary reference frame and a reference frame, which is rotating synchronous with the stator flux, becomes then the problem. This leads to the second fundamental idea behind vector control.

The second fundamental idea is that of reference frames. The idea of a reference frame is to transform a quantity that is sinusoidal in one reference frame, to a constant value in a reference frame, which is rotating at the same frequency. Once a sinusoidal quantity is transformed to a constant value by careful choice of reference frame, it becomes possible to control that quantity with traditional proportional integral (PI) controllers.

### 1.7.2 TYPES OF VECTOR CONTROL

The IM vector control can be either:

- Direct vector control.

- Indirect vector control.

### Direct vector control

This control method was proposed by Blaschke[3]. In this case, the knowledge of the flow module and its phase is required to ensure decoupling between torque and flow regardless of the point of operation.

In order to access information concerning the amplitude and phase of the flow, 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.

### Indirect vector control

The principle of this method is not to measure (or estimate) the amplitude of flow but only its position, the idea is proposed by Hasse. It consists in estimating the position of the flow 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 to achieve and the most used than the direct method, but the choice between the two methods varies from application to another.

### 1.7.3 Current powered asynchronous machine 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 asynchronous machine current, which is expressed by the two rotoric voltage equations:

$$\begin{aligned} R_r i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_s - \omega_r) \psi_{rq} &= 0 \\ R_r i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_s - \omega_r) \psi_{rd} &= 0 \end{aligned} \quad (1.33)$$

The rotor flow model from (1.33) and (1.19) is put in a state where the being imposed is the following:

$$\begin{aligned} \frac{d\psi_{rd}}{dt} &= -\frac{1}{T_r} \psi_{rd} + \omega_{gl} \psi_{rq} + \frac{M}{T_r} i_{sd} \\ \frac{d\psi_{rq}}{dt} &= -\frac{1}{T_r} \psi_{rq} - \omega_{gl} \psi_{rd} + \frac{M}{T_r} i_{sq} \\ J \frac{d\Omega_r}{dt} &= C_{em} - C_r - f_r \Omega_r \end{aligned} \quad (1.34)$$

With :  $\omega_{gl} = \omega_s - \omega_r$

In addition, in order to carry out vector control by orientation of the rotor flow, one must check the following conditions :

$$\begin{aligned} \psi_{rq} &= 0 & \text{et} & \dot{\psi}_{rq} = 0 \\ \psi_{rd} &= \psi_r & \text{et} & \dot{\psi}_{rd} = \dot{\psi}_r \end{aligned}$$

So the system of equations (1.34) and equation (1.22) become :

$$\begin{aligned} \frac{d\psi_r}{dt} &= -\frac{1}{T_r}\psi_r + \frac{M}{T_r}i_{sd} \\ J\frac{d\Omega_r}{dt} &= C_{em} - C_r - f_r\Omega_r \\ C_{em} &= \frac{3}{2}p\frac{M}{L_r}i_{sq}\psi_r \\ \omega_{gl} &= \frac{M}{T_r}\frac{i_{sq}}{\psi_r} \end{aligned} \quad (1.35)$$

It can be seen that the torque equation is analogous to that of the DC machine with separate excitation, and independent torque and of the flow is established.

#### 1.7.4 Speed adjustment of the three-phase asynchronous machine with flux oriented by a PI classic

The block diagram of the speed control of a machine-based drive asynchronous flux oriented by a conventional PI regulator is represented by the figure next :

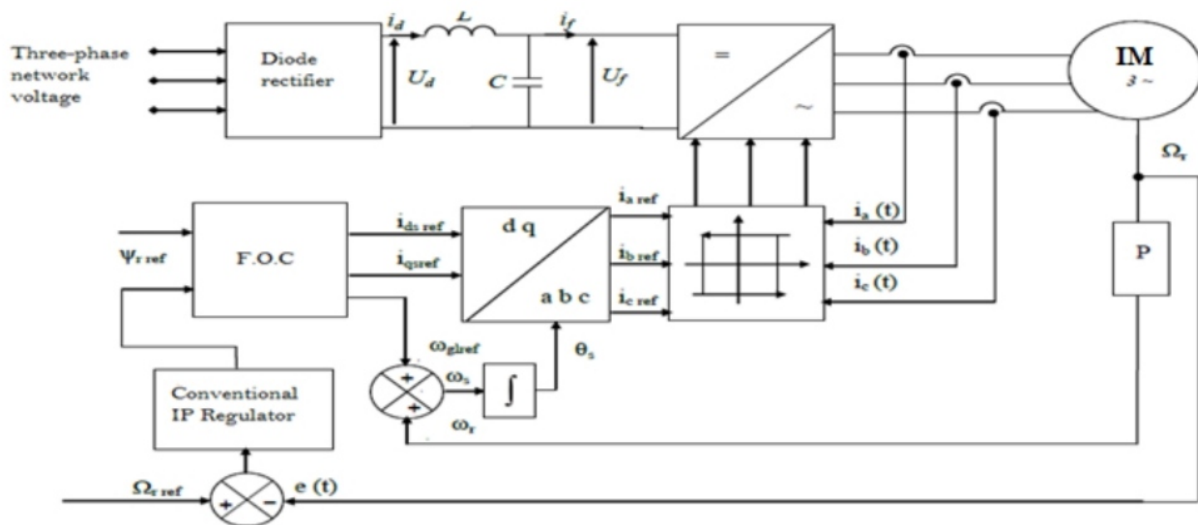


Figure 1.10: Vector control of an asynchronous machine with oriented rotor flux

## 1.8 Conclusion

In this chapter we have exposed the modeling of the MAS according to the benchmark of Park as well as its power supply constituted by a rectifier and a voltage inverter with *PWM* control.

Then we approached the fuzzy vector control of the MAS. Vector control provides good dynamic and static performance,

---

## Chapter 2

# Fuzzy Logic and PI Control of Induction Motor

### 2.1 Introduction

In this chapter, PI controller is proposed and A fuzzy logic controller to control the speed of the motor to be constant when the load varies. The speed error and the change of speed error are processed through the fuzzy logic controller whose output is the voltage command.

The system is simulated in a simulated MATLAB environment. The performance obtained is compared with a PI controller of the same environment.

### 2.2 FUZZY LOGIC CONTROL

Professor Lotfi Zadeh introduced the concept in the early 1970s Fuzzy Logic (FL) from University California Berkeley. it is not rendered as Control method, but handles data by allowing membership in subsets as a distinct set of members. FL includes a simple rule-based If X AND Y THEN Z approach to problem solving instead of trying to model the system mathematically. It takes an input value, performs some calculations and generates Returns an output value. This process is called fuzzy inference process (FIS).[13]

### 2.3 BASIC ELEMENTS OF FUZZY LOGIC

In this section, we show the elements of main basis of the theory of fuzzy logic.

### 2.3.1 Linguistic Variables

Fuzzy logic deals with imprecise, vague, or uncertain variables and introduces objective decisions through approximate reasoning. These variables form linguistic variables, whose values are estimated or assessed by words or expressions in natural language called fuzzy sets.

Linguistic variables, or fuzzy variables, are the inputs and outputs of the system to be controlled. For example, the rotational speed of an electric machine is a linguistic variable that can simultaneously take on several linguistic values: negative large (NL), negative small (NS), equal to zero (ZE), positive small (PS), positive large (PL).[14]

### 2.3.2 Fuzzy Set

A fuzzy set consists of a description of the phenomenon being studied, such as the motor electric (fast, medium, slow).

In classical set theory, a subset A of B is defined by the membership function  $\mu_A(x)$  characterizes all elements of B. This function takes the value 1 if x belongs to A, and otherwise the value is 0.

$$\mu_A(x) = \begin{cases} 0 & \text{si } x \notin A \\ 1 & \text{si } x \in A \end{cases} \quad (2.1)$$

In fuzzy logic, fuzzy subsets A and B are defined by membership functions that can take  $\mu_A(x)$ .

Different values between 0 and 1, depending on the membership of element x in its subset A.

$$\mu_A(x) \in [0 \quad 1] \quad (2.2)$$

### 2.3.3 Fuzzy Rules

Expert knowledge allows deducing a proposition or decision defining a control law from one or more fuzzy rules called inference rules. These rules are connected by fuzzy operators AND, OR, THEN, etc.

These rules can have the following form:

If condition one AND/OR if condition two THEN decision or action.

## 2.4 COMMAND BY FUZZY LOGIC:

A basic fuzzy logic controller is shown in Figure 2.1. FLC consists of four steps:

- Fuzzification block or fuzzifier
- Knowledge base
- Decision making block
- Defuzzification block or defuzzifier

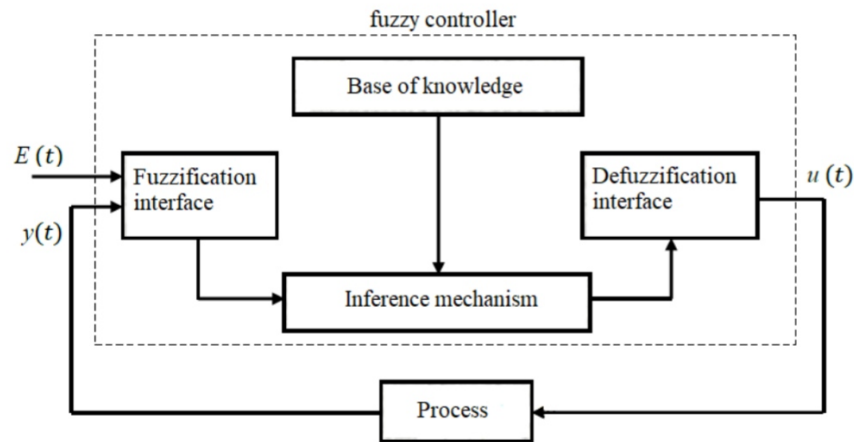


Figure 2.1: General diagram of a fuzzy controller

### 2.4.1 Fuzzification

The strategy of this operation is to convert the input and output quantities measured or estimated in linguistic variables, expressed in fuzzy terms.

### 2.4.2 Knowledge base

Generally, this knowledge base consists of all information and information available on the process to be addressed based on empirical analysis of the system, and which makes it possible to establish all functions and unclear rules of the regulator blur.

### 2.4.3 Fuzzy Inference Mechanism

Fuzzy inference is an important part of fuzzy controller Simulate human decision-making and derive (derived) fuzzy control measures. It uses fuzzy variables transformation through fuzzification

and inference rules to create and determine fuzzy output variables, Based on fuzzy operations applied to membership functions [13].

There are several ways to perform fuzzy operators applied to membership Function. We name the three most common inference methods:

- Max-Min
- Max-Product
- Sum Product

| Fuzzy operators<br>Inference methods | AND     | OR      | THEN    |
|--------------------------------------|---------|---------|---------|
| Max-Min                              | Minimum | Maximum | Minimum |
| Max-Product                          | Minimum | Maximum | Product |
| Sum Product                          | Product | average | Product |

Table 2.1: Methods of fuzzy inference

If we have two inputs ( $x_1, x_2$ ) and its output is  $x_r$ , the action of each rule is given by:

$$\mu_{Ri}(x_r) = \mu(x_1) \mu(x_2) \mu_{oi}(x_r) = \mu_{ci} \mu_{oi}(x_r) \quad (2.3)$$

$\mu(x_1) \mu(x_2)$  : Are the membership factors of the two linguistic variables  $x_1$  and  $x_2$  with respect to the condition of the rule.

$\mu_{ci}$  : Is the membership factor of the condition.

$\mu_{oi}(x_r)$  Is the membership function of the corresponding decision to the  $i^{\text{th}}$  rule.

The resulting membership function is given by:

$$\mu_{res}(x_r) = [\mu_{R1}(x_r) + \mu_{R2}(x_r) + \dots + \mu_{Rm}(x_r)] / m \quad (2.4)$$

With:  $m$  is the number of rules in the inference.

#### 2.4.4 Defuzzification Interface

Defuzzification consists in the Convert rules to numeric values. Several methods have been proposed, such as:

- centre of gravity
- mean of maxima
- first of maximum

### 2.4.4.1 Defuzzification By The Centre Of Gravity Method

The strategy of this method consists of graphically treating the areas associated with the membership functions of the linguistic terms of the conclusions  $\mu_{Ri}(x_r)$  that form  $\mu_{Res}(x_r)$ . These areas are weighted by the degree of truth of each rule, So it is logical to confuse the numerical value of the output and the abscissa of the center of gravity of the surface formed by the union of these areas  $\mu_{Res}(x_r)$ .

The abscissa of the center of gravity of  $\mu_{Res}(x_r)$  this surface is given by the following expression.

$$x_{Gr} = \frac{\int_{-1}^1 x_r \mu_{res}(x_r) dx_r}{\int_{-1}^1 \mu_{res}(x_r) dx_r} \quad (2.5)$$

The determination of the abscissa of the center of gravity  $x_{Gr}$  requires a significant computational effort. However, this calculation is notably simplified if  $\mu_{Res}(x_r)$  is determined using the sum-product inference method, which justifies its choice.

### 2.4.5 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[15].

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

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

with ,  $e = \Omega_{ref} - \Omega$ :speed error;  $\Delta e = e_k - e_{k1}$ error variation.  $k_e, k_{\Delta e}, k_{\Delta C_{em}}$  : 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:

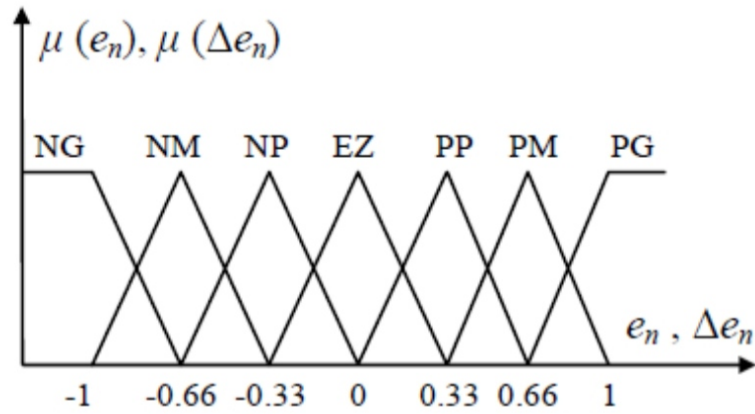


Figure 2.2: Functions of belonging the output variable(  $e_n, \Delta e_n$  ).

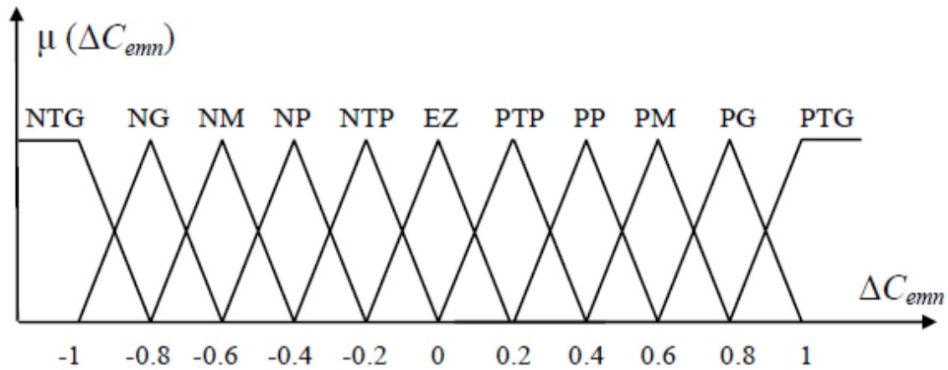


Figure 2.3: Functions of belonging the output variable (  $\Delta C_{emn}$  ).

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:

|             |     |     |     |     |     |     |
|-------------|-----|-----|-----|-----|-----|-----|
| $\Delta en$ | 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 2.2: Inference matrix.

## 2.5 Simulated Performance of Proposed System with Pi Control and FLC Control

In this part we use simulation for PI regulator with load and without load as well as with Fuzzy regulator. Then we'll compare them better in terms of performance. Give an explanation of the results.

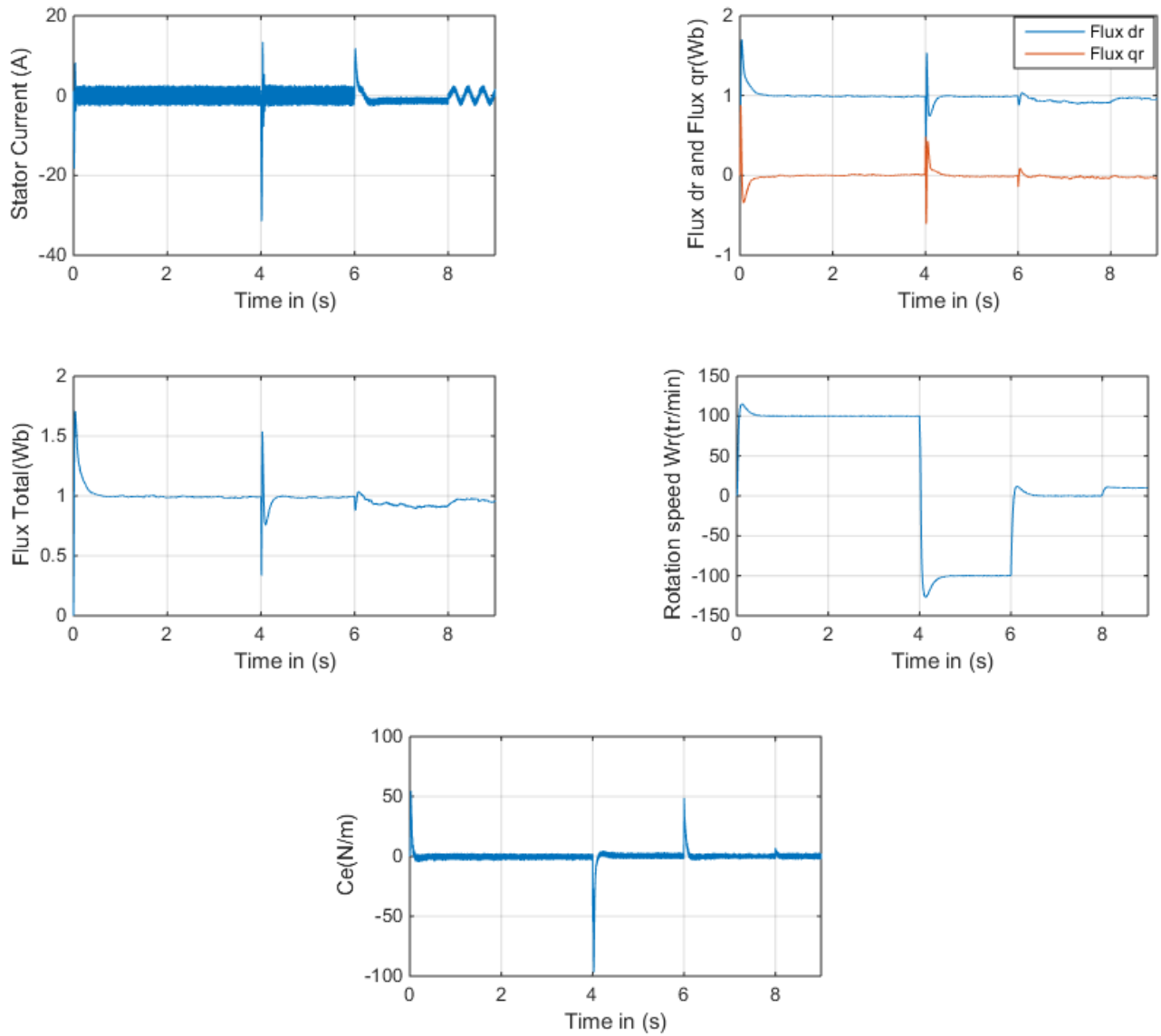


Figure 2.4: Performance of IM with regulator PI (Without Load)

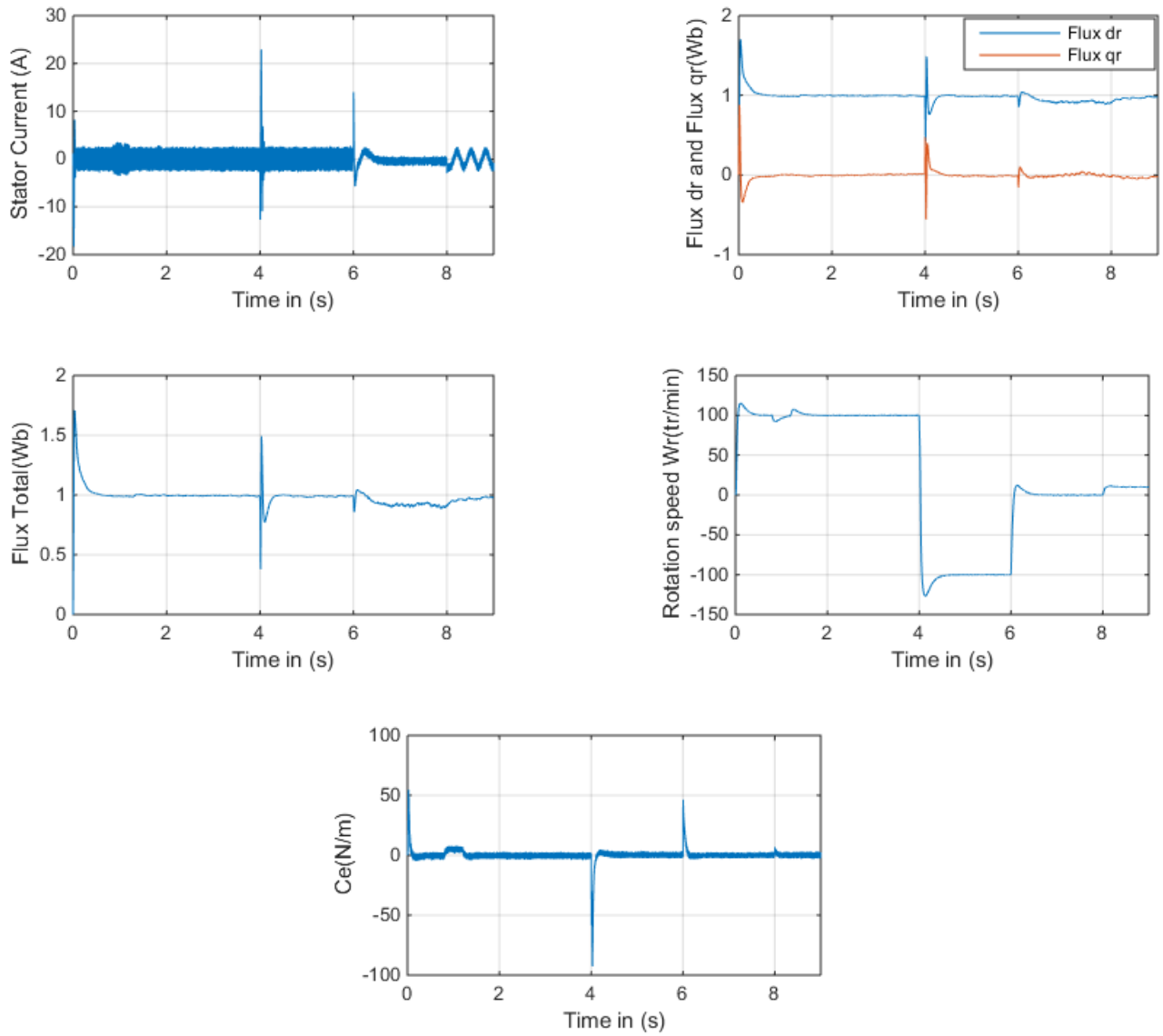


Figure 2.5: Performance of IM with regulator PI ( With Load)

### 2.5.1 Interpretation

- a) Without load

After a transient regime of 1.07 s (the beginning of the steady state), the speed stabilizes at 118 rad/s, which is almost synchronism speed, after increasing at first and in the transient regime.

Starting out, the torque reaches a maximum of 71 Nm. decreases after that and stabilizes at its lowest value of 0.21 Nm.

The current increases to a value of  $i_s=12.2$ , then decreases and stabilizes at  $i_s=2.4$  The flux  $\psi_{dr}$  initially exhibits oscillations before stabilizing at -1.6Wb in 0.12 s, while the flux  $\psi_{qr}$  initially exhibits transitory oscillations before stabilizing at the value.

- b) With Load

The speed value decreases to 95.1 rad/s when the torque is loaded in the time range [0.8,1.2]s.

In the time interval [0.8,1.2] s, the electromagnetic torque rises to a value of 8.25 N.m.

We observe an increase in stator currents ( $i_s=2.6$ ).

The flux,  $\psi_{dr}$  climbs to a value of -1.1Wb while the  $\psi_{qr}$  flux rises to 0 Wb.

Thus, we apply vector control, which offers independent control of the torque and flux, to enhance the machine's dynamic response and remove the present interaction between the various variables

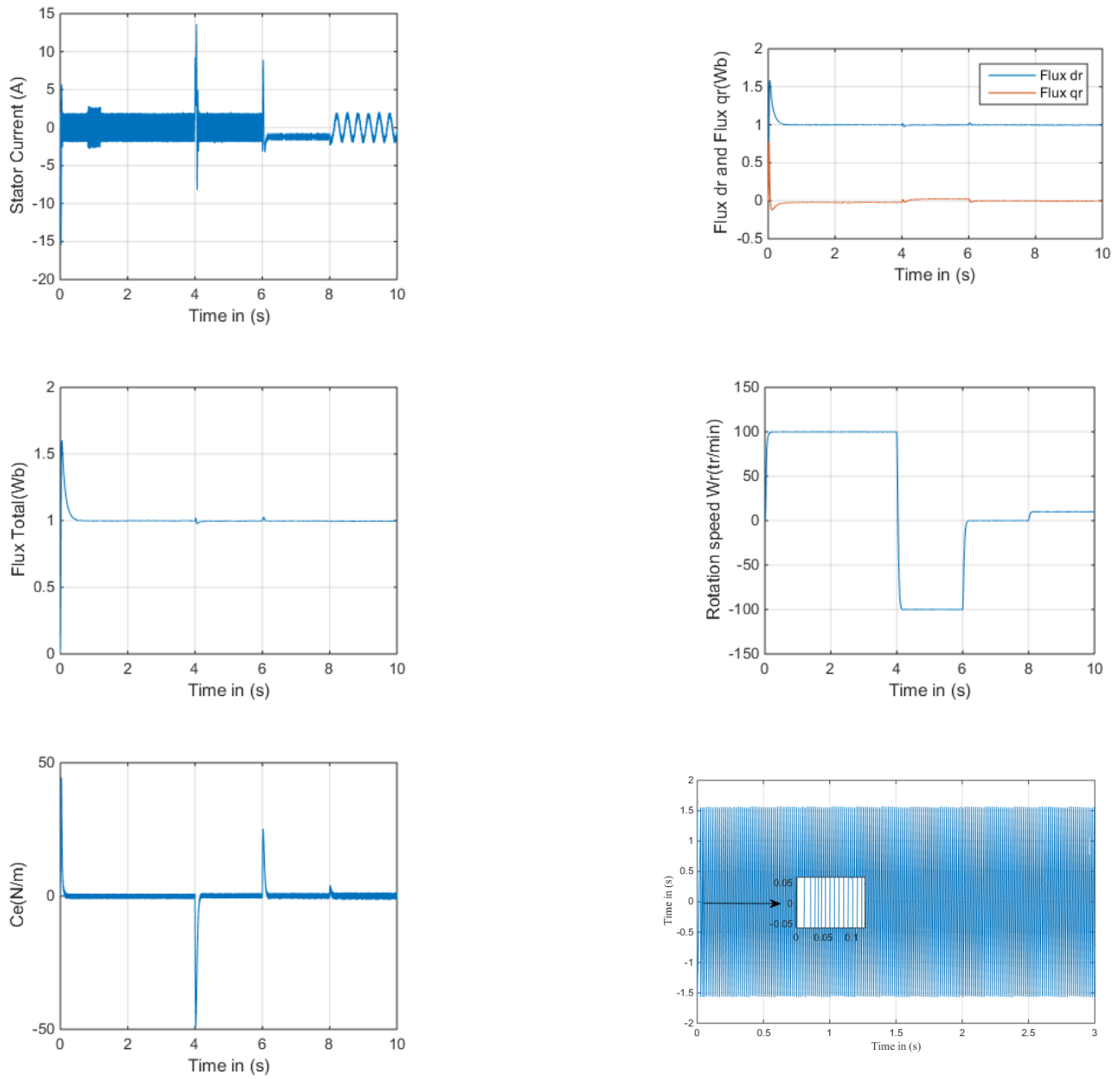


Figure 2.6: Performance of IM with Fuzzy regulator (Without Load)

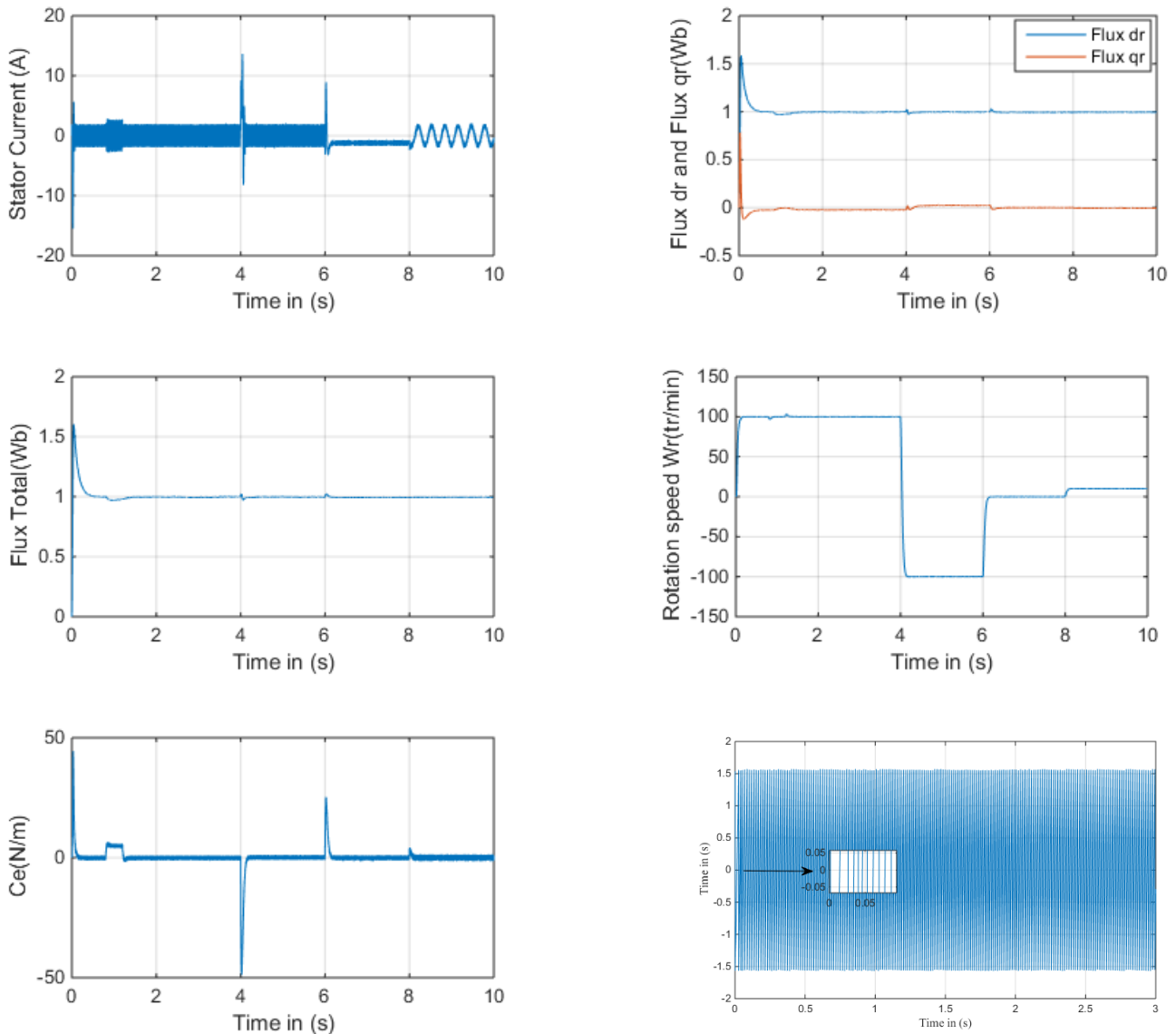


Figure 2.7: Performance of IM with Fuzzy regulator (With Load)

### 2.5.2 Interpretation

With a fuzzy regulator, simulation results showed better IM performance. When a load is applied, the velocity peaks at 0.1 sec and then gradually declines to approach 100 rad/sec before returning to its reference value, which takes 0.31 sec to reach in response. When [0.8-2]s of a load is applied, it increases ce to 8.3 N.m.

## 2.6 Conclusion

Fuzzy logic-based speed control of an IM is an alternative control method for induction motors.

The simulation results show that the performance and speed response of a proposed system with FLC is better compared with that of a PI controller. The overshoot and ripple is reduced substantially.

Thus soft-computing technique proved to be promising for better system performance.

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# Chapter 3

## Mutual- MRAS estimator for Induction Motor

### 3.1 INTRODUCTION

In recent years, the sensorless control of engine speed asynchronous has become a major concern for industrial, and an important research topic for the community scientist. Thus, many control strategies without a sensor have been developed in order to provide the induction machine with high performance ensuring fast and precise dynamics. A great part of the proposed methods is based on state observers such that the deterministic Luenberger observer [16], the stochastic filter of Kalman [17] or the estimators with adaptive system to model of reference (MRAS) [18] [3].

To this end, we present different estimates and observations in the first part of this chapter then we propose a sensorless vector control based on fuzzy MRAS-mutual Induction motor estimator for estimating stator and rotor resistance and speed.

At last In this chapter, the simulation results are given and commented on.

### 3.2 SPEED SENSORLESS CONTROL

Modern industrial applications with asynchronous variable speed drives have high demands Dynamic and static performance based on directional (and/or) flow control techniques.[19]. This is due to perfect knowledge of position and flow modulus (and/or). the speed of the machine. This information comes from feedback control via direct electrical control Sensor (current, voltage, flux) or mechanical (speed, angular position) Sometimes special processing of the received physical signal is required.

Additionally, the mechanical speed sensor can be omitted in the low power range Economic benefits and increased operational safety. However, control is without speed the performance of the sensor must not differ significantly from that of the physical sensor [15].

### 3.3 THE PROBLEM WITH SENSORLESS CONTROL

From an industrial perspective, sensorless control has become attractive and an important topic. The presence of sensors in electronic speed drives affects their robustness and performance. Reliability also increases the cost and complexity of assembly. so mechanics Sensors are replaced by computational algorithms that allow estimation of speed from an electrical point of view the terminal of the machine. The performance required by this estimator must be met Close to or similar to the value given by the physical sensor.

### 3.4 Estimation By The MRAS-Mutual Technique

#### 3.4.1 Speed Estimation Using MRAS Technic

This technique is designed on the basis of an adaptive system using a model of reference (MRAS) comprising two flow estimators. The first, not introducing the speed, is called reference model (or voltage model). The second, which is a function of the speed, is called adjustable model (or current model), (see Figure 3.1). The error produced by the offset between the outputs (flux,  $f_{em}$ , reactive power) of the two estimators, pilot an adaptation algorithm that generates the estimated speed  $\omega$ . [20][21][3]

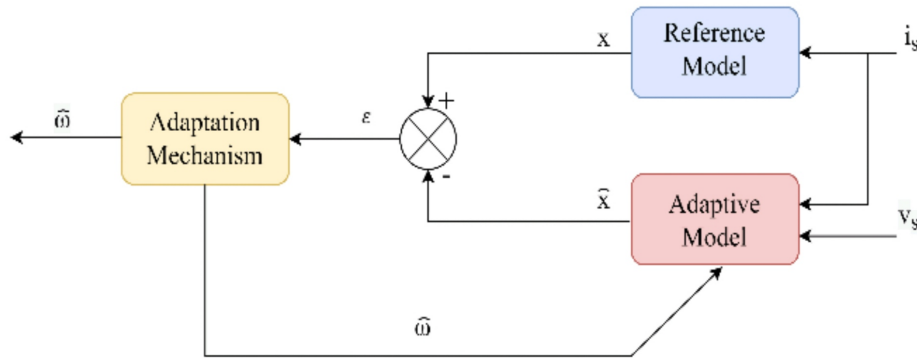


Figure 3.1: MRAS Structure

The error between the outputs can take various forms

- Error between estimated flux by current model and voltage model
- Resulting error from crossed multiplication between estimated emfs. This method used to eliminate pure integration of voltage model .
- Resulting error from crossed multiplication between error of stator currents and estimated rotor fluxes. [22]

However, the major inconvenience of speed estimation based on MRAS is huge sensibility to machine parameter. For that, various studies proposed online adaptation technic with stator resistance [3],[20] or online adaptation with rotor resistance. And, the current model is sensible to rotor time constant and his adaptation in the same time of speed estimation is difficult.

### 3.4.2 State Observer

A state observer is a structure that provides estimates for variables or internal values the size of a system. They are based on laws, i.e. mathematical models that describe this in the problem behavior of the machine. Estimated size is often non-measurable and/or non-measurable Want to measure (speed, position). Define observers based on available information These are usually measured inputs and outputs of physical systems.[23]

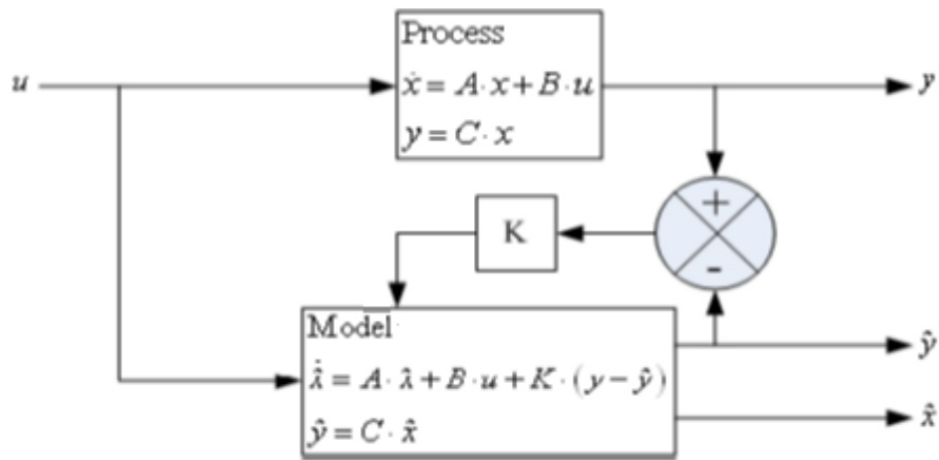


Figure 3.2: structure of a state observer

This observer schematic allows us to enforce all types of observers The difference is in K Matrix composition. Choosing an appropriate reference proved to be important Observer behavior. In fact, it is important to have a near-steady-state evolution matrix of the system A that allows checking the validity of the assumption of linearization of the system in question mode separation[23].

### 3.4.3 Determinist Observer

The deterministic observer (Luenberger) [24] is based on the equation No measurement noise or interference is considered. mainly that Observers are sensitive to disturbances and parameter variations.

### 3.4.4 Stochastic Observer

This observer, also known as a Kalman filter, is characterized by taking noise into account the estimation error variance can be minimized by the measurements and conditions of the stochastic algorithm. This is not the case for Luemberger observers, where the estimation error is close to zero. this the performance of the Kalman filter is satisfactory, combined with complex algorithms, the natural presence of noise Induction motors are controlled by inverters, which is a strong argument for choosing this type observer. In real life, the noise in the variable frequency motor system is polluted, causing errors Sometimes minimization is not guaranteed [25].

### 3.4.5 Sliding Mode Observer

The sliding mode observer is based on the theory of variable structure systems. this This method is applicable to many nonlinear dynamical systems. It also has Sliding mode controller. Over the past two decades, many researchers have proposed Various algorithms based on the float mode are characterized by discontinuous instructions acting on higher-order derivatives of float variables, thus breaking the float surface[26].

## 3.5 ESTIMATION OF SPEED WITHOUT A MODEL

### 3.5.1 Estimate speed from machine characteristics

In general, induction motors are theoretically constructed symmetrically and do not allow Include salience. Therefore, due to the inaccuracy of the design, the machine has a peculiarity Existence of notched and saturated rotors. characteristics of the machine Introduce parameter space variation (resistance or inductance) and allow current Or the voltage should contain information about the location of these expressions and thus contain information about The position of the rotor, so an information about the speed [25]. We can include various techniques in it Estimate speed from these machine physics data related to the presence of protrusions [27][28]. Insensitive to this On the other hand, the setup of the machine is a great advantage of this technique Efficient signal processing means are required. The challenging part is making it happen Real-time estimation, especially for loop instructions.

### 3.5.2 Estimation Base On Fuzzy Logic

For more than two decades, the fuzzy logic becomes a very important axe of research. It find his place in the field of control for a large range of systems and precisely in electrical engineering. It presents the advantages of using simple linguistic rules allowing to simply translate the expertise of an expert to answer a specific problematic [15].

## 3.6 SPEED OBSERVERS

### 3.6.1 Adaptive Observer Kubota

The structure of "Kubota" adaptive observer is shown in the figure (3.3)

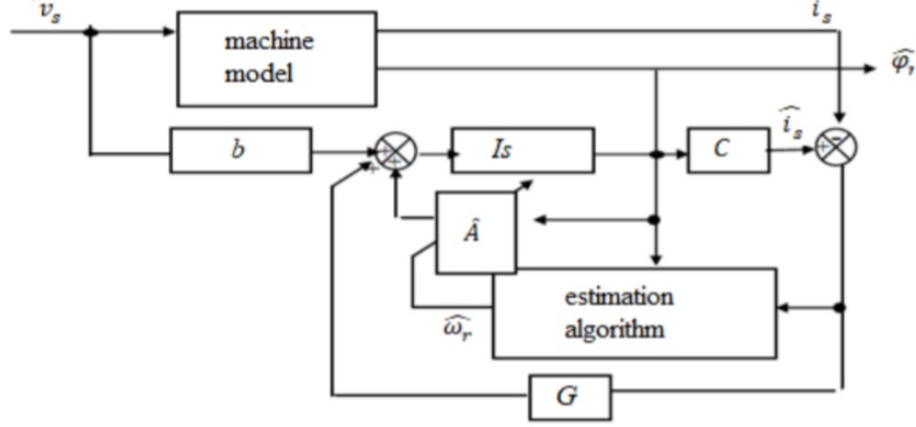


Figure 3.3: Block diagram of adaptive observer Kubota

### 3.6.2 MRAS-Mutual Approach

The MRAS-Mutuel method is based on comparing two Theoretical flow estimates obtained by different formulas. It was originally published by V. Vasic.[29] developed and allowed to estimate motor speed and stator resistance. estimate required rotor flow components for both estimators represents measured values of voltage and stator current only in the reference system  $(\alpha, \beta)$ .

- **Reference Model**

The first estimator is based on the static equation of the model in voltage, independent of speed and explicitly coupled to the resistor stator. Its expression is given by the system of equations (3.1):

$$\begin{cases} \frac{d\psi_{r\alpha}}{dt} = \frac{L_r}{L_m} \cdot (v_{s\alpha} - R_s \cdot i_{s\alpha} - \sigma \cdot L_s \cdot \frac{di_{s\alpha}}{dt}) \\ \frac{d\psi_{r\beta}}{dt} = \frac{L_r}{L_m} \cdot (v_{s\beta} - R_s \cdot i_{s\beta} - \sigma \cdot L_s \cdot \frac{di_{s\beta}}{dt}) \end{cases} \quad (3.1)$$

With:  $\sigma = 1 - \frac{L_m^2}{L_s L_r}$

- **Adaptive Model**

The second estimator is described by the rotor equation the current model, explicitly coupled to velocity and independent of stator resistor. Equations (3.2) determine its model:

$$\begin{cases} \frac{d\hat{\psi}_{r\alpha}}{dt} = \frac{L_m}{T_r} \cdot i_{s\alpha} - \frac{1}{T_r} \cdot \hat{\psi}_{r\alpha} - \hat{\omega}_r \cdot \hat{\psi}_{r\beta} \\ \frac{d\hat{\psi}_{r\beta}}{dt} = \frac{L_m}{T_r} \cdot i_{s\beta} + \hat{\omega}_r \cdot \hat{\psi}_{r\alpha} - \frac{1}{T_r} \cdot \hat{\psi}_{r\beta} \end{cases} \quad (3.2)$$

- **Adaptation Mechanism**

Stress model is used to estimate velocity reference model and current model as models adjustable. Stator resistance is determined by reverse the roles of the estimator. Two regulatory mechanisms taking the error signals  $e_{\psi_r}$  and  $e_{R_s}$  as input, the significant deviation between the two flux rate estimators.

$$e_{\psi_r} = \hat{\psi}_{r\beta V} \cdot \hat{\psi}_{r\alpha I} - \hat{\psi}_{r\alpha V} \cdot \hat{\psi}_{r\beta I} \quad (3.3)$$

$$e_{R_s} = i_{s\alpha} \cdot (\hat{\psi}_{r\alpha V} - \hat{\psi}_{r\alpha I}) + i_{s\beta} \cdot (\hat{\psi}_{r\beta V} - \hat{\psi}_{r\beta I}) \quad (3.4)$$

$(\hat{\psi}_{r\alpha V}, \hat{\psi}_{r\beta V})$  and  $(\hat{\psi}_{r\alpha I}, \hat{\psi}_{r\beta I})$  these are the flux components provided by the voltage and current estimators, respectively.

The adaptation mechanisms deliver the estimated values of the speed and the stator resistance by re-injecting them into their models respective adjustable, in order to minimize deviations  $e_{\psi_r}$  and  $e_{R_s}$  existing.

To provide a quick response by guaranteeing the stability of the system, V. Vasis [29] proposed two proportional and integral laws for define the adaptation mechanisms :

$$\hat{\omega}_r = k_{p\omega r} \cdot e_{\psi_r} + k_{i\omega r} \cdot \int e_{\psi_r} \cdot dt \quad (3.5)$$

$$\hat{R}_s = k_{pR_s} \cdot e_{R_s} + k_{iR_s} \cdot \int e_{R_s} \cdot dt \quad (3.6)$$

$k_{p\omega r}$ ,  $k_{pR_s}$  and  $k_{i\omega r}$ ,  $k_{iR_s}$  are respectively the gains of the two controllers PI constituting the adaptation mechanisms. To maintain the decoupling and enhance the precision of the estimator, it is necessary to take certain measures. Our proposal is concerned with the variation of the rotor resistor value. The version was expanded from its original form, with the assumption that in case the temperature of the windings in the motor are almost identical. The value of resistor is directly proportional to the variations in resistor. The relation below can be used to determine the rotor value:

$$\hat{R}_r = \hat{R}_s \cdot \frac{R_{rn}}{R_{sn}} \quad (3.7)$$

The rotor resistance is deduced from the sole estimate of the stator resistance, which reduces the algorithmic cost.

The Figure (3.4) illustrates the new structure of the MRAS-Mutuel Estimator.

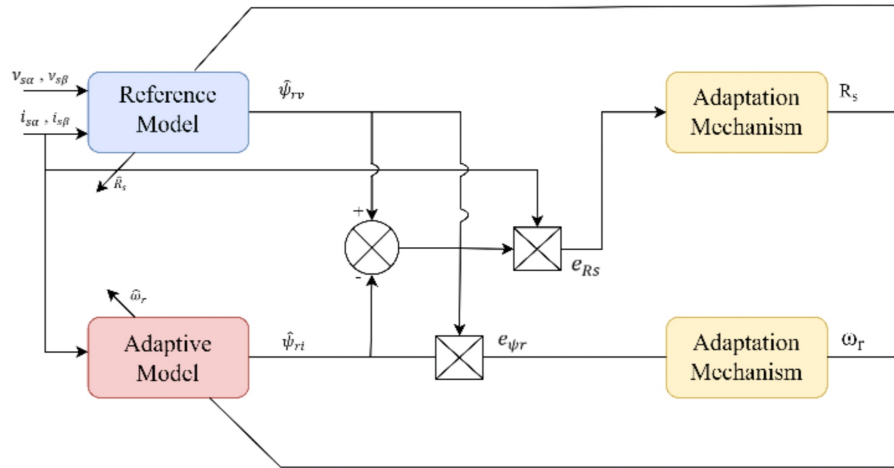


Figure 3.4: Structure of the proposed Mutual -MRAS estimator

### 3.7 SIMULATION RESULTS AND INTERPRETATION

In this part we have used reciprocal MRAS, a sensorless motor control technique that is based on comparing the actual motor flux with a calculated reference flux, with parameters adapted to determine the internal resistance of the motor.

It is used in motor speed control applications and improving system performance without the need for direct sensing of the motor in the following: the results obtained and an attempt to interpret them.

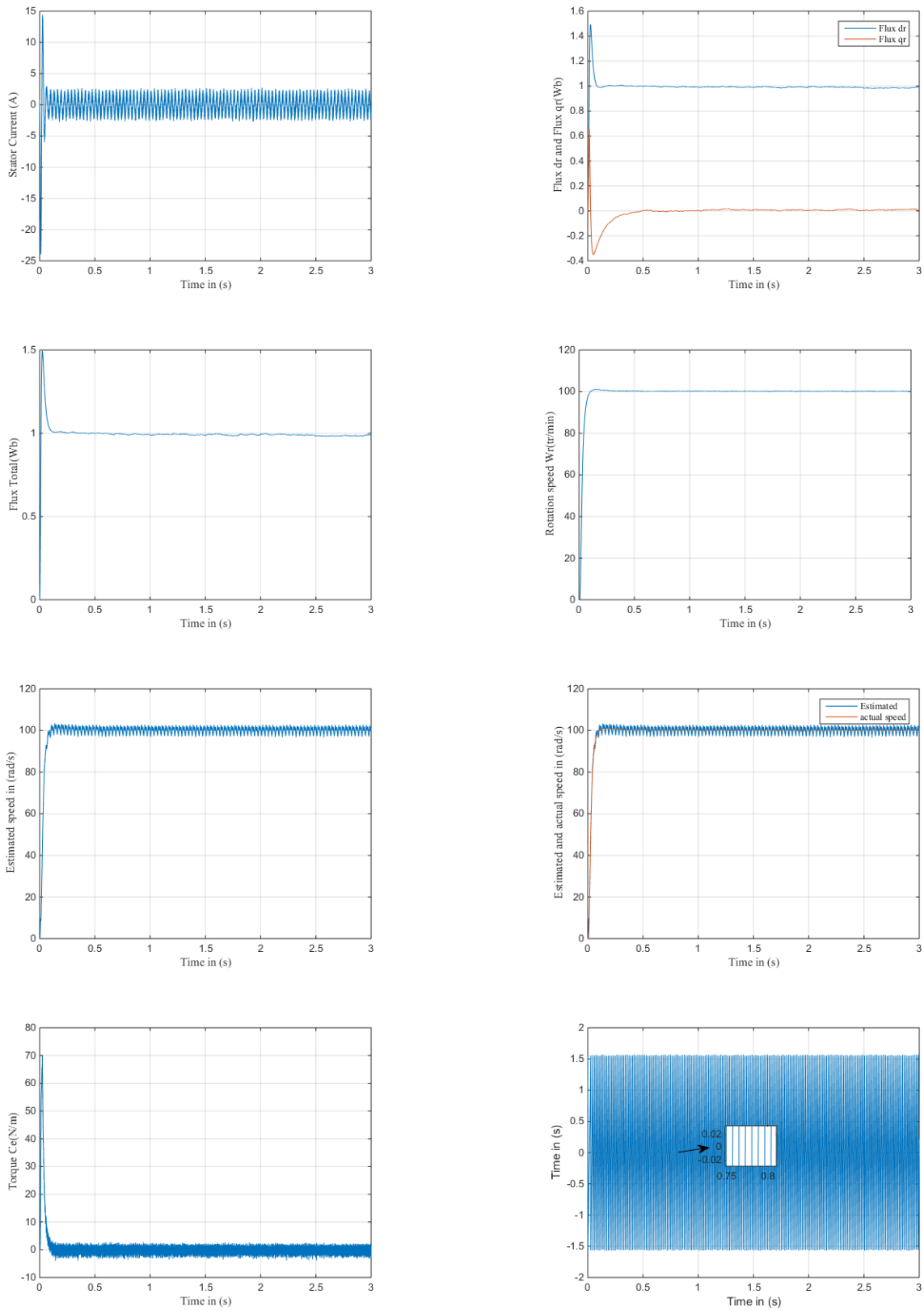


Figure 3.5: Performance of IM with mutual MRAS (Without Load)

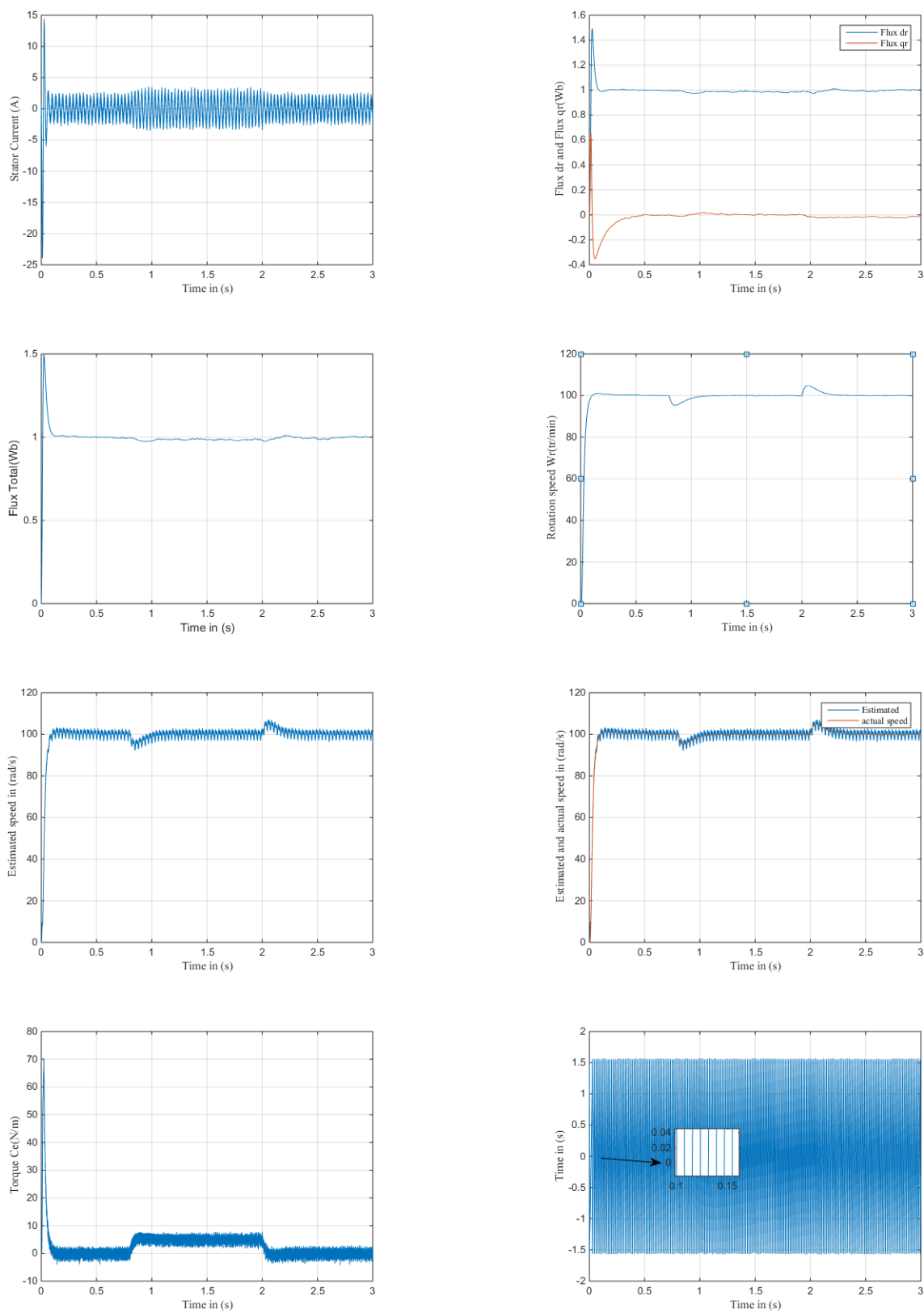
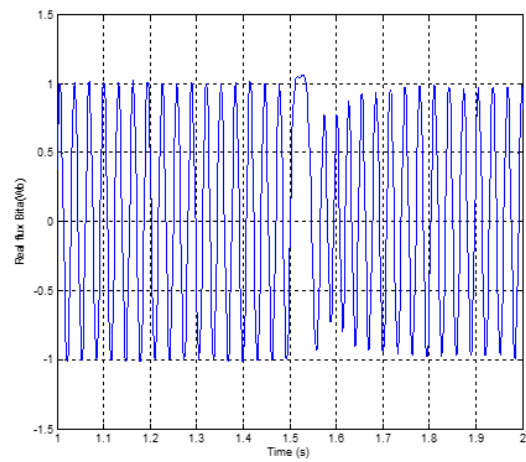
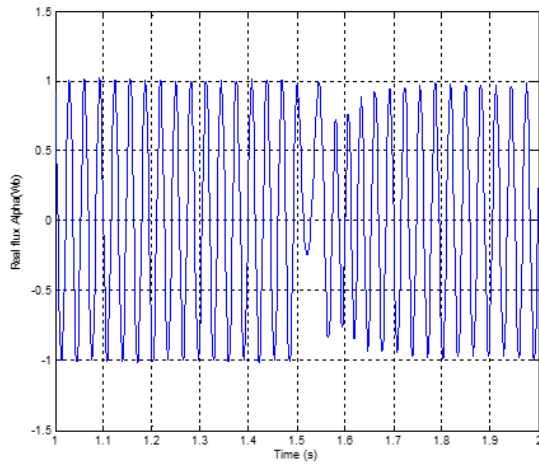
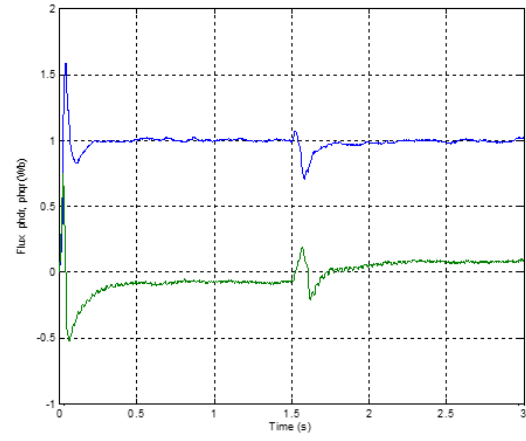
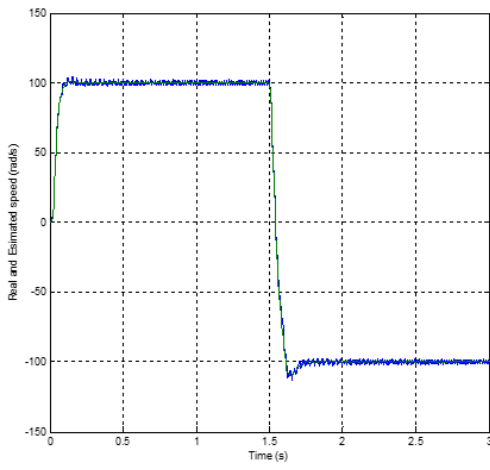
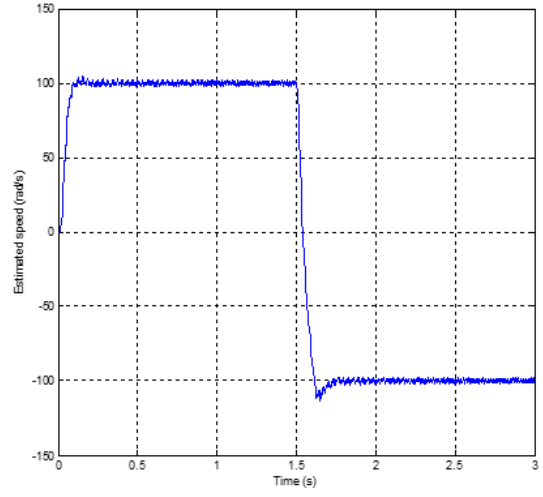
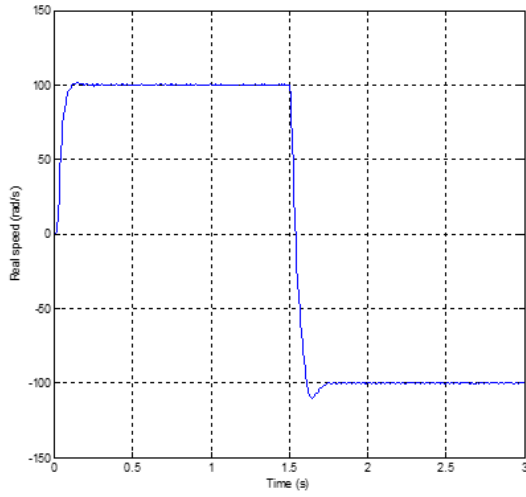


Figure 3.6: Performance of IM with mutual MRAS (With Load)



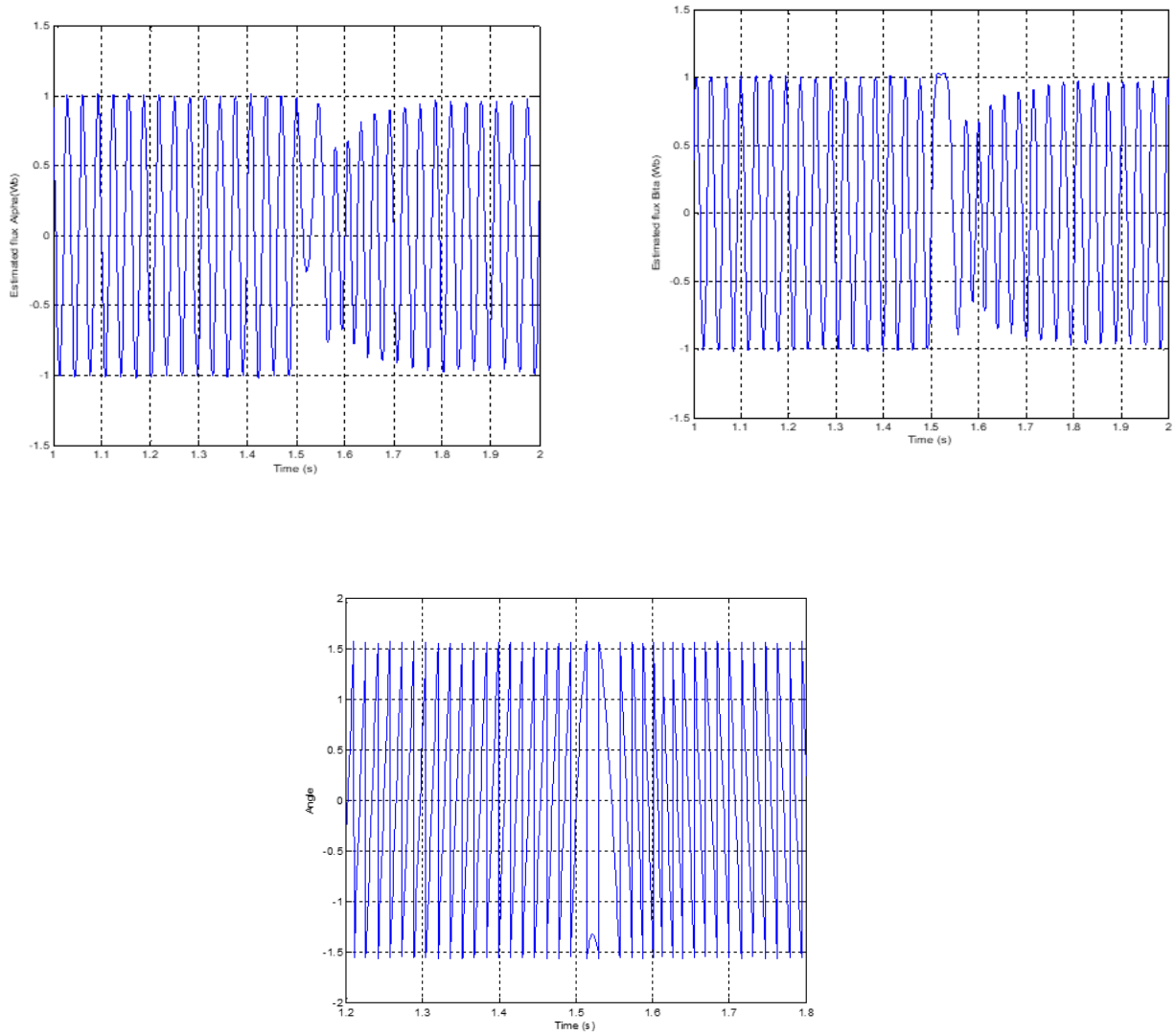


Figure 3.7: Performance of IM with mutual MRAS (speed reverse)

In the second step, we employed two scenarios for evaluating resistances in order to assess the effectiveness and accuracy of the suggested method estimator in terms of resistance estimation. The variation in stator and rotor resistance is shown in Figure (3.8), which increases linearly to 100% between 0 and 1 (s), then stays at twice its nominal value between 1 and 3 (s), decreases linearly to -50% of its nominal value between 3 and 5 (s), and then remains at -50% of its nominal value from 5.0 (s).

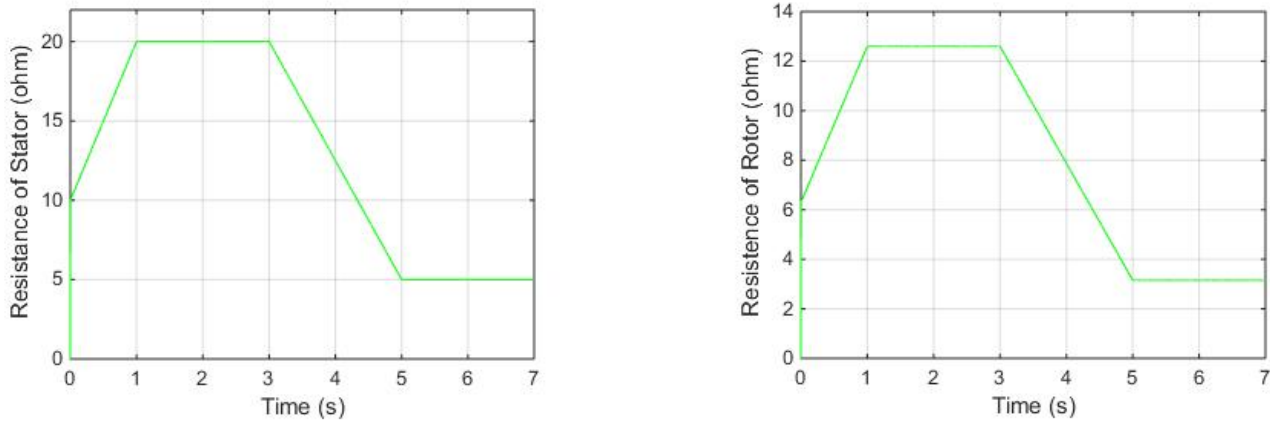


Figure 3.8: Stator resistance and Rotor resistance variation

From the results obtained in Fig (3.9) it can be seen that the estimated stator and rotor resistance track their actual values closely under steady-state conditions.

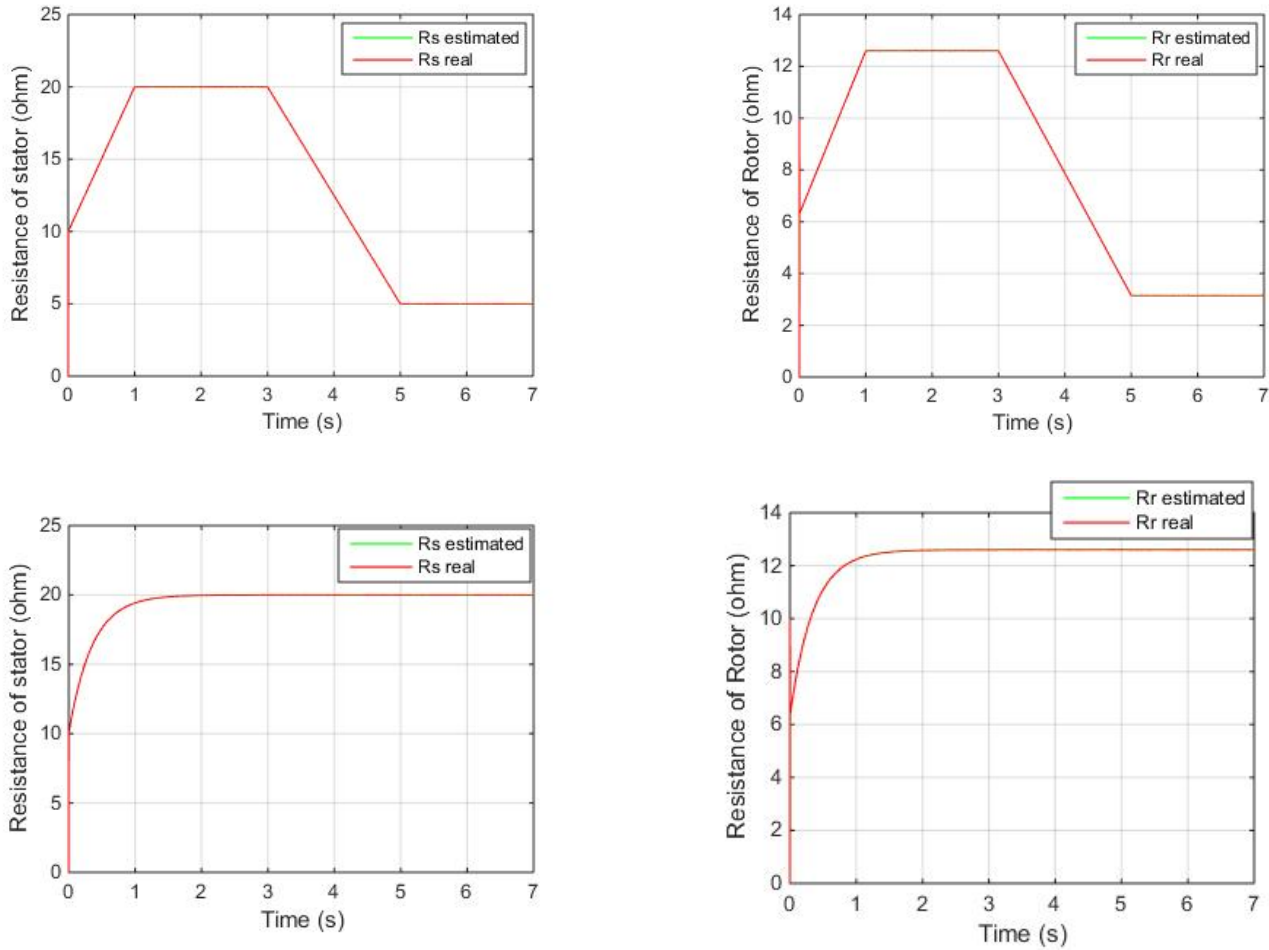


Figure 3.9: Stator and rotor resistance estimation using classical mutual MRAS estimator

### 3.8 Conclusion

This chapter presents a fuzzy speed sensorless vector control technique for induction motors, considering stator and rotor resistance as well as rotor speed. Simulation testing in the low-speed region confirms the efficacy of the parallel fuzzy Mutual-MRAS structure, demonstrating good convergence and closed-loop stability over a wide speed range during rated load operation.

This method provides an effective solution for precise motor control without the need for speed sensors.

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# General Conclusion

In this study, we were interested in fuzzy sensorless speed vector control of induction motor (IM) equipped with fuzzy Mutual- MRAS estimator. The question has been examined spatially for some key parameters variation of IM such as stator rotor resistance.

Generally, modern drive systems requiring high dynamic and static performance are controlled by so-called vector controls, especially those achieved by field-oriented. However, the major drawback of the latter lies in the strong dependence on the IM electric model.

To overcome this problem, fuzzy logic control seems good choice in terms of fast dynamic response, good rejection of disturbances and robustness against modeling errors and deviation parameters.

The MRAS-based speed estimation schemes have found widespread application in vector control induction motor (VC IM) drives for reasons of simplicity and comparatively low computational effort.

In this way, firstly, we have modeled IM using Park's model, then we have presented field-oriented control which allowing to obtain decoupled model of IM. The performance of classical vector control was illustrated by the simulation results.

In the second chapter, we have exhibit the design of fuzzy logic controller for speed IM regulation. The proposed control strategy was justified by the numeral results.

In order to reduce the cost of the control and increase the robustness, fuzzy Mutual- MRAS estimator has been developed allowing both the estimation of stator and rotor resistances, and rotor speed of IM controlled by field oriented. The main features of suggested estimator was illustrated by simulation results.

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

- Use another control method of IM such as DTFC
- Development of vector control of induction motor associated with synergetic observer
- Practical realization of the proposed control strategy

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