



PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
MOHAMED BOUDIAF UNIVERSITY – M'SILA



FACULTY :TECHNOLOGY
DEPARTMENT: ELECTRONICS

DOMAIN: TECHNOLOGY
FIELD OF STUDY: AUTOMATIC
OPTION: AUTOMATIC AND SYSTEMES

THESIS SUBMITTED FOR THE ATTAINMENT
OF THE ACADEMIC MASTER'S DEGREE

BY:

Mokhtari Mohamed

TITLE

**speed control of doubly-fed induction machine
using a fuzzy PD+I controller**

Defended before the jury composed of:

Dr.OUAGUENI fayssal	Universityof M'sila	President
Dr. HERIZI Abdelghafour	University of M'sila	supervisor
Dr.LAIB abderrzak	University of M'sila	Co- supervisor
Dr.BENYOUNES abdelhafid	Universityof M'sila	Examiner

Academic year: 2024 / 2025

Acknowledgements

At the conclusion of this work, we would like to express our deepest gratitude to Almighty God, whose guidance, strength, and perseverance enabled us to complete this project successfully.

Our heartfelt thanks go to Dr. Herizi Abdelghafour for his patience, dedication, and invaluable guidance throughout the preparation of our graduation project. His insightful advice and continuous support greatly enriched our understanding and shaped the outcome of this work.

We also extend our sincere appreciation to the teaching staff of the Electrical Engineering Department at M'sila University for their efforts, encouragement, and commitment to providing us with a solid academic foundation.

Our gratitude is equally directed to all those who contributed, in any way, to the completion of this thesis.

Finally, we would like to express our warmest thanks to our families and friends for their unwavering support, motivation, and understanding throughout this journey

Dedications

To my beloved parents,

*whose love, sacrifices, and unwavering support have been my greatest source of
strength and inspiration.*

To my family,

*for their constant encouragement, patience, and belief in me throughout this
journey.*

To my friends,

*for the moments of laughter, motivation, and companionship that made this path
more enjoyable.*

To everyone who believed in me,

thank you for being part of my success.

This work is dedicated to you all with love and gratitu

Summary

Table of Contents	I
List of Figures	II

General Introduction

I.1 General Introduction	1
--------------------------------	---

Chapter I Modeling of the DFIM

I.1 Introduction:	4
I.2 Overview of the Doubly-Fed Induction Machine.....	4
I.3 Mathematical Model of the (DFIM)	5
I.3.1 Electrical Equations	5
I.3.2 Magnetic Equations	6
I.3.3 Mechanical Equation	7
I. 4 Park Transformation	7
I.4.1 Electrical Equations	9
I.4.2 Magnetic Equations	9
I.4.3 Electromagnetic Equation.....	9
I.4.4 reference (d, q).....	10
I.5 State Equation Formulation:	11
I.6 Simulation results	12
I.7 System Power Supply Modeling:	14
I.7.1 The Structure of the Selected Power Supply Chain:	14
I.7.2 Rectifier Modeling:.....	15
I.7. 3 Filter Modeling	15
I. 8 Modeling of the Voltage Inverter:	16
I.8.1 Principle of the Two-Level Voltage Inverter:	16
I.8.2 Modeling of Pulse Width Modulation (PWM) Control:.....	19
I.8.3 Simulation of the DFIM Coupled with a PWM.....	21
I.8.4 Interpretation of the Results:	21
I.9 Conclusion	22

Chapter II The vector control

II.1 Introduction	24
II.2 Principle of Vector Contro	24
II.3 Variants of Vector Control	25
II.4 Flux Orientation Process	25
II.5 Types of Vector Control.....	25

II.5.1 Direct Contro	25
II.5.2 Indirect Control	26
II.6 Application of Vector Control to the Doubly-Fed Induction Mach	26
II.6.1 Choice of Reference Frame	27
II.6.2 Direct Vector Control Structure of the DFIM	28
II.6.3 Defluxing Block	29
II.6.4 Principle of Decoupling by Compensation	30
II.7 Sizing of the Controllers.....	30
II.7.1 Controller for the Current I_{rd}	31
II.7.2 Controller for the Current I_{rq}	32
II.7.3 Stator Flux Controller.....	33
II.7.4 Speed Controll	33
II.8 Simulation Results.....	34
II.8.1 Machine Operation During Load Variation	34
II.8.2 Machine Operation during Speed Variation.....	35
II.8.3 Operation of the machine during rotor resistance variation	36
II.8.4 Operation of the machine during stator resistance variation	37
II.8.5 Interpretation of the results.....	38
II.9 Conclusion.....	38

Chapter III

Fuzzy_ PD+I

III.1 Introduction.....	41
III.2 Fuzzy Logic Controller	41
III.2.1 Fuzzification in Fuzzy Logic	42
III.2.2. Rule Base in Fuzzy Logic	42
III.2.3 Inference Engine in Fuzzy Logic	43
III.2.4 Defuzzification in Fuzzy Logic.....	44
III.3 Principle of the PD+I Controller	45
III.4 Design of the Fuzzy PD+I Controller	45
III.4.1 Motivation for Combining Fuzzy PD and I	47
III.5 Application of the Fuzzy PD+I Controller to the (DFIM)	47
III. 6 Fuzzy PD+I Contro	47
III.6.1 Fuzzy logic control.....	48
III.6.2 Structure of the Fuzzy PD+I Control	49
III.6.3 Structure of the Fuzzy PD+I Control for DFIM	50
III.7 Simulation Results	51

III.7.1 Machine Operation during Load Variation..... 51

III.7.2 Machine Operation during Speed Variation 52

III.7.3 Machine Operation during Rotor Resistance Variation 53

III.7.4 Machine Operation during Stator Resistance Variation 54

III.7.5 Interpretation of the results 55

III.8 Conclusion 56

General Conclusion..... 58

LIST OF FIGURES

Chapter I

Modeling of the DFIM

Figure (I -1): Doublyfed three-phase induction machine with rotary transformer.....	4
Figure (I.2): Schematic Representation of the (DFIM) in the Three-Phase System.	5
Figure (I.3) : Conversion from a Three-Phase System to a Two-Phase System and Vice Versa.....	8
Figure (I.4): Definition of the Actual Axes of the MADA in Relation to..... the Different Reference Frames.....	10
Figure(I -5): Block diagram of the DFIM simulation supplied..... with voltage from the grid.	12
Figure (I.6): Simulation Results of the DFIM.....	13
Figure (I.7): Proposed Block Diagram for Supplying Power to the Machine.....	14
Figure (I.8): Representation of the Three-Phase Diode Rectifier	15
Figure (I.9): Low-Pass RLC Filter	16
Figure (I.10): Three-Phase Two-Level Voltage Inverte.....	17
Figure (I.11): Representation of a GTO (Gate Turn-Off Thyristor)	17
Figure (I.12): Simulink model of the three-phase inverter.....	19
Figure (I.13): Principle of Sinusoidal PWM (Sinus-Triangle Modulation) (Output line-to-line voltage of the inverter (V)).....	20
Figure (I.14): Simulation Results for DFIM with PWM.....	21

Chapter II

The vector control

Figure (II.1): Analogy between the vector control of an induction motor (DFIM) and the control of a DC motor (MCC).....	24
Figure (II.2): Principle of Stator Flux Orientation	27
Figure (II.3): Vector Control Structure of the DFIM.....	29
Figure (II.4): Reference stator flux profile (defluxing).....	29
Figure (II.5): Reconstruction of voltages V_{rq} and V_{rd}	30
Figure (II.6): Current control diagram of I_{rd}	31
Figure (II.7): Current control diagram of I_{rq}	32
Figure (II.8): Closed-loop stator flux control.....	33
Figure (II.9): Functional diagram of speed control.....	34
Figure (II.10): Simulation Results During Load Variation	35
Figure (II.11): Simulation results during speed variation	36
Figure (II.12): Simulation results during the variation of the Rotor resistance	37
Figure (II.13): Simulation results during the variation of the stator resistance.....	37

Chapter III

Fuzzy_ PD+I

Figure(III.1): Fuzzy PD+I controller (FPD+I).....	46
Figure (III.2): Membership functions of the fuzzy inputs and output, and the resulting control surface for the Fuzzy PD+I controller	49
Figure (III.3): Functional block diagram of the proposed Fuzzy PD+I controller	50
Figure (III.4): Structure of FUZZY PD+I Control for DFIM.....	51
Figure (III.5): Simulation Results During Load Variation	52
Figure (III.6): Simulation results during speed variation.....	53
Figure (III.7): Simulation results during the variation of the rotor resistance.	54
Figure (III.8): Simulation results during the variation of the stator resistance	55

General
Introduction

Doubly-fed induction machines (DFIM) have gained significant attention in modern electrical drive systems, particularly for variable-speed applications such as wind energy conversion, industrial drives, and energy recovery systems [1]. The DFIM is characterized by its dual power supply: the stator is directly connected to the grid, while the rotor is fed through a back-to-back converter. This configuration allows for variable-speed operation within a wide range while requiring power electronic converters rated at only 25–30% of the total machine power. Consequently, DFIMs offer a cost-effective and energy-efficient solution compared to fully-rated converter systems or synchronous generators [3].

Despite these advantages, the DFIM presents complex dynamic behavior due to the coupling between stator and rotor circuits, nonlinearity, and parameter variations [5]. Such characteristics make precise control of speed and torque particularly challenging, especially under varying load and grid conditions. Conventional PI controllers, although widely used for their simplicity and effectiveness under nominal conditions, often fail to maintain satisfactory performance when the system is subjected to disturbances, parameter uncertainties, or rapid load fluctuations. This limitation leads to degraded system performance, slower dynamic response, and increased steady-state error [7].

To overcome these limitations, several advanced control strategies have been proposed in recent years. Among them, the use of fuzzy logic control (FLC) has demonstrated strong potential due to its ability to handle nonlinearities, parameter uncertainties, and external disturbances without requiring an exact mathematical model of the system [7]. FLCs provide adaptive behavior by adjusting control actions based on real-time system conditions, leading to improved robustness and smoother responses compared to traditional controllers. However, classical fuzzy logic structures such as fuzzy PI or fuzzy PID may still face challenges in achieving optimal transient and steady-state performance simultaneously [8].

In this regard, the fuzzy PD+I control strategy represents a promising alternative. This hybrid controller combines the fast dynamic response of a PD controller with the zero steady-state error characteristics of an integral (I) component [9]. The fuzzy inference system enhances adaptability by continuously tuning the proportional and derivative gains based on system errors and their rate of change. As a result, the fuzzy PD+I controller can achieve better transient performance, reduced overshoot, and improved steady-state accuracy under varying operational conditions [10].

The application of a fuzzy PD+I controller to the DFIM aims to address the challenges posed by its nonlinear and coupled dynamics [7]. By combining fuzzy reasoning with the PD+I structure, the proposed controller ensures robust speed regulation, superior disturbance rejection, and minimal sensitivity to parameter uncertainties. Furthermore, such an approach enhances energy efficiency and reliability, making it suitable for renewable energy systems such as wind turbines, where operating conditions fluctuate continuously [9].

This study focuses on the modeling, design, and implementation of a fuzzy PD+I control strategy for the speed control of a doubly-fed induction machine. The main objectives are to evaluate its dynamic performance, robustness, and steady-state accuracy compared to conventional PI control. The thesis is organized as follows [9]

Chapter 1 presents the mathematical modeling of the DFIM in the Park reference frame ($d-q$) and reviews its steady-state and dynamic behavior, accompanied by block-diagram representations

Chapter 2 introduces the principle of vector control applied to the DFIM, highlighting the decoupling of flux and torque components and the challenges associated with conventional PI regulators .

Chapter 3 develops the proposed fuzzy PD+I control scheme, detailing the design of the fuzzy inference system, rule base, and integration of the PD+I structure. The controller's performance is validated through MATLAB/Simulink simulations under various operating conditions, including parameter variations and load disturbances.

Finally, the general conclusion summarizes the findings and suggests future research directions aimed at enhancing the intelligent control of DFIM, particularly through the combination of fuzzy logic and advanced adaptive control techniques [14]

Chapter I

Modeling of the DFIM

I.1 Introduction:

This chapter emphasizes the crucial role of accurate mathematical modeling in achieving efficient control of dynamic systems, particularly the Doubly-Fed Induction Machine (DFIM). Developing such a model requires a comprehensive understanding of the machine's electromechanical, electrical, and mechanical structures. The DFIM model enables the analysis of electromechanical behavior and the prediction of suitable control actions under various operating conditions, such as startup and speed variation.

The chapter presents the classical modeling of the DFIM in the three-phase reference frame (A, B, C) and simplifies it using the Park transformation to eliminate the dependence of inductance coefficients on rotor position. It also covers the modeling of the power supply system, including the voltage inverter responsible for DC-AC conversion through Pulse Width Modulation (PWM) and the grid-side converter (PWM rectifier). Finally, Matlab/Simulink simulations are performed to evaluate and validate the performance of the overall DFIM–converter system, laying the groundwork for the development of advanced control strategies in subsequent chapters

I.2 Overview of the Doubly-Fed Induction Machine

The Doubly-Fed Induction Machine (DFIM) is an electromechanical energy conversion system that has been recognized since the late nineteenth century, with its origins traced back to 1899 [1] . It is characterized by its dual electrical excitation, in which both the stator and rotor receive independent power supplies . The stator structure resembles that of conventional three-phase induction machines, whereas the rotor is uniquely designed with a wound configuration comprising three-phase windings connected in a star (Y) arrangement. The winding terminals are linked to slip rings, which maintain electrical contact through brushes during rotor motion [2] .

This configuration allows external access to the rotor circuit, providing independent control over its electrical parameters. Consequently, the DFIM exhibits high operational flexibility and efficiency under variable-speed and fluctuating load conditions, making it particularly suitable for advanced variable-speed drive and renewable energy applications such as wind power generation [2].

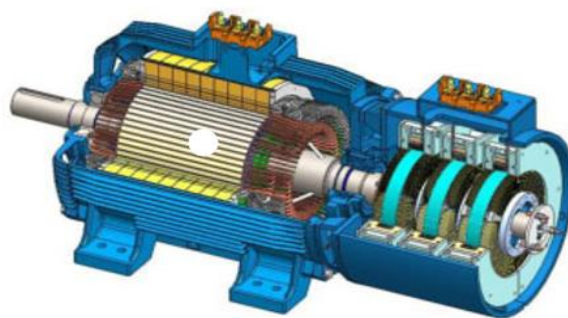


Figure (I -1):Doublyfed three-phase induction machine with rotary transformer

I.3 Mathematical Model of the (DFIM)

The fundamental structure of the asynchronous machine comprises six windings distributed in the electrical space. The stator axes are spaced by an angle of $2\pi/3$ radians from each other, and the rotor axes follow the same angular displacement. The angle θ represents the angular position between the reference axis of the rotor phase R_a and the fixed reference axis of the stator phase S_a [2], [3]

It is important to note that the rotor axes rotate at an angular velocity ω_r relative to the stationary stator axes, as illustrated in Figure (I.2):

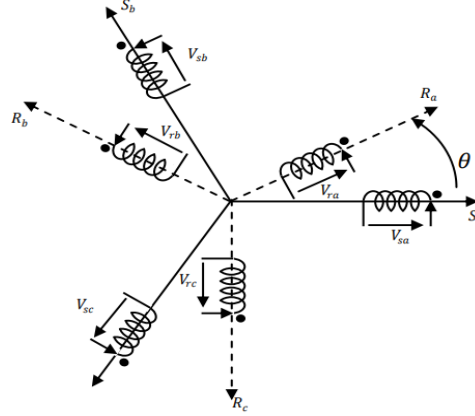


Figure (I.2): Schematic Representation of the (DFIM) in the Three-Phase System.

I.3.1 Electrical Equations

Based on Figure (2), the electrical equations corresponding to the model of the Doubly-Fed Induction Machine (DFIM) are formulated separately for the stator, indicated by the subscript (s), and the rotor, indicated by the subscript (r), as follow [2] [3] :

For the stator windings:

$$\begin{cases} V_{sa} = R_s I_{sa} + \frac{d\varphi_{sa}}{dt} \\ V_{sb} = R_s I_{sb} + \frac{d\varphi_{sb}}{dt} \\ V_{sc} = R_s I_{sc} + \frac{d\varphi_{sc}}{dt} \end{cases} \quad (I.1)$$

For rotor winding:

$$\begin{cases} V_{ra} = R_r I_{ra} + \frac{d\varphi_{ra}}{dt} \\ V_{rb} = R_r I_{rb} + \frac{d\varphi_{rb}}{dt} \\ V_{rc} = R_r I_{rc} + \frac{d\varphi_{rc}}{dt} \end{cases} \quad (I.2)$$

Or in matrix forms

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \end{bmatrix} \quad (I.3)$$

$$\begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \cdot \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix} \quad (I.4)$$

With:

V, I , and φ are the voltage, current, and flux, respectively.

R_s And R_r are the stator and rotor resistances, respectively [3], [11], [13].

I.3.2 Magnetic Equations

The hypotheses we previously presented lead to linear relationships between flux and currents [3], .

$$\begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \end{bmatrix} = \begin{bmatrix} l_s & M_s & M_s & M_1 & M_3 & M_2 \\ M_s & l_s & M_s & M_2 & M_1 & M_3 \\ M_s & M_s & l_s & M_3 & M_2 & M_1 \end{bmatrix} \cdot \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \\ I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} \quad (I.5)$$

$$\begin{bmatrix} \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix} = \begin{bmatrix} M_1 & M_2 & M_3 & l_r & M_r & M_r \\ M_3 & M_1 & M_2 & M_r & l_r & M_r \\ M_2 & M_3 & M_1 & M_r & M_r & l_r \end{bmatrix} \cdot \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \\ I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} \quad (I.6)$$

With:

l_s, l_r :Self-inductances of a stator phase and a rotor phase.

M_s, M_r : Mutual inductances between two stator phases and two rotor phases.

M_1, M_2, M_3 : Instantaneous mutual inductances between a stator phase and a rotor phase.

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = M_0 \begin{bmatrix} \cos(\theta) \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \quad (I.7)$$

M_0 : Maximum mutual inductance between a stator phase and a rotor phase.

The actual flux matrix reveals two sub-matrices of inductances:

$$[\varphi_{sabc}] = [L_s][I_{sabc}] + [M_{sr}][I_{rabc}] \quad (I.8)$$

$$[\varphi_{rabc}] = [M_{rs}][I_{sabc}] + [L_r][I_{rabc}] \quad (I.9)$$

With

$$[L_s] = \begin{bmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{bmatrix} \quad (I.10)$$

$$[L_r] = \begin{bmatrix} L_r & M_r & M_r \\ M_r & L_r & M_r \\ M_r & M_r & L_r \end{bmatrix} \quad (I.11)$$

$$[M_{sr}] = [M_{rs}]^T = M_0 \cdot \begin{bmatrix} \cos(\theta) & \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \cos(\theta) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos(\theta) \end{bmatrix} \quad (I.12)$$

I.3.3 Mechanical Equation

The mechanical equation of the machine is given as follows[3] :

$$T_{em} = T_r + f\Omega + j \frac{d\Omega}{dt} \quad (I.13)$$

With:

- T_{em} : Electromagnetic torque of the machine ;
- T_r : Resistive torque ;
- f : Viscous friction coefficient of the Doubly-Fed Induction Machine (DFIM);
- Ω : Rotational speed of the DFIM shaft;
- j : Inertia of the rotating parts.

The general expression of the electromagnetic torque is given by:

$$T_{em} = \frac{1}{2} P [I]^T \frac{d[L]}{dt} \cdot [I] \quad (I.14)$$

With:

$$[I] = [I_{sa} \ I_{sb} \ I_{sc} \ I_{ra} \ I_{rb} \ I_{rc}]^T = \begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix} \quad (I.15)$$

$[L]$: Total Inductance Matrix

$$[L] = \begin{bmatrix} [L_s] & [M_{sr}] \\ [M_{rs}] & [L_r] \end{bmatrix} \quad (I.16)$$

P : The number of pole pairs;

The matrices $[L_s]$ and $[L_r]$ contain only constant terms when the angle θ varies, which simplifies the expression of the torque[4], [10],.

$$T_{em} = p \cdot [I_s]^T \frac{d}{dt} [[M_{sr}] \cdot [I_r]] \quad (I.17)$$

I. 4 Park Transformation

The mathematical model of the Doubly-Fed Induction Machine (DFIM) expressed in the three-phase (a ,b, c) reference frame is inherently complex, as it results in a system of differential equations with time-varying coefficients. Such complexity arises from the dependence of the stator and rotor flux linkages on the instantaneous rotor position. To facilitate control and analysis, matrix transformations are applied to simplify the model by reducing the number of variables and eliminating the explicit dependence on rotor angular position. This approach yields a dynamic model characterized by equations with constant coefficients, which are more suitable for control design and simulation [2], [4] .

Among these transformations, the Park transformation (also known as the d q-transformation) is particularly significant. It converts the three-phase time-varying quantities of the stator or rotor—represented in the (a, b, c) stationary reference frame—into equivalent two-phase quantities in the rotating (d, q) reference frame. This transformation simplifies the mathematical representation of the machine, enabling easier implementation of vector control techniques and enhancing the understanding of its dynamic behavior under transient and steady-state conditions [4], [5].

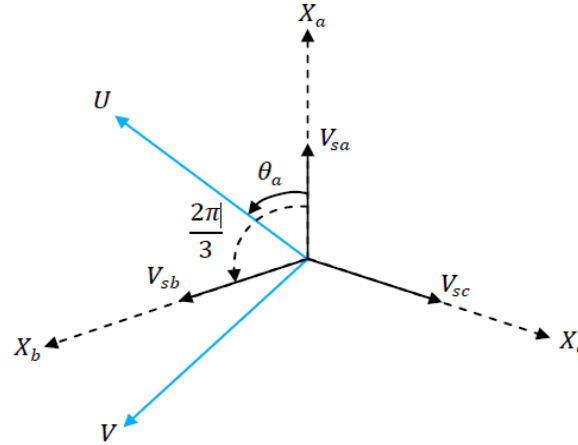


Figure (I.3) : Conversion from a Three-Phase System to a Two-Phase System and Vice Versa.

θ_a : Represents the instantaneous angle between the phase of the X_a axis and the U axis.

$\omega_a = \frac{d\theta_a}{dt}$ Angular velocity of the rotating two-phase reference frame relative to the three-phase reference frame.

According to Figure (I.2), the projection of the vector V_{sa} , V_{sb} , V_{sc} onto the two-phase axis gives us

$$\begin{cases} V_{su} = \sqrt{\frac{2}{3}} [V_{sa} \cdot \cos\theta_a + V_{sb} \cdot \cos(\theta_a - \frac{2\pi}{3}) + V_{sc} \cdot \cos(\theta_a - \frac{4\pi}{3})] \\ V_{sv} = -\sqrt{\frac{2}{3}} [V_{sa} \cdot \sin\theta_a + V_{sb} \cdot \sin(\theta_a - \frac{2\pi}{3}) + V_{sc} \cdot \sin(\theta_a - \frac{4\pi}{3})] \end{cases} \quad (I.18)$$

The term $\sqrt{\frac{2}{3}}$ expresses the conversion from the three-phase system to the two-phase system while preserving power.

The homopolar component V_{so} is added to equation (I.18) to balance the transformation.

$$V_{so} = \frac{1}{3} (V_{sa} + V_{sb} + V_{sc}) \quad (I.19)$$

The homopolar component V_{so} is zero for balanced three-phase systems.

From equations (I.18) and (I.19), we obtain:

$$\begin{bmatrix} V_{su} \\ V_{sv} \\ V_{so} \end{bmatrix} = [P(\theta_a)] \cdot \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (I.20)$$

The conversion from the three-phase system to the two-phase system is achieved using the transformation matrix $[P(\theta_a)]$:

$$[P(\theta_a)] = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_a) & -(\sin \theta_a) & \frac{1}{\sqrt{2}} \\ \cos(\theta_a - \frac{2\pi}{3}) & -(\sin \theta_a - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta_a - \frac{4\pi}{3}) & -(\sin \theta_a - \frac{4\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (I.21)$$

$$\begin{bmatrix} V_{su} \\ V_{sv} \\ V_{so} \end{bmatrix} = [P(\theta_a)]^{-1} \cdot \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (I.22)$$

$$[P(\theta_a)]^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta_a) & -(\sin \theta_a) & \frac{1}{\sqrt{2}} \\ \cos(\theta_a - \frac{2\pi}{3}) & -(\sin \theta_a - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta_a - \frac{4\pi}{3}) & -(\sin \theta_a - \frac{4\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (I.23)$$

I.4.1 Electrical Equations

The Park transformation involves applying a variable change to currents, voltages, and fluxes by incorporating the angle between the winding axis and the (u, v) axis.

Equations (I.3) and (I.4) then lead to the following system after the calculations detailed in Appendix [5], $[A]$:

$$\begin{bmatrix} V_{su} \\ V_{sv} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} I_{su} \\ I_{sv} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{su} \\ \varphi_{sv} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_a \\ \omega_a & 0 \end{bmatrix} \cdot \begin{bmatrix} \varphi_{su} \\ \varphi_{sv} \end{bmatrix} \quad (I.24)$$

$$\begin{bmatrix} V_{ru} \\ V_{rv} \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix} \cdot \begin{bmatrix} I_{ru} \\ I_{rv} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ru} \\ \varphi_{rv} \end{bmatrix} + \begin{bmatrix} 0 & -(\omega_a - \omega) \\ (\omega_a - \omega) & 0 \end{bmatrix} \cdot \begin{bmatrix} \varphi_{ru} \\ \varphi_{rv} \end{bmatrix} \quad (I.25)$$

I.4.2 Magnetic Equations

Similarly, from equations (II.5) and (II.6), the calculations detailed in [HER], we obtain:

$$\begin{bmatrix} \varphi_{su} \\ \varphi_{ru} \end{bmatrix} = \begin{bmatrix} L_s & M \\ M & L_r \end{bmatrix} \cdot \begin{bmatrix} I_{su} \\ I_{ru} \end{bmatrix} \quad (I.26)$$

$$\begin{bmatrix} \varphi_{sv} \\ \varphi_{rv} \end{bmatrix} = \begin{bmatrix} L_s & M \\ M & L_r \end{bmatrix} \cdot \begin{bmatrix} I_{sv} \\ I_{rv} \end{bmatrix} \quad (I.27)$$

$L_s = I_s - M$: Cyclic self-inductance of the stator.

$L_r = I_r - M$: Cyclic self-inductance of the rotor.

$M = \frac{3}{2} M_0$: Cyclic mutual inductance between the stator and rotor [3].

I.4.3 Electromagnetic Equation

The equation of the electromagnetic torque using the Park transformation is expressed by four formulas depending on the choice of state variables (stator/rotor flux and stator/rotor current) .

$$T_{em} = P [\varphi_{su} I_{sv} - \varphi_{sv} I_{su}] \quad (I.28)$$

$$T_{em} = P [\varphi_{ru} I_{rv} - \varphi_{rv} I_{ru}] \quad (I.29)$$

$$T_{em} = \frac{PM}{L_s} = [\varphi_{su} I_{rv} - \varphi_{sv} I_{ru}] \quad (I.30)$$

$$T_{em} = \frac{PM}{L_r} [\varphi_{ru} I_{sv} - \varphi_{rv} I_{su}] \quad (I.31)$$

P: Number of pole pairs [3], [5]

I.4.4 reference (d, q)

There are different possibilities for choosing the orientation of the $(u,)$ axis system, which generally depend on the application objectives. The choice is practically reduced to three orthogonal reference frames, as shown in Figure (I.4) : [5], [6].

- Reference frame with axes α : A two-phase system with orthogonal axes where $\theta_a = 0$.
- Reference frame with axes d : A two-phase system with orthogonal axes where $\theta_a = \theta_s$
- Reference frame with axes x : A two-phase system with orthogonal axes where $\theta_a = \theta_r$.

The angle θ_a represents an arbitrary observation position that can be chosen in three different ways.

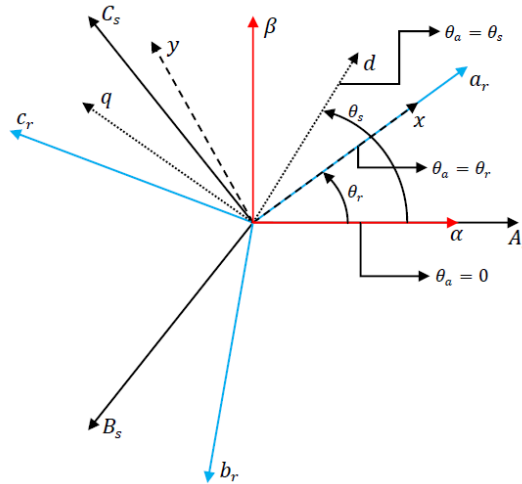


Figure (I.4): Definition of the Actual Axes of the MADA in Relation to the Different Reference Frames

$\omega_s = \frac{d\theta_s}{dt}$: Electrical rotational speed of the reference frame linked to the rotating field.

$\omega_r = \frac{d\theta_r}{dt}$: Electrical slip speed.

$\omega = \frac{d\theta}{dt}$: Electrical rotational speed of the rotor relative to the stator.

It is defined by the following conditions:

$$\theta_a = 0 \Leftrightarrow \begin{cases} u = d \\ v = q \end{cases}$$

$$\frac{d\theta_a}{dt} = \omega_a = \omega_s, \quad \text{with : } \omega_s - \omega = \omega_r$$

The electrical equations take the following form:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \cdot \begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} \quad (I.32)$$

$$\begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix} \cdot \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{rd} \\ \varphi_{rq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \cdot \begin{bmatrix} \varphi_{rd} \\ \varphi_{rq} \end{bmatrix} \quad (I.33)$$

The flux expressions, based on equations (I.26) and (I.27), are given by:

$$\begin{cases} \varphi_{sd} = L_s I_{sd} + M I_{rd} & (a) \\ \varphi_{sq} = L_s I_{sq} + M I_{rq} & (b) \\ \varphi_{rd} = L_r I_{rd} + M I_{sd} & (c) \\ \varphi_{rq} = L_r I_{rq} + M I_{sq} & (d) \end{cases} \quad (I.34)$$

This reference frame is often used in the study of variable-frequency asynchronous motor control. It is particularly utilized in the control of electrical machines in closed-loop systems, where the controlled quantities must necessarily be in a continuous form[6] .

I.5 State Equation Formulation:

The model of the doubly-fed asynchronous machine (DFIM) supplied by voltage includes stator voltages (V_{sd}) and rotor voltages (V_{sd}, V_{sq}), with the resistant torque C_r as a disturbance. The system can be described using multiple state variables. However, our study will be limited to a specific case represented by the stator flux components and the rotor current components ($\varphi_{sd} \varphi_{sq} I_{rd} I_{rq}$)

After rearranging equations (I.36), (I.37), and (I.38), we obtain [7] :

$$\begin{cases} V_{sd} = R_s I_{sd} + L_s \frac{dI_{sd}}{dt} + M \frac{dI_{rd}}{dt} - \omega_s L_s L_{sq} - \omega_s M I_{rq} \\ V_{sq} = R_s I_{sq} + L_s \frac{dI_{sq}}{dt} + M \frac{dI_{rq}}{dt} - \omega_s L_s L_{sd} + \omega_s M I_{rd} \\ V_{rd} = R_r I_{rd} + L_r \frac{dI_{rd}}{dt} + M \frac{dI_{sd}}{dt} - \omega L_r L_{rq} - \omega M I_{sq} \\ V_{rq} = R_r I_{rq} + L_r \frac{dI_{rq}}{dt} + M \frac{dI_{sq}}{dt} - \omega L_r L_{rd} - \omega M I_{sd} \end{cases} \quad (I.35)$$

Moreover, the equations representing the mechanical motion are given by:

$$T_{em} = P \frac{M}{L_s} (\varphi_{sq} I_{rd} - \varphi_{sd} I_{rq}) \quad (I.36)$$

$$T_{em} - T_r = j \frac{d\Omega}{dt} + F\omega \quad (I.37)$$

This system can be written in state-space form:

$$\dot{X} = [A] \cdot X + [B] \cdot U \quad (I.38)$$

With:

$$X = [\varphi_{sd} \varphi_{sq} I_{rd} I_{rq}]^T : \text{State vector}$$

$$U = [V_{sd} V_{sq} V_{rd} V_{rq}]^T : \text{Control vector}$$

A: State evolution matrix of the system

B: Control matrix of the system.

Such that:

$$[A] = \begin{bmatrix} \frac{-1}{T_s} & \omega_s & \frac{M}{T_s} & 0 \\ -\omega_s & \frac{-1}{T_s} & 0 & \frac{M}{T_s} \\ \alpha & -\beta\omega_s & -\delta & (\omega_s - \omega) \\ \beta\omega & \alpha & -(\omega_s - \omega) & -\delta \end{bmatrix}, \quad [B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\beta & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & -\beta & 0 & \frac{1}{\sigma L_r} \end{bmatrix}$$

α, β , and δ are constants defined as follows:

$$\alpha = \frac{M}{\sigma T_s L_s L_r}, \beta = \frac{M}{\sigma L_s L_r} \text{ and } \delta = \frac{1}{\sigma} \cdot \left(\frac{1}{T_r} + \frac{M^2}{T_s L_s L_r} \right)$$

Where:

$$T_s = \frac{L_s}{L_r} \text{ And } T_r = \frac{L_r}{R_r}$$

To facilitate the simulation, the matrix $[A]$ is decomposed as follows [6] [7]:

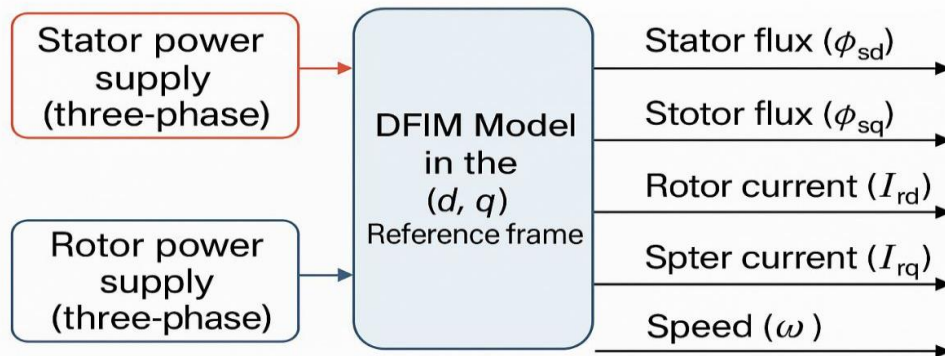
$$[A] = [A1] + \omega_s [A2] + \omega [A3] \quad (I.39)$$

"Such that:

$$[A1] = \begin{bmatrix} \frac{-1}{T_s} & 0 & \frac{M}{T_s} & 0 \\ 0 & \frac{-1}{T_s} & 0 & \frac{M}{T_s} \\ \alpha & 0 & -\delta & 0 \\ 0 & \alpha & 0 & -\delta \end{bmatrix}, [A2] = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}, [A3] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0 & 0 & 0 & 0 \\ 0 & -\beta & 0 & -1 \\ \beta & 0 & 1 & 0 \end{bmatrix},$$

I.6 Simulation results

The state-space representation of the doubly-fed induction machine model allows for its simulation. The objective of this study, presented in this section, is to develop a block diagram, as illustrated in Figure (I.5), from which the DFIM is directly supplied by the three-phase network [220/380V, 50Hz]. The parameters of the doubly-fed induction machine used in this work are provided in Appendix [A].



Figure(I -5):Block diagram of the DFIM simulation supplied with voltage from the grid.

the motor is started under no-load conditions ($Cr = 0 \text{ N}\cdot\text{m}$), and a mechanical load of $15 \text{ N}\cdot\text{m}$ is applied at $t = 2 \text{ s}$. The corresponding simulation results are presented in Figure II.6.

We perform a no-load start-up ($Cr = 0 \text{ N}\cdot\text{m}$), and at the moment ($t = 2 \text{ s}$), a load is applied ($Cr = 15 \text{ N}\cdot\text{m}$). The simulation results are presented in Figure (I.6).

In this case, we observe a decrease in speed that stabilizes at a value of 151 rad/s , indicating an increase in the machine's slip. The electromagnetic torque reaches the value that compensates for the applied resistant torque, showing good tracking of the reference value ($15 \text{ N}\cdot\text{m}$), which offsets the effect of the load and friction.

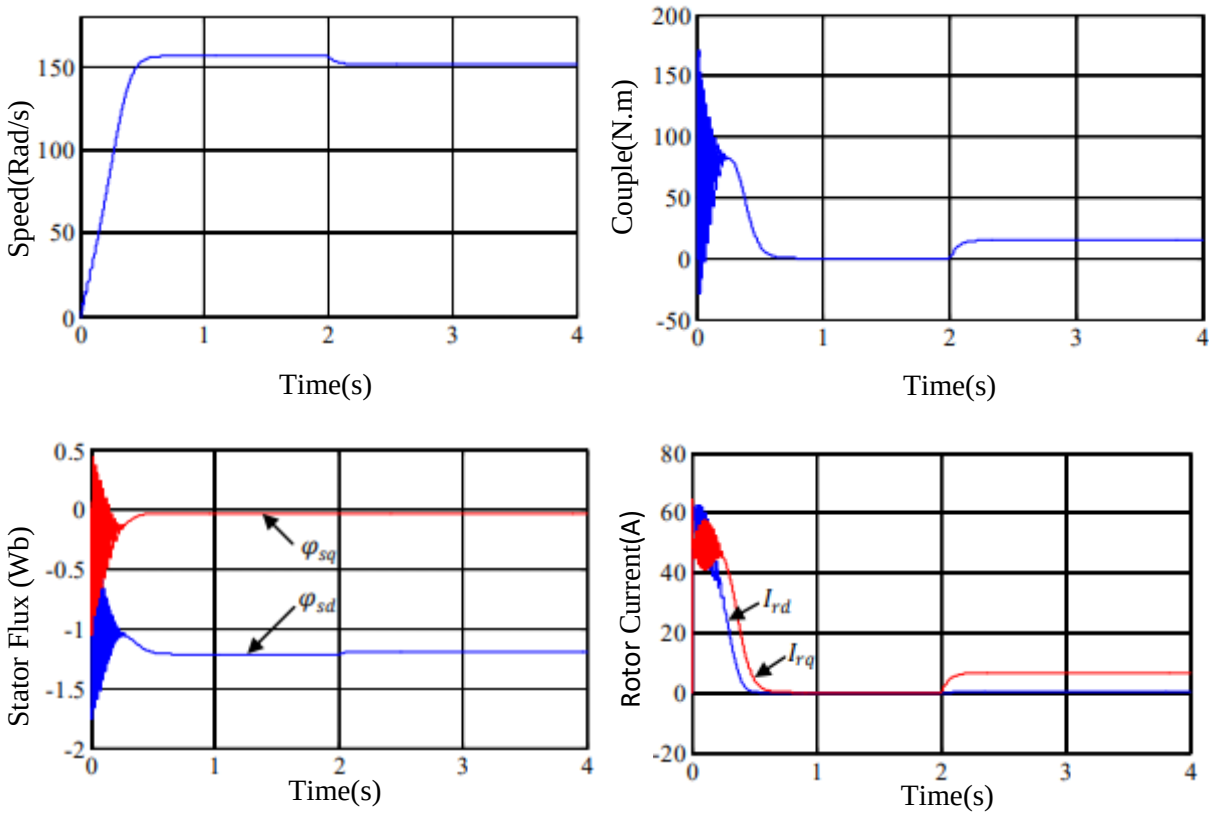


Figure (I.6): Simulation Results of the DFIM

The stator flux waveforms retain their sinusoidal profiles, exhibiting only a minor reduction in amplitude. Conversely, the rotor currents experience a noticeable increase in magnitude as the load demand rises. This behavior indicates that the electromagnetic flux is sensitive to variations in mechanical load, thereby highlighting the strong coupling relationship between the electromagnetic torque and the flux within the Doubly-Fed Induction Machine (DFIM). Such coupling underscores the importance of precise flux and current control strategies to maintain optimal machine performance under variable operating conditions.

I.7 System Power Supply Modeling:

In variable-speed drive systems, the Doubly-Fed Induction Machine (DFIM) relies on a flexible and efficient power conversion structure to ensure stable operation and effective control. The stator is directly connected to the grid, while the rotor is supplied through a back-to-back converter composed of a rectifier, a DC-link filter, and an inverter. This setup allows bidirectional energy flow between the grid and rotor, enabling both motoring and generating modes with reduced converter power rating (about 25–30% of the machine's nominal power). The configuration ensures independent control of active and reactive power while maintaining constant stator flux and frequency. Overall, this structure enhances energy efficiency, stability, and control flexibility, supporting advanced strategies like the Fuzzy PD+I controller to improve dynamic response, reduce overshoot, and increase robustness under variable operating conditions [8], .

I.7.1 The Structure of the Selected Power Supply Chain:

The power supply system of the Doubly-Fed Induction Machine (DFIM) enables efficient bidirectional energy exchange with the electrical grid while ensuring precise control of torque and speed . In this structure, the stator is directly connected to the grid, providing constant voltage and frequency, whereas the rotor is fed through a back-to-back converter composed of a Grid-Side Converter (GSC), a DC-link filter, and a Rotor-Side Converter (RSC) . The GSC maintains a stable DC-link voltage and unity power factor, while the RSC generates variable-frequency and variable-amplitude AC voltages to control the rotor currents. A DC-link filter smooths voltage fluctuations and stabilizes energy transfer between the converters. This configuration allows efficient operation across a wide speed range and supports advanced control techniques such as the Fuzzy PD+I controller, which enhances the system's dynamic response, accuracy, and robustness under varying load and parameter conditions [8], [9] .

Figure (I.7) illustrates the detailed diagram of the converters supplying power to the Doubly-Fed Induction Machine

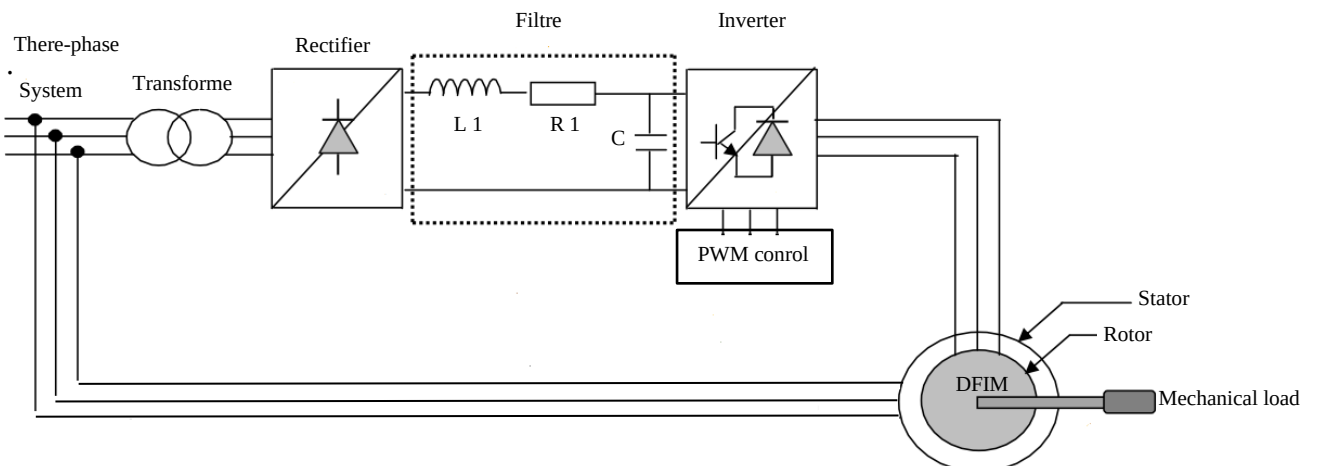


Figure (I.7): Proposed Block Diagram for Supplying Power to the Machine

I.7.2 Rectifier Modeling:

The rectifier represents the first stage of the power conversion system, responsible for converting the three-phase AC voltage from the grid into a stable DC voltage that supplies the DC-link of the back-to-back converter. Its primary role is to provide a smooth and ripple-free DC output, ensuring efficient and reliable operation of the rotor-side converter and, consequently, the Doubly-Fed Induction Machine (DFIM) [7], [8],.

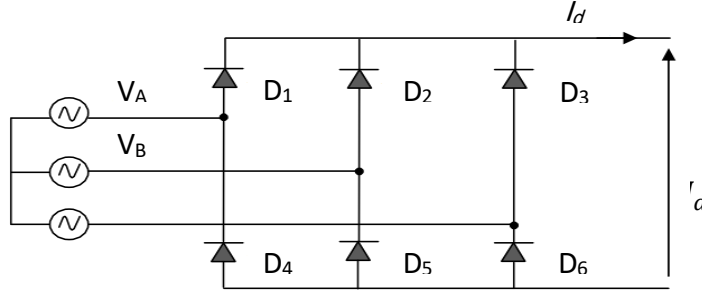


Figure (I.8): Representation of the Three-Phase Diode Rectifier

Diodes **D1**, **D2**, and **D3** share a common cathode and provide the forward conduction path for the direct current **Id**, while diodes **D4**, **D5**, and **D6** share a common anode and provide the return path for **Id**. The three-phase supply feeding the rectifier is assumed to be perfectly balanced, with constant voltage amplitude and frequency. Additionally, voltage drops due to commutation overlap and diode losses are neglected. Under these assumptions, the rectifier operates with an ideal three-phase AC supply system defined by [8], [9] :

$$\begin{cases} V_A = V_m \sin(\omega t) \\ V_B = V_m \sin(\omega t - \frac{2\pi}{3}) \\ V_C = V_m \sin(\omega t - \frac{4\pi}{3}) \end{cases} \quad (\text{I.40})$$

The voltage at the output of the rectifier is given by:

$$U_{red}(t) = \max[V_A(t), V_B(t), V_C(t)] \min[V_A(t), V_B(t), V_C(t)] \quad (\text{I.41})$$

And its average value is given by:

$$\bar{U}_{red} = \frac{3\sqrt{3}}{\pi V_m} \quad (\text{I.42})$$

Its ripple factor is given by:

$$K\% = \frac{U_{dmax} - U_{dmin}}{2\bar{U}_d}$$

I.7.3 Filter Modeling

To minimize voltage ripple at the rectifier output, a low-pass RLC filter is used. It includes a series inductor (L) to limit current variations, a parallel capacitor (C) to stabilize the DC voltage, and a small

resistor (R) for damping. This configuration smooths the rectified voltage and ensures stable inverter operation [10].

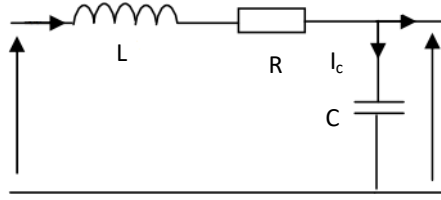


Figure (I.9): Low-Pass RLC Filter

The capacitor maintains a nearly constant voltage at the inverter input and absorbs the reverse current returned by the load, while the inductor ensures a smooth and nearly constant current flow. The filter equations are expressed as [10].:

$$U_d(t) = L \frac{dI_d}{dt} + R I_d + U_{dc}(t) \quad (I.43)$$

$$\frac{dU_{dc}}{dt} = \frac{1}{C} (I_d(t) - I(t)) \quad (I.44)$$

The transfer function of the filter is given by:

$$\frac{U_{dc}}{U_d(t)} = \frac{U_{filtree}}{U_{Rectifier}} = \frac{1}{L.C.S^2 + R.C.S + 1} \quad (I.45)$$

It is a second-order filter whose cutoff angular frequency is:

$$\omega_c = \frac{1}{\sqrt{L.C}} = 2\pi.f_c$$

f_c : is the cutoff frequency of the filter

I. 8 Modeling of the Voltage Inverter:

Inverters are essential components in power electronics, widely used for controlling the speed of AC motors. They operate as static converters that transform DC voltage into AC voltage by alternately switching the input across the load in both directions. The switching control directly influences the waveform and quality of the output voltage. Recent advancements in inverter technology are driven by the development of high-performance, fully controllable semiconductor devices and the widespread use of Pulse Width Modulation (PWM) techniques.

In this section, a two-level voltage inverter is modeled, along with the PWM control methods—specifically the sinusoidal-triangular and space vector modulation (SVM) techniques [11].

I.8.1 Principle of the Two-Level Voltage Inverter:

The three-phase two-level voltage inverter is a key component in the DFIM drive system. It consists of a DC voltage source and six power electronic switches arranged in a bridge configuration. The DC voltage is generally obtained from a three-phase diode rectifier followed by an RLC filter, which ensures a stable and ripple-free DC-link voltage [11]

This type of inverter is widely employed in Pulse Width Modulation (PWM) applications to supply balanced three-phase loads with variable amplitude and frequency. The inverter operates by switching the DC voltage across the load in both directions, thereby generating an alternating output voltage[11].

Each of the three line-to-line output voltages is a bistable waveform, alternating between $+E$ and $-E$, and phase-shifted by 120° ($2\pi/3$ radians) with respect to one another. Through appropriate switching sequences, the inverter can synthesize three-phase AC voltages whose fundamental frequency and amplitude are controlled by the modulation strategy [12]

When supplied by an ideal DC source, the inverter generates an AC output composed of two-level rectangular voltage pulses. The fundamental component of this waveform determines the effective AC voltage delivered to the machine, while the switching control system governs the output frequency. This control flexibility allows the inverter to feed the rotor of the DFIM with variable-frequency voltages, enabling precise regulation of speed and electromagnetic torque [12].

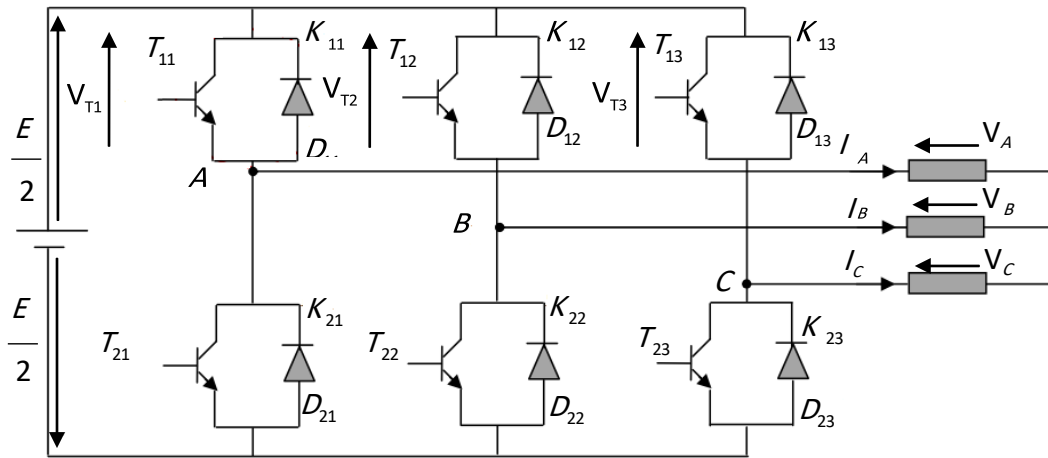


Figure (I.10): Three-Phase Two-Level Voltage Inverte

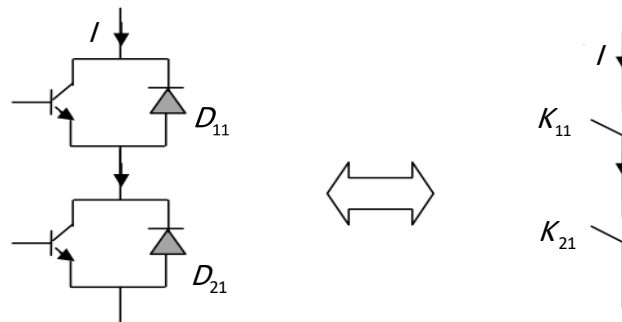


Figure (I.11): Representation of a GTO (Gate Turn-Off Thyristor)

The inverter modeling is based on the following simplifying assumptions:

- The semiconductor switches are considered ideal, meaning they have instantaneous switching and no conduction or switching losses.
- The current flowing through each inverter leg is assumed to be non-zero, either positive or negative.
- The output phase voltages of the inverter are measured with respect to a virtual neutral point (0) at the inverter output.
- To avoid short-circuiting the DC-link voltage source, the switching signals in the same inverter leg are designed to be complementary, ensuring that the upper and lower switches never conduct simultaneously.
- For simplicity, the machine load is connected in a star (Y) configuration without a neutral connection. This configuration effectively eliminates third-order harmonics and their multiples, ensuring that the output three-phase voltage system remains balanced and contains only odd harmonics that are not multiples of three[13].

To generate an alternating voltage (AC) from a direct voltage (DC), the inverter alternately applies the input DC voltage to the load in both directions through a controlled switching sequence. When supplied by an ideal DC source, the inverter produces an AC output waveform composed of rectangular voltage pulses, whose fundamental frequency is determined by the switching control strategy [13].

Assuming that the system operates under balanced conditions, the phase voltages satisfy the relation:

$V_{an} + V_{bn} + V_{cn} = 0$ we can write:

$$\begin{cases} V_{an} = V_{ao} + V_{on} \\ V_{bn} = V_{bo} + V_{on} \\ V_{cn} = V_{co} + V_{on} \end{cases} \quad (I.46)$$

By summing the equations of system (I.46), we obtain:

$$V_{an} + V_{bn} + V_{cn} = V_{ao} + V_{bo} + V_{co} + 3V_{on} = 0 \quad (I.47)$$

Where:

$$V_{ao} + V_{bo} + V_{co} = -3V_{on} \quad (I.48)$$

Therefore:

$$V_{on} = \frac{-1}{3} V_{ao} + V_{bo} + V_{co} \quad (I.49)$$

By substituting equation (I.46) into system (I.49), we then obtain:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (I.50)$$

With:

$$\begin{cases} V_{an} = \frac{E}{2} S_1 \\ V_{bn} = \frac{E}{2} S_2 \\ V_{cn} = \frac{E}{2} S_3 \end{cases} \quad (I.51)$$

Such that:

$$\begin{cases} S_1 = 1 \text{ if } K_{11} \text{ is closed, then } S_1 = +1; \text{ otherwise, } S_1 = -1, \text{ which means } K_{11} \text{ is open} \\ S_2 = 1 \text{ if } K_{12} \text{ is closed, then } S_2 = +1; \text{ otherwise, } S_2 = -1, \text{ which means } K_{12} \text{ is open} \\ S_3 = 1 \text{ if } K_{13} \text{ is closed, then } S_3 = +1; \text{ otherwise, } S_3 = -1, \text{ which means } K_{13} \text{ is open} \end{cases}$$

By substituting equation (I.51) into equation (I.50), we obtain the following system:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{E}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (I.52)$$

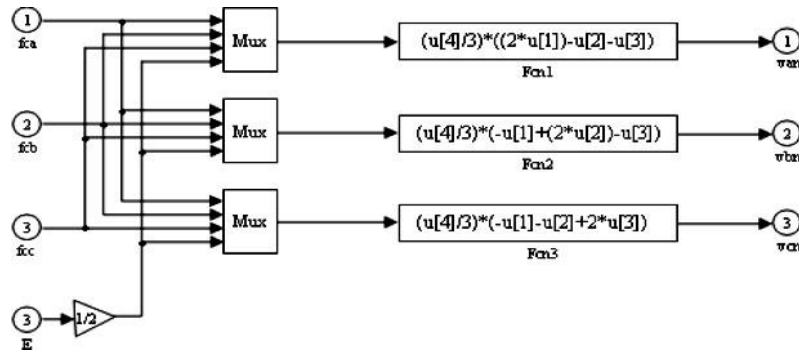


Figure (I.12): Simulink model of the three-phase inverter.

I.8.2 Modeling of Pulse Width Modulation (PWM) Control:

The triangular-sinusoidal modulation, also known as intersected pulse-width modulation (PWM), operates by comparing a low-frequency modulating signal, typically a sinusoidal reference voltage, with a high-frequency carrier signal, generally of triangular shape. The outcome of this comparison determines the switching states (ON/OFF) of the power electronic devices in the inverter, thereby controlling the output voltage and frequency applied to the [13] [14]

machine. When the reference is sinusoidal, two key parameters characterize this modulation :

- The modulation index, which defines the ratio between the carrier frequency f_b and the reference frequency f_{ref} of the reference $m = \frac{f_b}{f_{ref}}$

- The modulation ratio rrr (also known as the voltage control coefficient or duty cycle) defines the ratio between the amplitude of the modulating signal V_b and the peak value of the carrier signal V_{ref} of the carrier $r = \frac{v_b}{v_{ref}}$

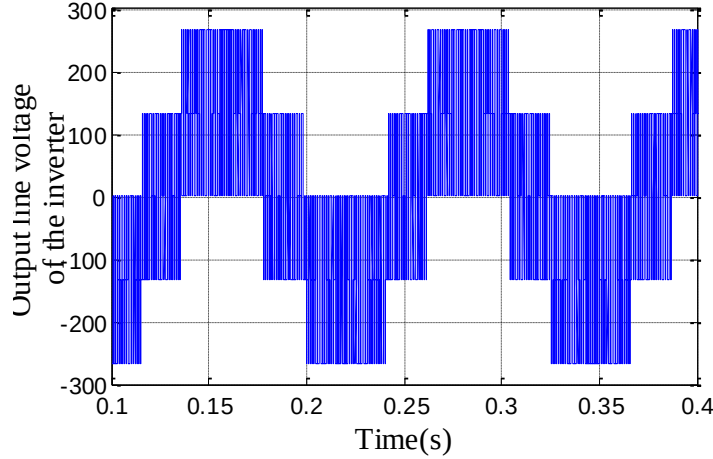


Figure (I.13): Principle of Sinusoidal PWM (Sinus-Triangle Modulation)
(Output line-to-line voltage of the inverter (V))

The carrier is a triangular signal characterized by its frequency f_b and its peak value v_b

The equation of the carrier is defined over its period $[0, t_p]$ as follows:

$$\begin{cases} x_1(t) = v_b(-1 + 4\frac{t}{T_p}) \\ x_2(t) = v_b(3 - 4\frac{t}{T_p}) \end{cases} \quad \text{If} \quad \begin{cases} t \in [0; \frac{T_p}{2}] \\ t \in [\frac{T_p}{2}; T_p] \end{cases} \quad (I.53)$$

The reference is a sinusoidal signal with amplitude V_r and frequency f_r . The three sinusoidal reference voltages are given by:

$$\begin{cases} V_{rA}(t) = V_r \sin 2\pi f_r t \\ V_{rB}(t) = V_r (\sin 2\pi f_r t - \frac{2\pi}{3}) \\ V_{rC}(t) = V_r (\sin 2\pi f_r t + \frac{2\pi}{3}) \end{cases} \quad (I.54)$$

The sinusoidal–triangular PWM control method determines the switching states S_1 , S_2 , and S_3 of the inverter switches by comparing the high-frequency triangular carrier signal with the three sinusoidal components of the reference voltage. This comparison defines the exact instants at which each switch turns ON or OFF, allowing the inverter to generate a three-phase output voltage with controllable amplitude and frequency [14]

These states are given by the following equation (I.52)

$$S_{123} = \begin{cases} 1 & \text{if } (V_{r_{ABC}} - x(t)) \geq 0 \\ -1 & \text{if } (V_{r_{ABC}} - x(t)) < 0 \end{cases}$$

It is important to note that Pulse Width Modulation (PWM) enables a substantial reduction of current harmonics by increasing the switching frequency. This technique shifts the voltage harmonics toward higher frequencies, making them easier to filter and improving the quality of the output waveform. Moreover, PWM provides precise control over the fundamental component of the output voltage, allowing effective regulation of the inverter's output amplitude and frequency [14] [15].

I.8.3 Simulation of the DFIM Coupled with a PWM

The results obtained from the simulation are summarized in the following figure, which illustrates the inverter's output waveforms and the corresponding system response under the applied PWM control. These results demonstrate the effectiveness of the sinusoidal–triangular modulation technique in generating a balanced three-phase voltage with reduced harmonic distortion and improved control precision.

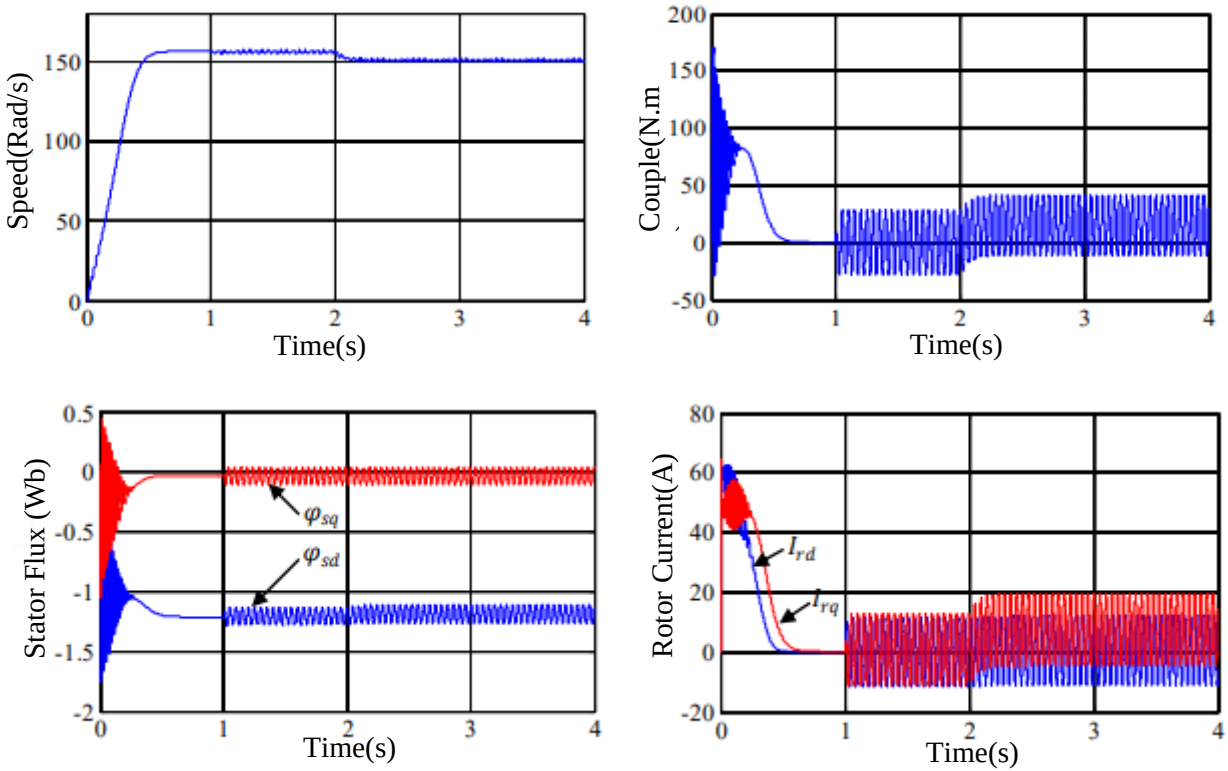


Figure (I.14): Simulation Results for DFIM with PWM

I.8.4 Interpretation of the Results:

The stator fluxes maintain a nearly sinusoidal waveform with only minor amplitude variations, reflecting good magnetic stability and smooth operation of the machine. The rotor currents exhibit a noticeable peak during the startup phase, followed by a gradual decrease and stabilization once the load is applied, which highlights the system's strong capability to manage dynamic variations. These

observations confirm the close coupling between torque and flux, as well as the effectiveness of the PWM technique in minimizing harmonics and improving the overall waveform quality. Consequently, the inverter demonstrates stable and efficient performance, ensuring precise control of torque and flux while significantly enhancing the quality of the electrical signals

I.9 Conclusion

In this chapter, several simplifying assumptions were presented, along with the application of the Park transformation, which enabled the derivation of the mathematical model of the doubly fed induction machine (DFIM) in the rotating reference frame. The modeling process focused on developing a structure suitable for implementing control strategies aimed at regulating the machine's performance.

The simulation of the DFIM and its power supply system, carried out using MATLAB/Simulink, provided open-loop results that clearly showed the natural behavior of the machine without control. It was observed that when the load torque increases, the rotor speed decreases, confirming the need for an appropriate control mechanism to maintain stable operation .

The inverter supplying the rotor was then modeled to allow for the application of advanced control techniques capable of regulating the power transferred to the stator. Additionally, the inverter's power source—a three-phase rectifier—was modeled and analyzed to ensure stable DC-link voltage regulation and to improve the grid-side power factor. [15]

Chapter II

The Vector Control

II.1 Introduction

Vector control (VC) based on flux orientation offers an efficient solution for achieving improved performance in variable-speed applications, particularly for the doubly-fed induction machine (DFIM), whether operating in generator or motor mode

One of the main challenges of the DFIM is its open-loop instability. Without precise control of the relative position between the magnetomotive forces (f_{mm} 's), the system is highly susceptible to instability and eventual loss of synchronism. To address this issue, various strategies have been proposed, many of which are based on the conventional principle of flux-oriented vector control .

To emulate the control characteristics of a separately excited DC machine, the flux must be aligned perpendicularly to the torque. This technique, known as flux-oriented control, transforms the expression of the electromagnetic torque into a form similar to that of a DC machine

II.2 Principle of Vector Control

Vector control allows an asynchronous machine to operate similarly to a separately excited DC motor, where the electromagnetic torque depends on two independent quantities: the magnetic flux and the armature current. Controlling such a machine involves managing torque, speed, or even position[14]. However, the torque equation in asynchronous machines is complex, unlike in DC machines, where the natural decoupling between flux and torque simplifies control. In DC motors, the armature's magnetomotive force is always perpendicular to the flux axis regardless of rotation speed, resulting in a torque directly proportional to the product of the flux and armature current. When the flux is held constant, torque control becomes directly dependent on the armature current, offering fast dynamic response. In contrast, asynchronous machines exhibit a variable angle between stator and rotor magnetic fields depending on the load, leading to complex interactions and oscillatory responses. Vector control solves this decoupling issue by transforming the electrical variables into a rotating reference frame aligned with the flux vector. This makes the direct-axis current I_{sd} analogous to the excitation current and the quadrature-axis current I_{sq} analogous to the armature current, allowing independent control similar to a DC motor [16]

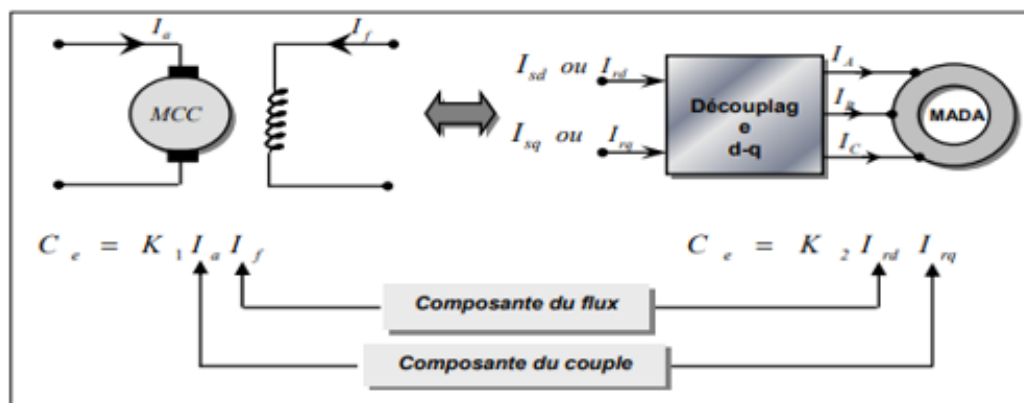


Figure (II.1): Analogy between the vector control of an induction motor (DFIM) and the control of a DC motor (MCC).

II.3 Variants of Vector Control

Field-oriented control (FOC) applied to electric motors is used to achieve the desired operating mode by optimally aligning the current vectors and the resulting flux vectors. Numerous variations of this control principle have been proposed in the literature, which can be classified into different categories [16], [17]

Field-oriented control methods can be classified according to several criteria:

- Based on the energy source:
 - Voltage-controlled drive (Voltage Source Inverter)
 - Current-controlled drive (Current Controlled Inverter)
- Based on the flux reference point:
 - Rotor flux-oriented vector control
 - Stator flux-oriented vector control
 - Air-gap (or magnetizing) flux-oriented vector control
- Based on the method of flux position determination:
 - Direct method: by measuring or observing the flux vector (magnitude and angle)
 - Indirect method: by controlling the slip frequency [17]

II.4 Flux Orientation Process

- Orientation of the stator flux with the conditions : $\varphi_{sq} = 0 \Leftrightarrow \varphi_{sd} = \varphi_s$
- Rotor flux orientation with the conditions: $\varphi_{rq} = 0 \Leftrightarrow \varphi_{rd} = \varphi_r$
- Air gap flow orientation with the conditions: $\varphi_{gq} = 0 \Leftrightarrow \varphi_{gd} = \varphi_g$

In our case the orientation of the stator flux is the chosen method [17].

II.5 Types of Vector Control

II.5.1 Direct Contro

This control strategy was proposed by Blaschke in 1970. In this case, accurate knowledge of the flux magnitude and its phase is required to achieve complete decoupling between torque and flux, regardless of the transient operating conditions.

The flux is regulated using negative feedback, meaning it must either be measured directly or estimated from stator voltage and current signals.

To obtain reliable information about the flux amplitude and phase, sensors such as Hall effect

probes or measuring coils can be placed beneath the stator teeth (within the air gap of the machine) [16].

The advantage of this method lies in its reduced sensitivity to parameter variations. However, it also has drawbacks: the sensors used are mechanically fragile and may not withstand harsh conditions such as strong vibrations or high temperatures. Moreover, the captured signals are often distorted by harmonics, and their frequency varies with rotor speed, requiring the use of automatically adjustable filters[18].

II.5.2 Indirect Control

The indirect method was introduced by K. Hasse. Its principle is based on not measuring (or estimating) the flux magnitude, but only its position. This method involves estimating the angle (position) of the flux vector, while its magnitude is set in open-loop mode. The voltages or currents required to achieve flux orientation and torque-flux decoupling are computed from a dynamic model of the machine during transient operation [17].

The development of microprocessors has significantly contributed to the widespread adoption of this method. However, it is highly sensitive to parameter variations in the machine. It is worth noting that the indirect method is simpler to implement and more commonly used than the direct method. Nevertheless, the choice between the two approaches depends on the specific requirements of the application [17]

II.6 Application of Vector Control to the Doubly-Fed Induction Mach

Unlike the squirrel-cage asynchronous machine, where only stator currents can be measured, the doubly-fed slip ring induction machine (DFIM) allows current measurements on both the stator and rotor sides. This offers greater flexibility in controlling the machine [18].

The expression of the electromagnetic torque in a DFIM enables us to interpret the machine, from an energy conversion perspective, as a mechanical combination of two separately excited DC machines. This analogy helps in better understanding the coupling issue between the direct and quadrature axes components. [18]

In fact, for a separately excited and compensated DC machine without magnetic saturation, the electromagnetic torque is given by :

$$T = K\phi_{I_f}I_a \quad (II.1)$$

ϕ_{I_f} : is the flux imposed by the excitation current I_f

I_a : It is the armature current.

According to equation (II.1), the flux is determined by the excitation current. Hence, when the flux is kept constant, the torque can be controlled exclusively by adjusting the current. This implies that torque production and flux generation are independent processes[19]

II.6.1 Choice of Reference Frame

Vector control is based on the selection of a reference frame. In principle, the reference axes can be chosen based on one of the machine's fluxes, namely: the stator flux, the rotor flux, or the air-gap flux [19]

Flux-oriented control involves regulating the flux using one component of the current and controlling the torque with another. To orient the stator flux, a (d, q) reference frame must be chosen such that the stator flux is aligned with the d-axis. This allows the torque expression to be separated into two current components—one responsible for generating the flux, and the other for generating the torque. When the stator flux is oriented, the following condition is met [20]

$$\varphi_{sq} = 0 \Leftrightarrow \varphi_{sd} = \varphi_s \quad (\text{II.2})$$

The principle of this type of flux orientation is illustrated in Figure (II.2).

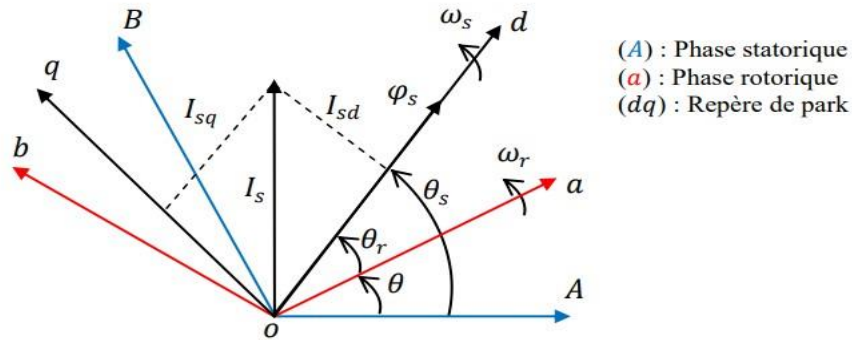


Figure (II.2): Principle of Stator Flux Orientation

Given the adopted working assumptions, this leads us to set the stator current in the d-axis to zero, $I_{sd} = 0$. The current and voltage in this axis are then in phase, $V_s = V_{sq}$ and $I_s = I_{sq}$.

Modeling our system in steady-state operation as follows[20]:

$$\begin{cases} V_{sd} = R_s I_{sq} \\ V_{sq} = R_s I_{sq} + \omega_s \varphi_{sd} \\ V_{rd} = R_r I_{rd} - \omega_r \varphi_{rq} \\ V_{rq} = R_r I_{rq} + \omega_r \varphi_{rd} \end{cases} \quad (\text{II.3})$$

The equation of the stator flux is given by substituting equation (II.2) into equation (II.38), we obtain:

$$\begin{cases} I_{sd} = 0 \\ \varphi_{sq} = 0 \end{cases} \iff \begin{cases} \varphi_{sd} = M I_{rd} \\ I_{rd} = \frac{\varphi_{sd}}{M} = \frac{\varphi_s}{M} \\ I_{sd} = -\frac{M}{L_s} I_{rq} \end{cases} \quad (\text{II.4})$$

The expression of the electromagnetic torque:

$$T_{em} = P \frac{M}{l_s} (\varphi_{sq} I_{rd} - \varphi_{sd} I_{rq}) \quad (\text{II.5})$$

The stator flux $\varphi_{sq} = 0$, we obtain:

$$T_{em} = -P \frac{M}{l_s} \varphi_{sd} I_{rq} = -P \frac{M}{l_s} \varphi_s^* I_{rq} \quad (\text{II.6})$$

$$I_{rq} = -\frac{l_s}{PM} \frac{T_{em}}{\varphi_s^*} \quad (\text{II.7})$$

From equation (II.3), we have:

$$\omega_s = (V_{sq} + \frac{R_s M}{L_s} I_{rq}) / \varphi_s^* \quad (\text{II.8})$$

According to the stator flux equations, we obtain:

$$V_{sd} = L_s I_{sd} + M I_{rd} \gg I_{sd} = \frac{1}{L_s} (\varphi_{sd} - M I_{rd}) \quad (\text{II.9})$$

$$V_{sq} = L_s I_{sq} + M I_{rq} \gg I_{sq} = \frac{1}{L_s} (\varphi_{sq} - M I_{rq}) \quad (\text{II.10})$$

By substituting equations (II.9) and (II.10) into (I.36), we obtain:

$$\frac{d\varphi_{sd}}{dt} = V_{sd} + \frac{M}{T_s} I_{rd} - \frac{1}{T_s} \varphi_{sd} \quad (\text{II.11})$$

$$\frac{d\varphi_{sq}}{dt} = V_{sq} + \frac{M}{T_s} I_{rq} - \omega_s \varphi_{sd} \quad (\text{II.12})$$

To express the rotor flux as a function of the stator flux φ_{sd} and the rotor current I_{rd} by substituting equation (II.9) and equation (II.10) into equation (I.38), we obtain the following two equations[17]:

$$\varphi_{rd} = \sigma L_r I_{rd} + \frac{M}{L_s} \varphi_{sd} \quad (\text{II.13})$$

$$\varphi_{rq} = \sigma L_r I_{rq} + \frac{M}{L_s} \varphi_{sq} \quad (\text{II.14})$$

By introducing equations (II.13) and (II.14) into equation (I.37), we obtain:

$$V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} + \frac{M}{L_s} V_{sd} - (\omega_s - \omega) \sigma L_r L_{rq} \quad (\text{II.15})$$

$$V_{rd} = (R_r + \frac{M^2}{L_s T_s}) I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + \frac{M}{L_s} V_{sq} - \frac{M}{L_s} \omega \varphi_{sd} + (\omega_s - \omega) \sigma L_r L_{rd} \quad (\text{II.16})$$

II.6.2 Direct Vector Control Structure of the DFIM

The block diagram of the direct vector control with stator flux orientation for the Doubly-Fed Induction Machine (DFIM) is shown in Figure (II.3). It comprises four PI controllers: one dedicated to flux regulation, one for speed control, and two for the current components. These regulators work together to ensure precise control of the machine's dynamic behavior, maintaining stable flux and speed while effectively managing torque production [21].

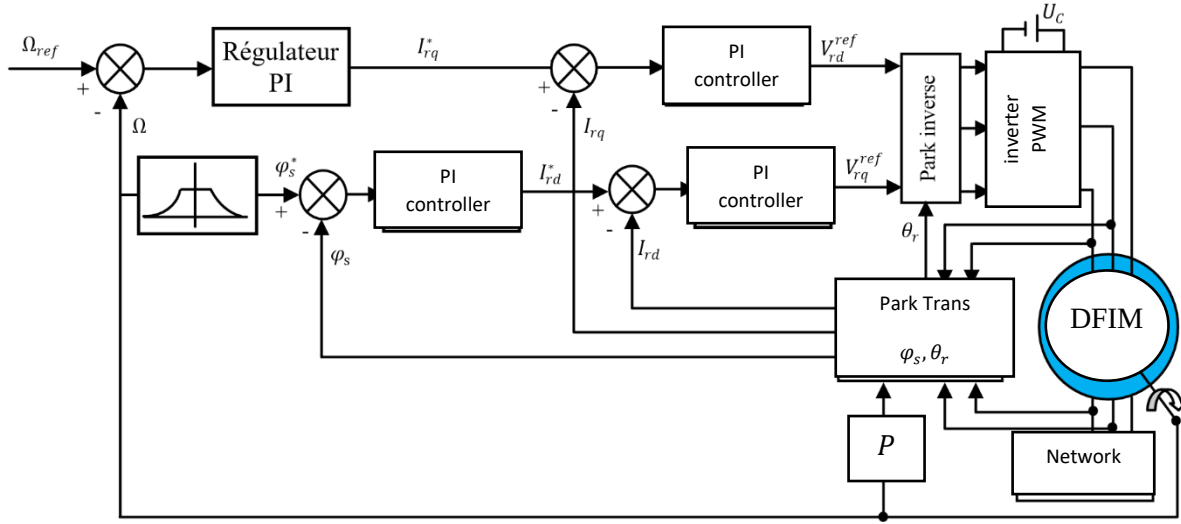


Figure (II.3): Vector Control Structure of the DFIM

III.6.3 Defluxing Block

The machine operates normally up to its nominal values of speed, power, and torque. However, when the speed exceeds the nominal value, the machine risks overloading due to the increase in power demand. To prevent this, the magnetic flux must be reduced proportionally to the speed increase, ensuring that the machine operates at constant (nominal) power. This process is known as defluxing or field weakening.

Under these conditions, the machine can safely operate above its nominal speed without exceeding its rated power, thereby avoiding overload and overheating. To achieve this mode of operation, a reference flux is applied as defined by the following relation [21], [22]:

$$\varphi_s^* = \begin{cases} \varphi_{sn} & \text{if } |\omega| \leq \omega_n \\ \varphi_{sn} \frac{\omega_n}{|\omega|} & \text{if } |\omega| > \omega_n \end{cases}$$

With:

ω_n : $P * \Omega_{sn}$ Is the nominal angular speed of the machine

φ_{sn} : Is the nominal stator flux

Ω_{sn} : Is the nominal mechanical rotational speed of the machine [21]

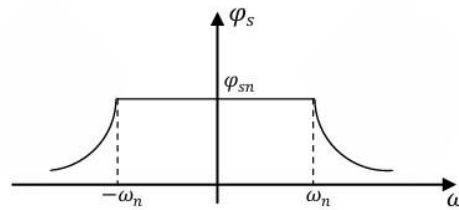


Figure (II.4): Reference stator flux profile (defluxing)

II.6.4 Principle of Decoupling by Compensation

The goal of decoupling is to eliminate the interaction between control channels so that each input influences only one specific output. This allows the system to be represented as a set of independent single-input single-output (SISO) subsystems operating in parallel, simplifying control design and implementation. [20],

From the voltage equations, it is evident that coupling terms exist between the d-axis and q-axis components. To compensate for these coupling effects, two new control variables, V_{rd} and V_{rq} , are introduced such that : , [22].

$$V_d = V_{rd1} - e_{rd} \quad (\text{II.18})$$

$$V_q = c - e_{rq} \quad (\text{II.19})$$

With:

$$e_{rd} = \delta L_r(\omega_s - \omega)I_{rq} - \frac{M}{L_s}V_{sd} \quad (\text{II.20})$$

$$e_{rd} = \frac{M}{L_s}\omega\phi_{sd} - \delta L_r(\omega_s - \omega)I_{rd} - \frac{M}{L_s}V_{sq} \quad (\text{II.21})$$

Figure (II.5) shows the reconstruction of voltages V_{rd} and V_{rq} based on e_{rd} and e_{rq}

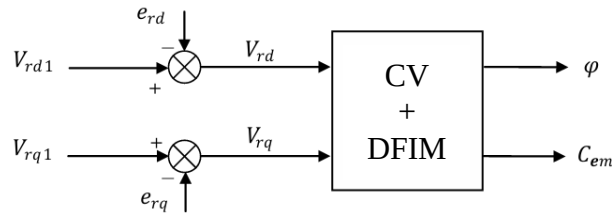


Figure (II.5): Reconstruction of voltages V_{rq} and V_{rd}

This decoupling approach relies on introducing compensatory terms e_{rd} and e_{rq} , which are computed using an estimate of the actual stator flux ϕ_s . The controller is designed under the assumption of a linear system; however, any parameter drift or estimation error can degrade performance. Variations in the machine parameters may cause the coupling effects to reappear, making the system non-stationary and potentially unstable. Therefore, robust control strategies are necessary to maintain stability and ensure reliable performance under parameter uncertainties and operating condition changes [20], [23]

II.7 Sizing of the Controllers

The sizing of the controllers for the rotor current, stator flux, and speed control loops is based on the use of Proportional–Integral (PI) controllers, selected for their simplicity, reliability, and ease of implementation in real-time systems. The integral component of the PI controller eliminates the steady-state error, ensuring accurate tracking of the reference signal, while the proportional

component determines the dynamic response speed of the system. The tuning and parameter adjustment of these controllers are performed using the pole placement method, which allows the closed-loop system to achieve the desired transient and steady-state performance by appropriately positioning the poles of the system in the complex plane [24].

II.7.1 Controller for the Current I_{rd}

The current controller for I_{rd} is designed to regulate the direct-axis component of the rotor current, which directly influences the stator flux. The reference value of I_{rd} is defined and measured to control the rotor voltage V_{rd1} . By maintaining I_{rd} at a constant value, the stator flux remains stable, ensuring proper magnetic field orientation and efficient energy conversion[25]

The transfer function of the direct-axis rotor current control loop is obtained from equation (II.18) by neglecting the compensating term e_{rd} . This simplification allows for a clearer representation of the current regulation dynamics and facilitates the design of the PI controller, which ensures accurate current tracking and stable flux control within the vector control framework of the doubly fed induction machine [24] [25]

$$V_{rd1} = V_{rd} + e_{rd} = R_r I_{rd} + \sigma I_r \frac{dI_{rd}}{dt} = R_r (1 + \sigma T_r \cdot S) I_{rd} \quad (\text{II.22})$$

$$\frac{I_{rd}}{V_{rd1}} = \frac{\frac{1}{R_r}}{1 + \sigma T_r \cdot S} \quad (\text{II.23})$$

The block diagram of the I_{rd}^* current control is shown in Figure (II.6)

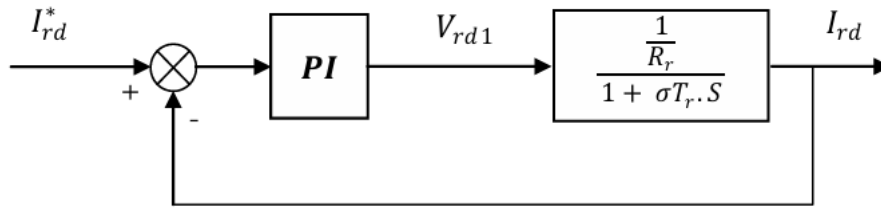


Figure (II.6): Current control diagram of I_{rd}

The transfer function of the PI controller is given by the following equation.

$$PI(s) = K_p + \frac{k_i}{s} \quad (\text{II.24})$$

The open-loop transfer function (OLTF) of Figure (II.6)

$$FTBO(s)_{I_{rd}} = \frac{K_{id}}{R_r \cdot S} \left(\frac{K_{pd}}{K_{id}} s + 1 \right) \frac{1}{1 + \sigma T_r \cdot S} \quad (\text{II.25})$$

By pole compensation, which is expressed by the condition

$$\frac{K_{pd}}{K_{id}} = \sigma T_r \quad (\text{II.26})$$

Then the open-loop transfer function is written as follows:

$$FTBO(s)_{I_{rd}} = \frac{K_{id}}{R_r \cdot s} \quad (II.27)$$

In order to have the behavior of a first-order system whose transfer function is of the form

$$G(s) = \frac{1}{1 + \tau s} \quad (II.28)$$

The closed-loop transfer function (CLTF) is given by

$$FTBO(s)_{I_{rd}} = \frac{1}{1 + \frac{R_r}{K_{id}}} = \frac{1}{1 + \tau s} \quad (II.29)$$

Thus:

$$\tau = \frac{R_r}{K_{id}} \quad (II.30)$$

From expressions (II.25) and (II.30), we have:

$$\begin{cases} K_{id} = \frac{R_r}{\tau} \\ K_{pd} = K_{id} \sigma T_r = \frac{\sigma T_r}{\tau} \end{cases} \quad (II.31)$$

II.7.2 Controller for the Current I_{rq}

The transfer function of the quadrature rotor current is obtained from equation (II.16) by canceling e_{rq} .

$$V_{rq1} = V_{rq} + e_{rq} - \frac{M}{L_s} V_{sq} = \left(R_r + \frac{M^2}{L_s T_s} \right) I_{rq} + \sigma L_s \frac{dI_{rq}}{dt} = K_p \left(1 + \frac{\sigma T_r}{K_p} \cdot s \right) I_{rq} \quad (II.32)$$

Where

$$K_p = R_r + \frac{M^2}{L_s T_s}$$

Thus

$$\frac{I_{rq}}{V_{rq1}} = \frac{\frac{1}{K_p}}{1 + \frac{\sigma L_r}{K_p} \cdot s} \quad (II.33)$$

The current control loop of I_{rq}^* can be represented by the block diagram in Figure (II.7).

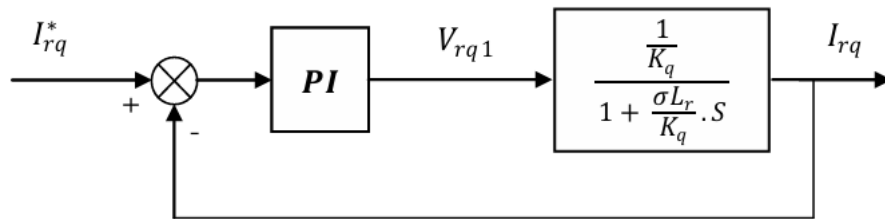


Figure (II.7): Current control diagram of I_{rq}

To determine the two coefficients K_{pd} and K_{iq} , the same procedure used for the I_{rd} current is applied[26]

Thus, we obtain:

$$\begin{aligned} K_{iq} &= \frac{K_p}{\tau} = \frac{R_r + \frac{M^2}{L_s T_s}}{\tau} \\ K_{pq} &= K_{iq} \frac{\sigma L_r}{K_q} = \frac{\sigma L_r}{\tau} \end{aligned} \quad (II.34)$$

II.7.3 Stator Flux Controller

The stator flux orientation allows us to write, based on equation (II.11), we have $V_{sd} = 0$

$$\frac{\varphi_{sd}}{I_{rd}} = \frac{M}{1 + T_s s} \quad (II.35)$$

We aim to obtain a first-order response in closed-loop operation. The closed-loop system can be represented by the block diagram in Figure (II.8).

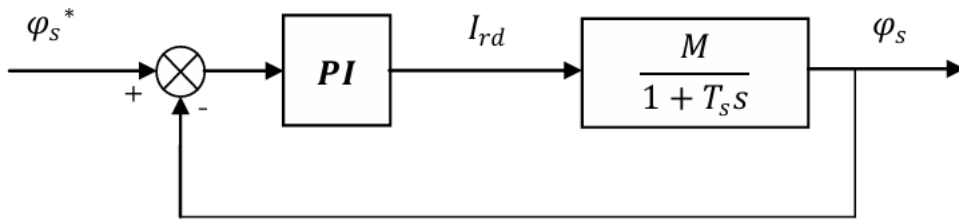


Figure (II.8): Closed-loop stator flux control

Pole compensation allows us to obtain the following condition:

$$T_s = \frac{k_{p\varphi}}{k_{i\varphi}} \quad (II.36)$$

The closed-loop transfer function is now expressed as follows:

$$FTBF(s) = \frac{1}{1 + \tau_{\varphi} s} \quad (II.37)$$

With:

$$\tau_{\varphi} = \frac{1}{M k_{i\varphi}} \quad (II.38)$$

Based on conditions (II.36) and (II.38), the parameters of the flux controller are:

$$\begin{cases} k_{i\varphi} = \frac{1}{M \tau_{\varphi}} \\ k_{p\varphi} = \frac{T_s}{M \tau_{\varphi}} \end{cases} \quad (II.39)$$

II.7.4 Speed Control

The speed control loop, implemented using a PI controller, is illustrated in the functional diagram of Figure (II.9). In this control structure, the speed controller continuously compares the actual rotor speed with the reference speed and generates the reference electromagnetic torque required to minimize the speed error. The proportional term provides a fast dynamic response by reacting immediately to speed deviations, while the integral term eliminates steady-state errors, ensuring that the machine maintains the desired speed accurately under varying load conditions [27]

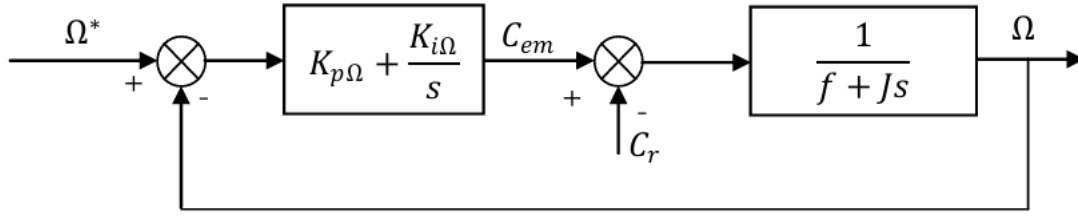


Figure (II.9): Functional diagram of speed control

The mechanical equation gives:

$$\omega = \frac{C_{em} - C_r}{f + Js} \quad (II.40)$$

White

$$\Omega = P\omega \quad (II.41)$$

The closed-loop transfer function, calculated from the previous diagram, is given by:

$$\frac{\Omega}{\Omega^*} = \frac{(k_{p\Omega}s + k_{i\Omega})}{Js^2 + (k_{p\Omega} + f)s + k_{i\Omega}} \quad (II.41)$$

This transfer function has a second-order dynamic. By matching the denominator to the canonical form:

$$F(s) = \frac{1}{\frac{1}{\omega_n^2}s^2 + \frac{2\xi}{\omega_n}s + 1} \quad (II.42)$$

We will have:

$$\begin{cases} k_{i\Omega} = J\omega_n^2 \\ k_{p\Omega} = 2J\xi\omega_n - f \end{cases} \quad (II.43)$$

II.8 Simulation Results

The objective of this section is to implement direct vector control with stator flux orientation to regulate the performance Doubly-Fed Induction Machine (DFIM). of the The system is simulated under various operating conditions, including changes in rotor speed, applied load, and variations in both rotor and stator resistances, in order to evaluate the robustness and efficiency of the proposed control approach. In this configuration, the stator is directly connected to the power grid, while the rotor is supplied through a voltage converter, allowing independent control of the rotor currents and enabling precise adjustment of torque and flux for effective speed regulation.

II.8.1 Machine Operation During Load Variation

To verify the effectiveness of the vector control, a load torque of $C_r = 15 \text{ N}\cdot\text{m}$ is applied between $t = 1.5\text{s}$ and $t = 2.5\text{s}$. The corresponding simulation results are presented in Figure (II.10). These results show that during the load variation, all quantities such as speed, torque, flux, and currents are affected, hich confirms that the system is properly controlled

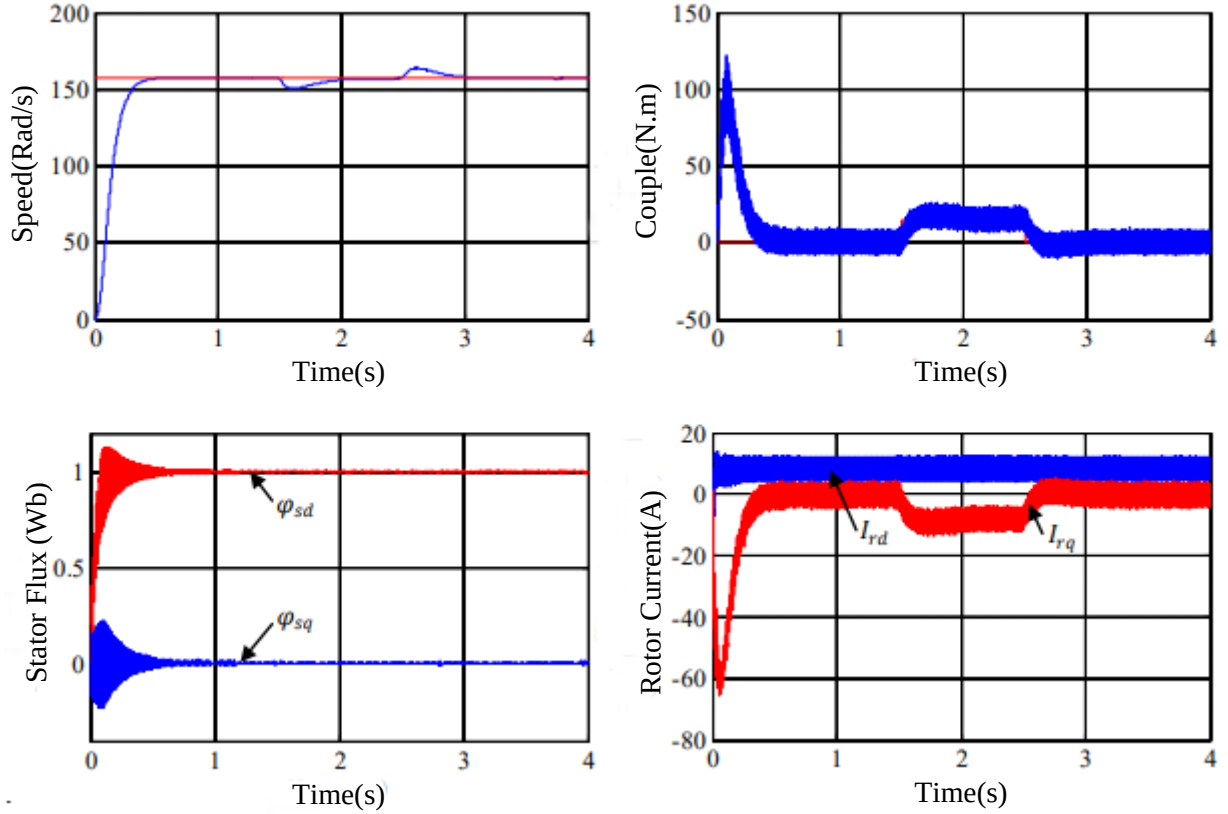


Figure (II.10): Simulation Results During Load Variation

II.8.2 Machine Operation during Speed Variation

The machine is initially operating under no-load conditions with a torque of $C_r = 0 \text{ N}\cdot\text{m}$ rotating at its nominal speed of 157 rad/s. At time $t = 1.5 \text{ s}$, the direction of rotation is reversed to -157 rad/s , and at $t = 3 \text{ s}$, the machine operates at a lower speed of 50 rad/s. A load torque of $C_r = 15 \text{ N}\cdot\text{m}$ is applied between $t = 1.5 \text{ s}$ and $t = 2.5 \text{ s}$. The corresponding simulation results are illustrated in Figure (II.11), showing the evolution of speed, torque, flux, and the direct and quadrature components of the control currents generated by the stator flux orientation principle.

It can be observed that the speed follows its new reference accurately, with a slight overshoot during the transition between operating states. Similarly, the electromagnetic torque tracks its reference value, exhibiting perfect decoupling between torque and flux. The stator flux experiences only a minor variation during the change in speed, confirming the stability and robustness of the vector control strategy.

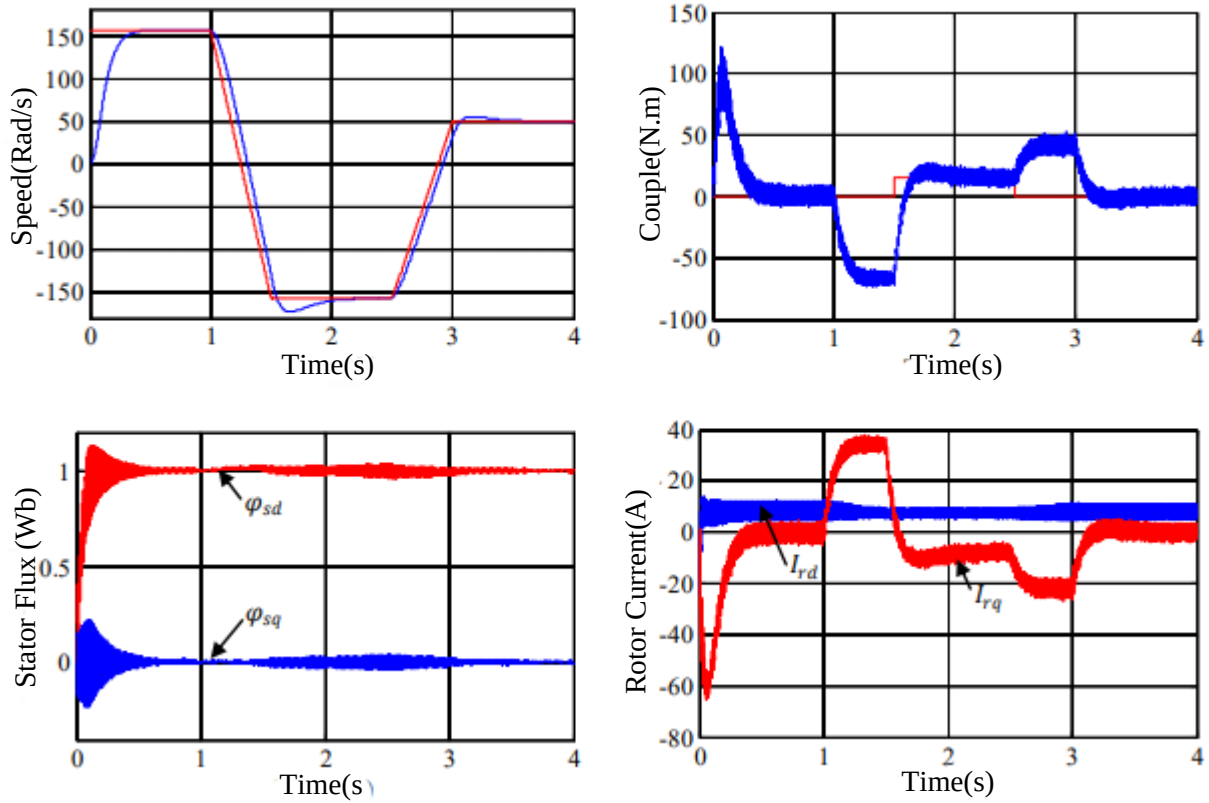
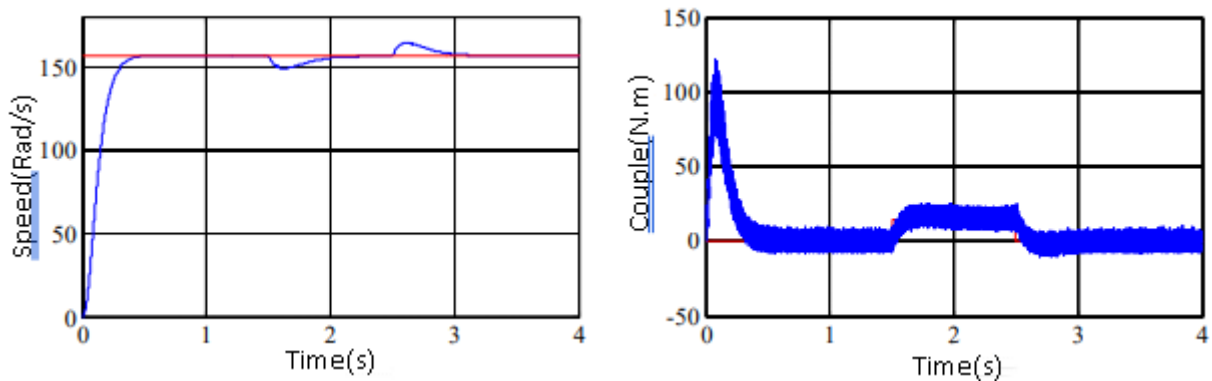


Figure (II.11): Simulation results during speed variation

II.8.3 Operation of the machine during rotor resistance variation

Figure (II. 12) presents the simulation results corresponding to a +100% variation of the rotor resistance (R_s) from its nominal value, which simulates the effect of machine heating. This variation is applied between $t = 1.5s$ and $t = 2.5s$. During the same interval, a load torque of $C_r = 15N \cdot m$ is also applied.

The results show that the increase in rotor resistance has no significant influence on the machine speed, as the speed error remains nearly zero. The most noticeable variation is due to the applied load torque C_r , which the control system compensates effectively. The electromagnetic torque tracks its reference value accurately, while the stator flux exhibits only a slight change in its magnitude, confirming that the decoupling between torque and flux is preserved.



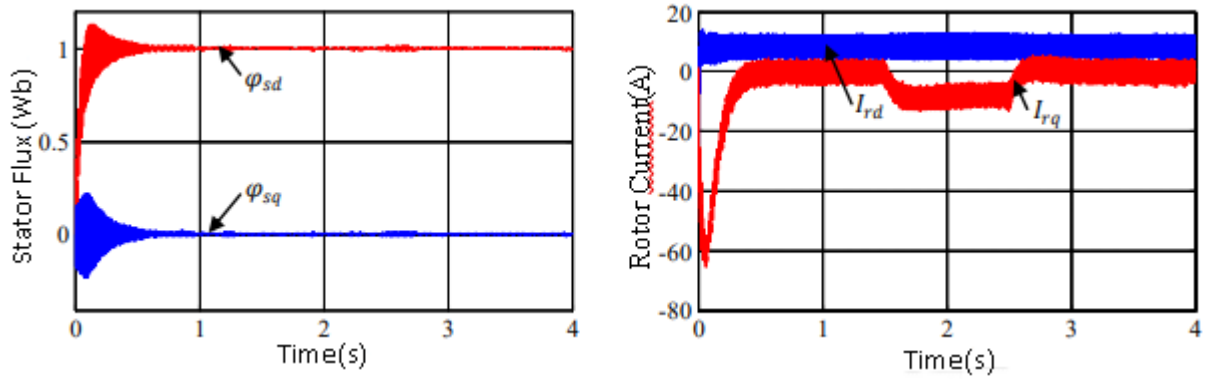


Figure (II.12): Simulation results during the variation of the Rotor resistance

II.8.4 Operation of the machine during stator resistance variation

In this case, a +100% variation of the stator resistance (R_s) from its nominal value was applied between $t = 1.5s$ and $t = 2.5s$. The simulation results show no noticeable change in either the speed or flux waveforms, indicating that the system maintains stable performance. This demonstrates that the control strategy is robust with respect to variations in the stator resistance, ensuring reliable operation of the machine even under parameter deviations caused by factors such as temperature rise.

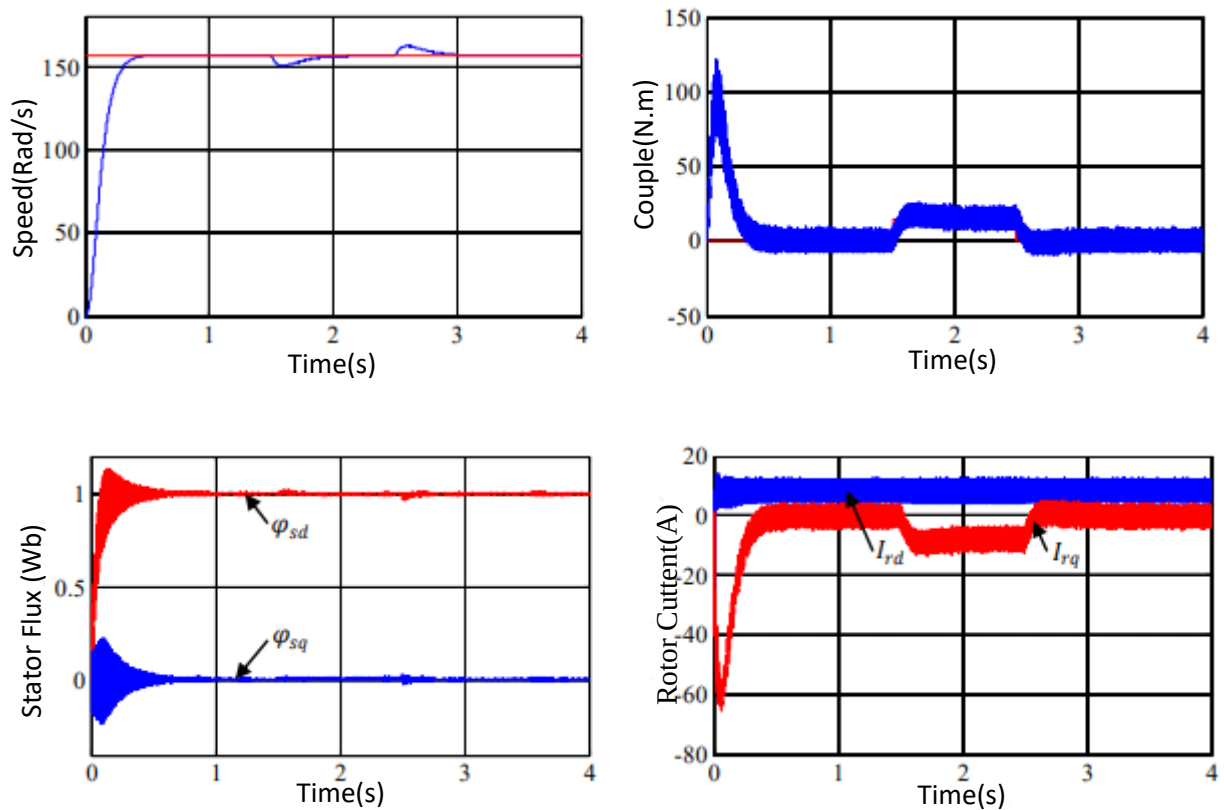


Figure (II.13): Simulation results during the variation of the stator resistance.

II.8.5 Interpretation of the results

Based on the simulation results of the Doubly-Fed Induction Machine (DFIM), the vector control strategy combined with a PI speed regulator has proven to be highly effective in managing the machine's dynamic and steady-state performance. The rotor speed exhibits a rapid and smooth response, accurately following its reference under various operating conditions, with a minimal tracking error during transients that completely disappears in steady-state operation.

A precise stator flux orientation is achieved, contributing to enhanced operational efficiency and optimal electromagnetic energy conversion. The electromagnetic torque follows its reference value with high accuracy, ensuring stable and reliable operation even under variable load conditions.

The system demonstrates excellent disturbance rejection capability, as the speed regulator responds instantaneously to load torque variations by promptly adjusting the reference electromagnetic torque, thereby maintaining speed stability.

With respect to mechanical parameters, variations in the moment of inertia have a limited influence on flux orientation but affect the rotor speed response, particularly during transient periods and external disturbances. Conversely, variations in rotor inductance significantly influence rotor speed while having only a minor effect on the flux orientation, which shows small deviations mainly during transient states.

However, variations in rotor resistance (R_r) and stator resistance (R_s) were not considered in the current control design, which may slightly affect performance under thermal or parametric changes. To further improve control precision, robustness, and adaptability, an advanced intelligent control approach based on fuzzy logic will be introduced. The following section presents the fundamentals of Type-1 Fuzzy Logic and its application to DFIM speed regulation, aiming to enhance control accuracy and ensure stable operation under parameter variations and external disturbances

II.9 Conclusion

In this chapter, the principle of direct vector control with stator flux orientation applied to the doubly-fed induction machine (DFIM) was presented and analyzed. This control approach is based on transforming the machine currents into the rotating reference frame (d,q), allowing for the decoupling of current components and enabling independent and precise control of both the flux and torque-producing elements. By employing state feedback, vector control achieves input–output decoupling and ensures optimal regulation through transfer functions that directly relate the controlled currents to their corresponding references.

The proposed vector control strategy was implemented in combination with a classical PI speed regulator, where the PI controller minimizes the speed error between the reference and actual values, while the vector control maintains accurate stator flux orientation, ensuring stable and efficient machine operation. The simulation results validated the system's effectiveness in accurate

speed tracking, stable flux regulation, and strong disturbance rejection under different load conditions, confirming the robustness and reliability of the vector control approach. [28] [29]

Chapter III

Fuzzy_ PD+I

III.1 Introduction

In the previous chapter, the vector control strategy combined with a classical PI speed regulator was successfully implemented for controlling the Doubly-Fed Induction Machine (DFIM), demonstrating good dynamic performance and satisfactory steady-state accuracy. However, the conventional PI controller shows limited robustness when system parameters vary, such as changes in rotor or stator resistance, or when the machine is subjected to sudden load disturbances. These factors can deteriorate control precision and reduce the system's responsiveness. To overcome these limitations, intelligent control techniques have been developed, among which fuzzy logic control has proven to be one of the most effective due to its ability to handle system uncertainties and nonlinearities without requiring an exact mathematical model. In this chapter, a Fuzzy PD+I controller is proposed for the speed regulation of the DFIM. This control strategy combines the fast dynamic response of the PD controller with the zero steady-state error ensured by the integral action, while the fuzzy logic system adaptively adjusts the proportional and derivative gains according to the system's operating conditions. The following sections present the fundamental principle of fuzzy logic control, the structure and design of the proposed Fuzzy PD+I controller, and the simulation results that demonstrate its superior performance compared to the conventional PI regulator.

III.2 Fuzzy Logic Controller

Fuzzy Logic Control (FLC) is an intelligent control approach inspired by the way humans make decisions based on imprecise or qualitative information rather than exact mathematical models. Unlike conventional control methods that rely on precise system equations, fuzzy logic uses linguistic rules and approximate reasoning to determine control actions, making it particularly suitable for complex and nonlinear systems such as the Doubly-Fed Induction Machine (DFIM) [30] .

The main concept of fuzzy logic control is to translate the knowledge and experience of a human operator into a set of if-then rules, which describe how the system should react to various conditions. This rule-based reasoning allows the controller to handle parameter variations, uncertainties, and nonlinearities effectively, ensuring robust performance even under unpredictable operating conditions [30] .

A typical fuzzy logic control system consists of four essential components:

1. **Fuzzification**
2. **Rule Base**

3. Inference Engine

4. Defuzzification

Through these steps, the fuzzy logic controller emulates human reasoning, enabling adaptive and robust control performance without requiring detailed mathematical modeling of the machine. When applied to the DFIM, fuzzy logic control allows precise speed and torque regulation, improved dynamic response, and increased resilience against parameter variations and load disturbances[30] [31] .

III.2.1 Fuzzification in Fuzzy Logic

Fuzzification is the first stage in a fuzzy logic control system, where precise numerical inputs—known as *crisp inputs*—are converted into fuzzy values that the system can interpret. The purpose of this transformation is to represent quantitative variables using linguistic terms (such as *Negative*, *Zero*, or *Positive*), allowing the controller to handle the uncertainty and imprecision inherent in real-world systems. This process relies on membership functions, which mathematically define the degree to which a numerical input belongs to a given fuzzy set. The membership degree varies continuously between 0 and 1, meaning that a single input value can simultaneously belong to several linguistic categories with different degrees of confidence. This property allows fuzzy logic to interpret inputs in a smooth and gradual manner rather than through abrupt thresholds[31]

Several types of membership functions are commonly used in fuzzification, including triangular, trapezoidal, and Gaussian shapes. The choice of function depends on the application, data characteristics, and the desired level of precision in modeling. This stage is fundamental because it prepares the input variables for processing by the fuzzy inference mechanism, where control decisions are made based on linguistic rules instead of strict mathematical relationships. The ability to represent a single input with multiple degrees of membership provides fuzzy logic controllers with their well-known flexibility, robustness, and effectiveness in managing complex, nonlinear, and uncertain control systems [32]

III.2.2. Rule Base in Fuzzy Logic

Rule Base is one of the fundamental components of a fuzzy inference system, responsible for storing a set of fuzzy IF–THEN rules that guide the decision-making or control actions of the system based on fuzzified inputs. These rules represent the core of the system’s intelligence, as they encapsulate expert knowledge and human reasoning in linguistic form rather than mathematical equations. A typical rule takes the form: “*IF the speed is high AND the torque is low,*

THEN the voltage should be medium.” Each rule defines the relationship between input conditions and corresponding output actions using linguistic variables such as *low*, *medium*, or *high*[32].

The rules are evaluated according to the fuzzy input values obtained during the fuzzification process, allowing the system to interpret and respond to complex conditions in a manner similar to human reasoning. A typical Rule Base consists of: (1) a collection of fuzzy IF–THEN rules, (2) linguistic variables representing input and output quantities, and (3) logical connectors such as AND and OR used to combine multiple conditions within a rule. These rules are generally constructed manually by domain experts familiar with the system’s dynamics, though they may also be generated or refined using empirical or experimental data[32].

The effectiveness of a fuzzy control system largely depends on the completeness and accuracy of its Rule Base. A well-designed Rule Base that covers a wide range of operating scenarios enables the controller to make consistent, accurate, and adaptive decisions. Essentially, the Rule Base serves as the knowledge repository of the fuzzy system, translating human understanding and experience into a structured logic framework that can be processed by the fuzzy inference engine. This capability gives fuzzy systems their strength in managing uncertainty and complexity, allowing them to emulate intelligent human decision-making in nonlinear and dynamic environments[33].

III.2.3 Inference Engine in Fuzzy Logic

Inference Engine is the central component of a fuzzy logic system responsible for performing the reasoning and decision-making process. It functions by applying the Rule Base to the fuzzified input values in order to derive appropriate conclusions or control actions. The inference engine determines which rules are relevant for the current input conditions and evaluates the degree to which each rule is satisfied by calculating the corresponding membership values. Based on these evaluations, it generates the fuzzy output for each active rule and then combines or aggregates all the resulting outputs into a single fuzzy set representing the overall system response[31]

The inference process commonly relies on one of two widely used fuzzy reasoning models: the Mamdani model and the Sugeno model. The Mamdani inference method, proposed by Ebrahim Mamdani in 1975, is the most popular in control applications. It uses fuzzy sets for both inputs and outputs, making it intuitive and easy to interpret, particularly in systems that aim to emulate human reasoning. On the other hand, the Sugeno model, introduced by Takagi and Sugeno in 1985,

employs fuzzy inputs but produces a crisp output through mathematical functions, allowing for simpler computation and easier integration with adaptive and optimization algorithms[33]

Regardless of the model used, the inference engine plays a crucial role in combining fuzzy logic with control theory by translating linguistic rules into actionable decisions. It ensures that the system responds appropriately to dynamic and uncertain conditions, making it an essential component in achieving smooth, adaptive, and intelligent control performance[34].

III.2.4 Defuzzification in Fuzzy Logic

Defuzzification is the final stage of a fuzzy logic control system, in which the fuzzy output generated by the inference engine is transformed into a precise numerical value, known as a *crisp output*. This value can then be applied directly to a physical system—such as a motor, actuator, or converter control signal—to execute the appropriate action. Since the output of the inference process consists of fuzzy sets formed by combining the results of multiple fuzzy rules, these sets cannot be directly used in real-world systems. Therefore, defuzzification is a crucial step that converts the fuzzy conclusions into meaningful and applicable numerical values[34].

Several defuzzification methods are commonly used, each with its advantages and computational characteristics. The Centroid Method (or *Center of Gravity*) is the most widely used, as it calculates the center of the area under the aggregated output membership function to determine the crisp value. Although this method provides high accuracy, it requires complex integration and may be computationally demanding. The Center of Area (COA) method is conceptually similar but simplifies the computation by dividing the fuzzy output into basic geometric shapes to balance the area. Simpler methods such as the Mean of Maximum (MOM) and First of Maximum (FOM) focus only on the output values with the highest membership degree; these approaches are computationally faster but generally offer lower precision compared to the centroid method. [35]

The choice of defuzzification technique significantly influences the accuracy, stability, and responsiveness of the fuzzy control system. It depends on the application's specific requirements—whether the priority is high precision or real-time computational efficiency—and on the complexity of the membership functions involved. Ultimately, the defuzzification process serves as the interface between fuzzy reasoning and the real world, converting linguistic decisions into actionable control signals that ensure the system's practical and efficient operation. [35]

III.3 Principle of the PD+I Controller

The PD+I controller is a modified structure of the classical PID controller that separates the proportional–derivative (PD) and integral (I) actions into two distinct control paths. This configuration allows the transient response to be primarily governed by the PD component, while the integral part operates independently to eliminate steady-state error without influencing the fast dynamics. [36]

The mathematical formulation of the PD+I controller is given as:

$$u(t) = K_p [e(t) + K_d \frac{de(t)}{dt}] + K_i \int e(t) dt$$

where:

- $u(t)$ is the controller output,
- $e(t)$ is the instantaneous error ($e(t) = \omega_{ref} - \omega(t)$)
- K_p , K_d , and K_i denote the proportional gain, derivative time constant, and integral gain respectively.

In this structure, the PD part produces a control signal that reacts immediately to variations in the error and its rate of change, thereby enhancing damping and reducing overshoot during transients. The I part, implemented separately, accumulates the error over time and compensates for steady-state deviations caused by model uncertainties, external disturbances, or load variations. [36]

Compared to a conventional PID controller, the PD+I structure provides better decoupling between transient and steady-state performance.

By tuning the PD and I terms independently, the controller achieves both fast dynamic response and high steady-state accuracy.

This makes the PD+I controller particularly suitable for nonlinear and time-varying systems such as the Doubly-Fed Induction Machine (DFIM), where robustness and precision are essential under fluctuating operating conditions. [37]

III.4 Design of the Fuzzy PD+I Controller

The most widely used fuzzy controllers are the fuzzy proportional–derivative (FPD) controllers, which operate on two input signals: the error and the change in error (derivative of error).

Designing the rule base for these controllers is generally well established and straightforward.

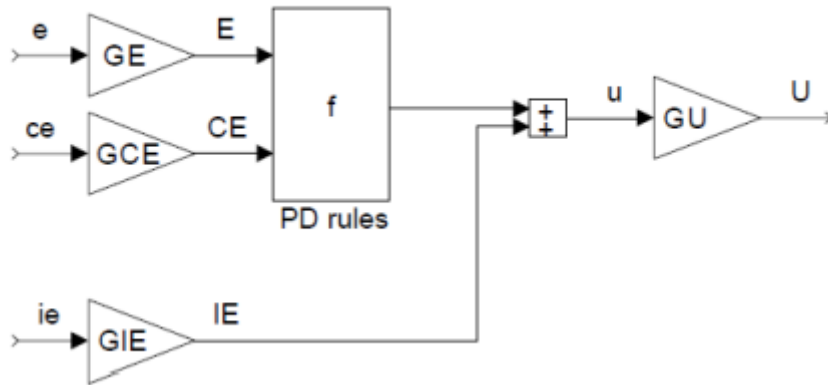
This configuration ensures a good transient response due to the derivative term, but it tends to perform poorly at steady-state, where the error approaches zero. [43]

To improve steady-state performance, an integral action is typically added, leading to the fuzzy proportional–integral (FPI) controller. Although this structure improves accuracy in steady-state, it often results in a slower dynamic response.

Achieving both fast transient behavior and minimal steady-state error requires a controller that combines derivative and integral actions. Such a system is known as the fuzzy proportional–derivative–integral (FPID) controller[38]

In the literature, several configurations have been proposed for implementing FPID controllers. One of the most efficient and simplified versions is the fuzzy PD+I structure, where a conventional fuzzy PD controller is augmented by an external integral component. This approach retains the fast response and reduced overshoot of the fuzzy PD controller, while the added integral term compensates for residual steady-state error[45].

The general block diagram of this controller is shown in Figure III.1, where the integral action is applied in parallel with the fuzzy PD output, forming the combined control law:



Figure(III.1): Fuzzy PD+I controller (FPD+I) [45]

where:

GE :gain of the error input signal.

GCE :gain of the change of error (derivative of error) signal.

GIE :gain of the integral of error signal

III.4.1 Motivation for Combining Fuzzy PD and I

The motivation behind combining a fuzzy proportional–derivative (Fuzzy PD) controller with an integral (I) action arises from the need to achieve both fast dynamic response and zero steady-state error in control systems such as the Doubly-Fed Induction Machine (DFIM) [39].

The Fuzzy PD controller is known for its excellent transient performance because it reacts quickly to changes in the system error and its rate of change. It provides strong damping and reduces overshoot, making it ideal for systems where fast response and stability are critical. However, Fuzzy PD controllers often suffer from small steady-state errors since they lack an integrating mechanism that can accumulate and correct residual deviations over time[39]

On the other hand, an integral controller eliminates the steady-state error by continuously integrating the error signal, ensuring the output eventually matches the reference input. Nevertheless, excessive integral action can slow down the response or cause overshoot if used alone[43].

By combining these two control philosophies — the intelligent and adaptive nature of fuzzy PD logic with the error-correcting property of the integral term — the resulting Fuzzy PD+I controller offers a balanced performance. It maintains the fast response and low overshoot of the Fuzzy PD controller while ensuring steady-state accuracy through the integral component. This hybrid configuration also simplifies the fuzzy rule base, as only two fuzzy inputs (error and change of error) are required, while the integral term operates as a separate linear block[38] [39]

III.5 Application of the Fuzzy PD+I Controller to the (DFIM)

This study aims to apply a Fuzzy PD+I controller for the speed regulation of the Doubly-Fed Induction Machine (DFIM), based on a model oriented by the stator flux. The DFIM system is decoupled along the d–q axes and controlled through a cascade control structure, where the outer loop manages the rotor speed using the Fuzzy PD+I algorithm, while the inner current loops regulate the rotor currents[40]

III. 6 Fuzzy PD+I Contro

With the continuous advancement of modern electric drive systems, there is an increasing demand for advanced control strategies capable of ensuring high accuracy, fast dynamic response, and strong robustness against external disturbances. The Doubly-Fed Induction Machine (DFIM), also

known in French as *Machine Asynchrone à Double Alimentation (MADA)*, is one of the most widely used machines in renewable energy applications, particularly in variable-speed wind power generation systems, due to its wide speed control range, high efficiency, and bidirectional power flow capability. In this context, an intelligent control strategy known as the Fuzzy PD+I Control is proposed. This approach integrates the advantages of both fuzzy logic and classical control theory, where the fuzzy PD component provides an adaptive nonlinear response that improves transient performance and reduces overshoot, while the integral (I) component ensures the elimination of steady-state error and maintains accurate speed tracking under varying load conditions. The fuzzy inference mechanism dynamically adjusts the control output based on the magnitude and variation of the speed error, enabling smooth and stable system operation. This strategy effectively combines the benefits of both fuzzy logic and conventional control methods to overcome their individual drawbacks. While classical PI controllers provide good steady-state accuracy but relatively slow transient response, and standard fuzzy controllers may exhibit steady-state offset, the Fuzzy PD+I controller achieves a superior balance between fast response, stability, and accuracy. The intelligent fuzzy decision-making process allows continuous adaptation of the control effort to maintain optimal system performance under nonlinear and uncertain operating conditions. The main objective of this section is to apply and analyze the Fuzzy PD+I control structure for the DFIM, by analyzing the control architecture, formulating the mathematical structure of the fuzzy PD+I control law, and evaluating the system's dynamic performance through MATLAB/Simulink simulations under various load and speed conditions. Finally, the obtained results will be compared with conventional PI and Fuzzy PI control strategies to highlight the superior performance of the proposed Fuzzy PD+I controller in terms of transient response, steady-state precision, and robustness[40] [41]

III.6.1 Fuzzy logic control

The Fuzzy PD+I control strategy relies on fuzzy logic to provide an adaptive nonlinear response to variations in the system's speed error and its rate of change. Figure (III.3) illustrates the fuzzy inference system used in this study, which consists of two input variables—error (e) and change of error (de/dt)—and one output variable representing the fuzzy control signal. Each variable is characterized by seven linguistic terms: Negative Great (NG), Negative Medium (NM), Negative Small (NP), Equal Zero (EZ), Positive Small (PP), Positive Medium (PM), and Positive Great (PG). The triangular membership functions define smooth transitions between these linguistic regions, allowing the controller to operate effectively under a wide range of operating conditions. The fuzzy rule base is constructed according to expert knowledge of the system's dynamic behavior.

When the error and its derivative are both large, the controller generates a strong corrective action to minimize deviation rapidly, while as the system approaches the reference, the control effort is reduced to avoid overshoot and oscillation. The defuzzification process, implemented using the centroid method, converts the fuzzy output into a crisp control signal that drives the machine. This configuration allows the fuzzy logic component to act as an intelligent nonlinear PD controller capable of adjusting the control signal according to the instantaneous system state, while the addition of an external integral term ensures the elimination of steady-state error, forming the complete Fuzzy PD+I controller. The resulting control surface, shown in the lower-right part of Figure (III.3) illustrates how the control output varies smoothly with respect to the input variables, confirming the controller's stability and continuity across the full operating range[32] [33] [35].

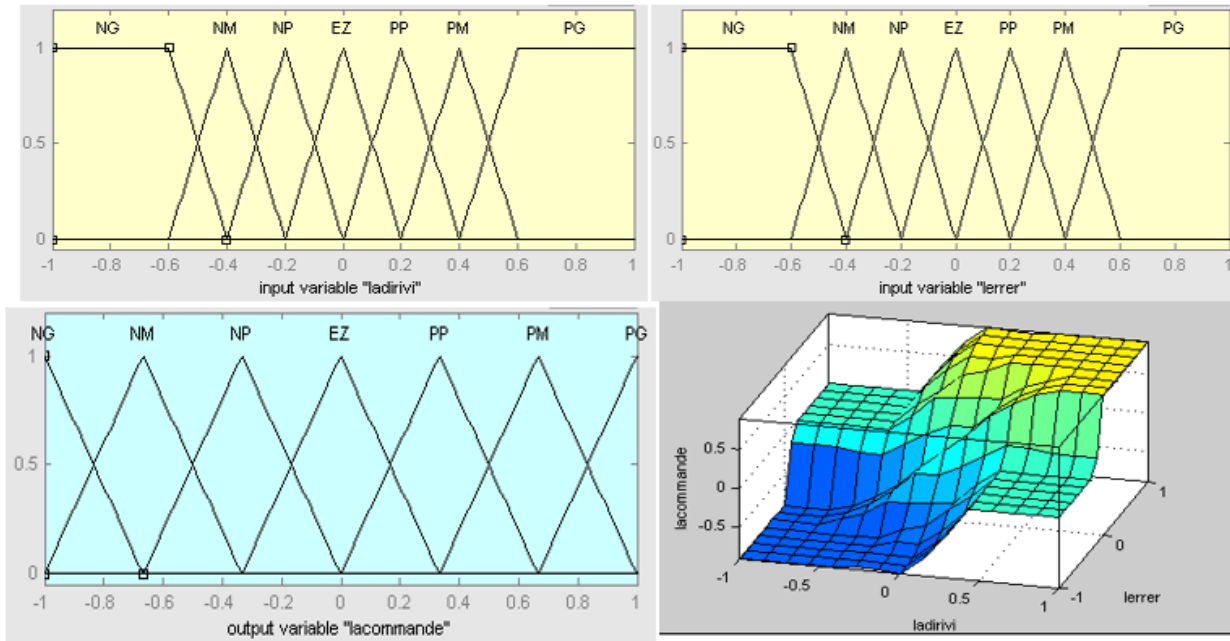


Figure (III.2): Membership functions of the fuzzy inputs and output, and the resulting control surface for the Fuzzy PD+I controller

III.6.2 Structure of the Fuzzy PD+I Control

The Fuzzy PD+I controller combines the advantages of fuzzy logic and classical control techniques to achieve high-performance regulation of the Doubly-Fed Induction Machine (DFIM). Its structure integrates a fuzzy PD controller with an additional integral action to ensure zero steady-state error while maintaining fast and stable dynamic behavior. Figure (III.3) illustrates the functional block diagram of the proposed Fuzzy PD+I control structure.

The reference input is compared with the measured output to produce the error signal, which represents the difference between the desired and actual speed. This error, along with its derivative and integral, are the main input signals used by the controller. The error and its rate of change are processed through scaling factors and then fed into the fuzzy logic system, where a rule base and inference mechanism determine the fuzzy corrective output. The fuzzy part of the controller, equivalent to a nonlinear PD action, provides a rapid dynamic response, minimizes overshoot, and enhances system stability during transient conditions, while the integral component, added in parallel, ensures the elimination of steady-state error and maintains accurate tracking of the reference signal under constant load or parameter variations. The combined effect of the fuzzy PD and integral components results in an adaptive and robust controller capable of compensating for nonlinearities, parameter uncertainties, and external disturbances, effectively improving both transient and steady-state performance. Consequently, the Fuzzy PD+I controller represents a reliable and efficient solution for the speed control of the DFIM under various operating conditions[44] [45]

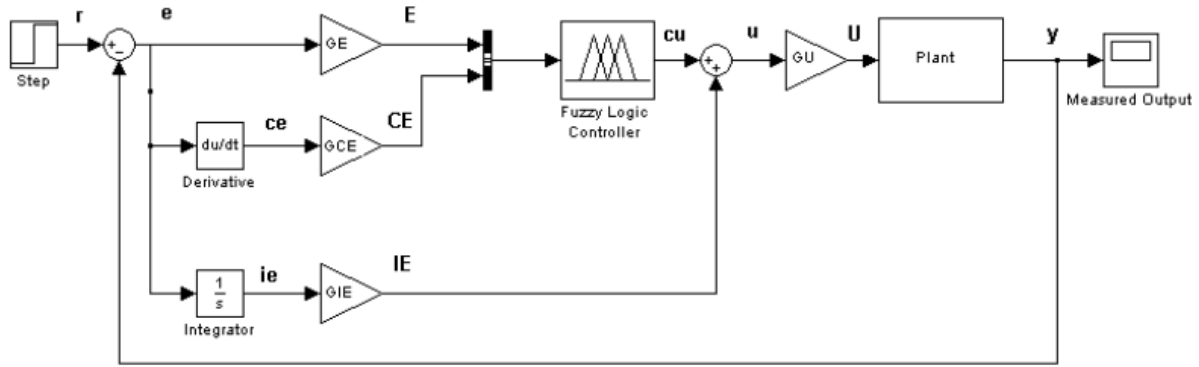


Figure (III.3): Functional block diagram of the proposed Fuzzy PD+I controller[45]

III.6.3 Structure of the Fuzzy PD+I Control for DFIM

Figure (III.4) illustrates the block diagram of the direct vector control scheme based on stator flux orientation applied to the Doubly-Fed Induction Machine (DFIM). In this configuration, the overall control system is organized into several interconnected loops that ensure accurate control of speed, flux, and rotor currents. The diagram includes four controllers: one PI controller dedicated to flux regulation, one Fuzzy PD+I controller responsible for speed control, and two current controllers for the regulation of the ddd- and qqq-axis rotor current components. [41] The Fuzzy PD+I controller generates the reference torque by processing the speed error and its derivative through the fuzzy inference mechanism, while the integral action ensures the elimination of steady-state error.

. The torque reference produced by this block is then used by the current control loops to determine the appropriate rotor voltage references. This hierarchical structure allows precise decoupling between flux and torque control, ensuring fast dynamic response and robust operation of the DFIM under varying load and parameter conditions[42]

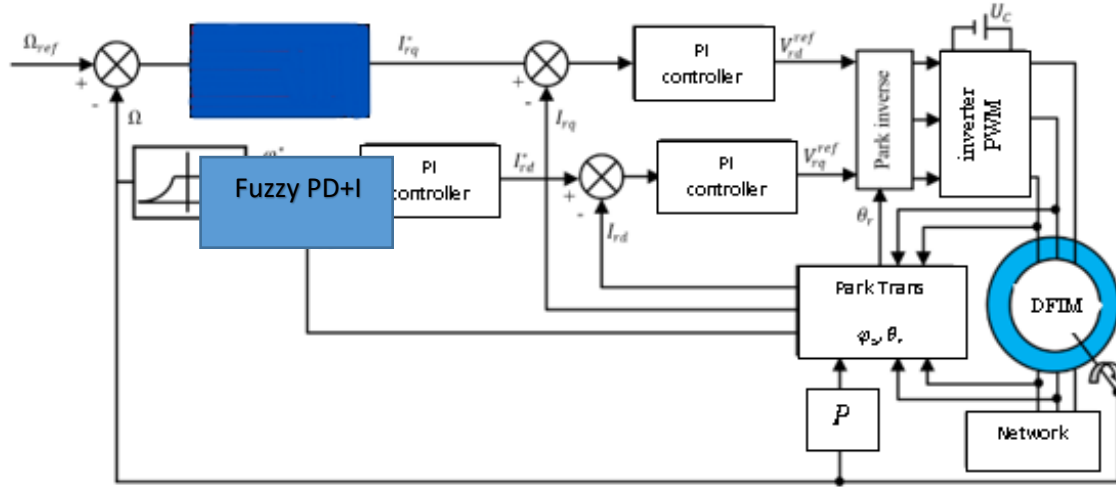


Figure (III.4): Structure of FUZZY PD+I Control for DFIM

III.7 Simulation Results

The objective of this step is to apply an intelligent Fuzzy PD+I control strategy to enhance the overall performance of the Doubly-Fed Induction Machine (DFIM). Through simulation, the proposed method is evaluated under various operating scenarios, including reference speed changes, load disturbances, and parameter variations. The Fuzzy PD component provides fast and adaptive transient response, while the integral (I) action ensures the complete elimination of steady-state error. This hybrid approach aims to improve system dynamics, enhance robustness against model uncertainties, and provide smoother control behavior compared to conventional PI or fuzzy PI techniques. Consequently, the Fuzzy PD+I strategy offers a more flexible, precise, and intelligent control structure suitable for modern high-performance electric drive systems.

III.7.1 Machine Operation during Load Variation

A load torque of $C_r = 15 \text{ N}\cdot\text{m}$ is applied between $t = 1.5 \text{ s}$ and $t = 2.5 \text{ s}$. The simulation results show that only minor variations appear in the rotor speed, electromagnetic torque, and stator flux during the load disturbance. The system quickly compensates for the applied torque change and maintains stable operation throughout the test.

The rotor speed remains very close to the reference value, with negligible steady-state error and minimal overshoot. This confirms the effectiveness of the Fuzzy PD+I controller, whose adaptive fuzzy PD component provides rapid dynamic adjustment while the integral action eliminates residual steady-state deviation. Overall, the system demonstrates strong robustness and smooth behavior under sudden load changes.

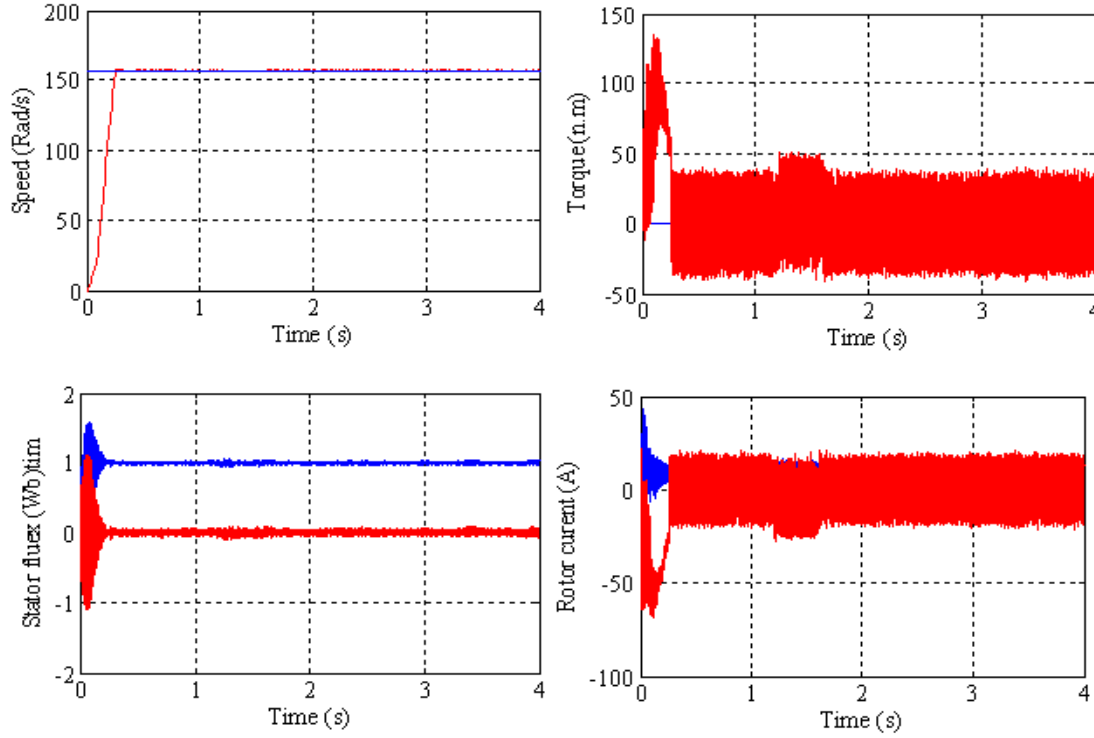


Figure (III.5): Simulation Results During Load Variation

III.7.2 Machine Operation during Speed Variation

The machine speed is varied from 157 rad/s to -157rad/s , and then to 50rad/s at different time intervals, while a load torque of $C_r = 15\text{N}\cdot\text{m}$ is applied between $t = 1.5\text{s}$ and $t = 2.5\text{s}$. The simulation results indicate that the rotor speed follows the reference signal smoothly during all transitions, including the reversal of rotation direction. The electromagnetic torque exhibits a fast and stable response, adapting rapidly to the changing speed commands, while the stator flux remains almost constant, showing minimal deviation. These results confirm the high adaptability and precision of the Fuzzy PD+I control strategy, which ensures smooth speed tracking and effective torque regulation without overshoot or oscillations. Overall, the controller demonstrates excellent performance in maintaining system stability and dynamic accuracy under varying speed conditions.

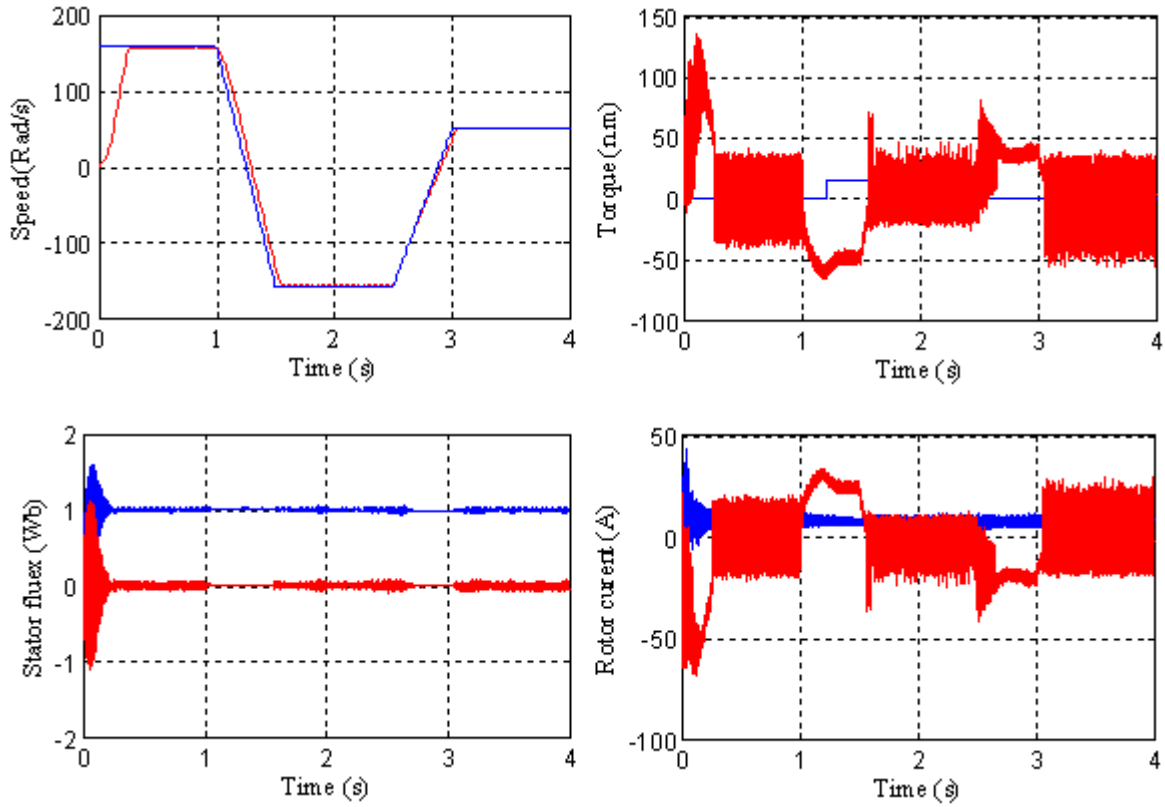


Figure (III.6): Simulation results during speed variation

III.7.3 Machine Operation during Rotor Resistance Variation

A +100% increase in rotor resistance is applied between $t = 1.5\text{s}$ and $t = 2.5\text{s}$, together with a load torque of $C_r = 15\text{N}\cdot\text{m}$. The simulation results show that the machine speed remains practically unaffected despite the sudden parameter variation. The electromagnetic torque and stator flux exhibit excellent stability with negligible oscillations, while the phase currents show only a slight increase in amplitude due to the higher rotor resistance. These results confirm the robustness and adaptability of the Fuzzy PD+I control strategy, which effectively compensates for parameter changes and maintains precise speed tracking without compromising system stability. This demonstrates the controller's strong ability to handle uncertainties and nonlinearities inherent in the Doubly-Fed Induction Machine.

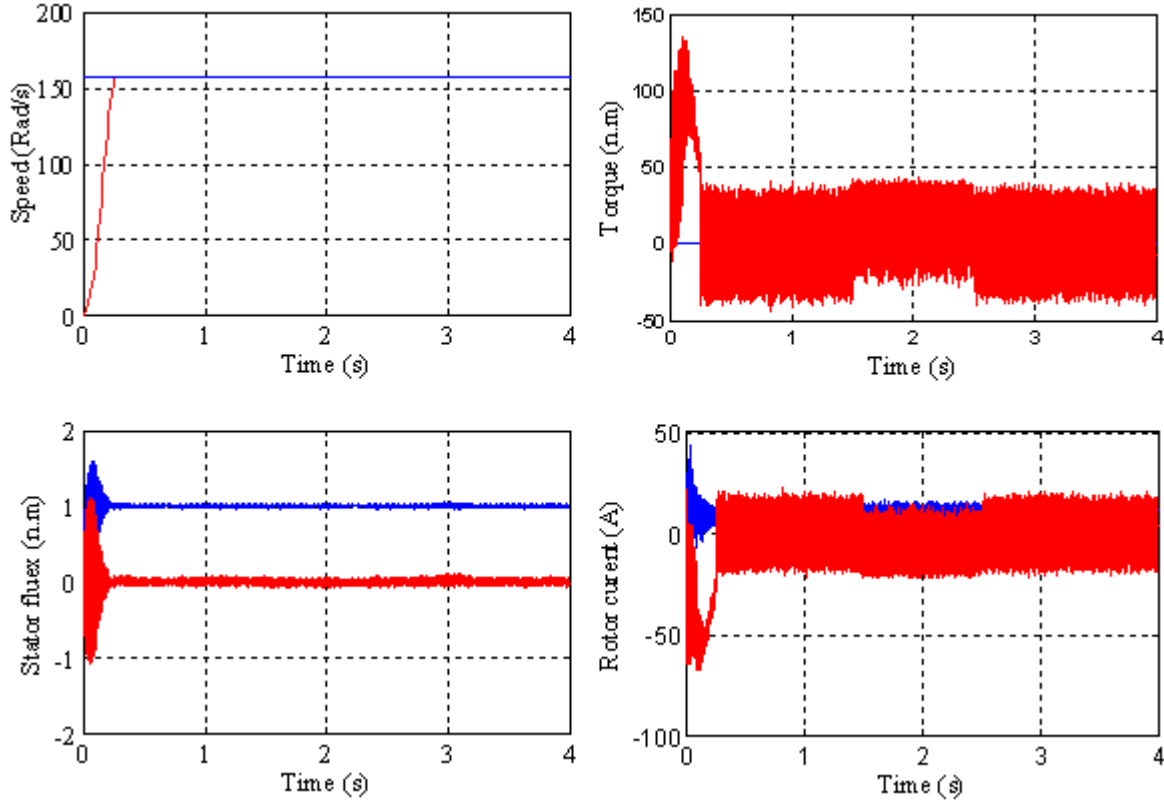


Figure (III.7): Simulation results during the variation of the rotor resistance.

III.7.4 Machine Operation during Stator Resistance Variation

A +100% increase in stator resistance R_s is applied between $t = 1.5s$ and $t = 2.5s$. The simulation results show that this parameter change has no significant effect on the system's performance. The rotor speed remains constant and accurately follows the reference value, while the stator flux exhibits negligible variation. The electromagnetic torque remains stable, and only a slight increase in the current amplitude is observed due to the higher stator resistance. These results clearly demonstrate the robustness and reliability of the proposed Fuzzy PD+I control strategy, which effectively compensates for parameter variations and maintains excellent steady-state and dynamic performance of the Doubly-Fed Induction Machine (DFIM).

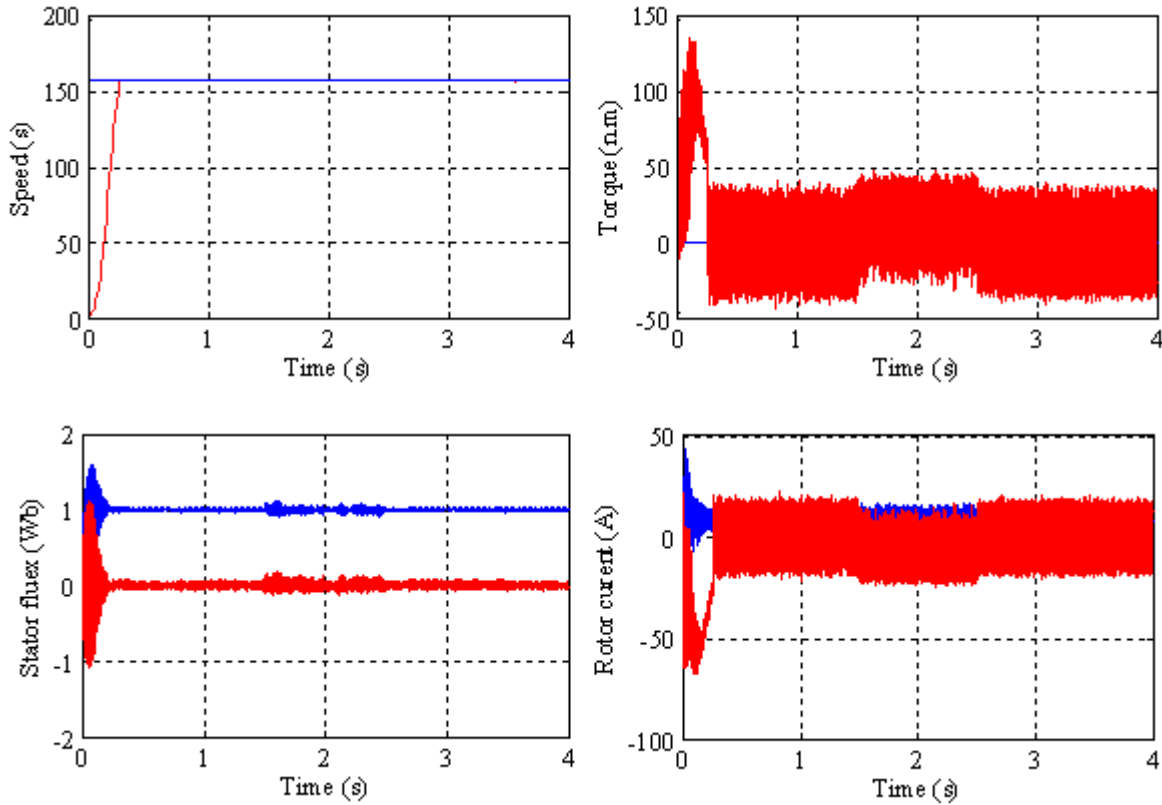


Figure (III.8): Simulation results during the variation of the stator resistance

III.7.5 Interpretation of the results

The simulation results confirm the effectiveness of the proposed Fuzzy PD+I controller in improving the dynamic and steady-state performance of the Doubly-Fed Induction Machine (DFIM). The rotor speed accurately follows the reference signal under various operating conditions, including load variations, speed changes, and parameter disturbances, with significantly reduced tracking error and faster settling time. During load variation tests, the electromagnetic torque rapidly compensates for changes in the applied resistant torque, while the rotor speed remains stable and the stator flux exhibits minimal deviation, demonstrating the controller's strong ability to reject external disturbances. In speed variation scenarios, the Fuzzy PD+I controller ensures smooth transitions between different operating points, achieving rapid acceleration and deceleration without noticeable oscillations or overshoot.

When parameter changes were introduced—such as variations in rotor and stator resistances—the system maintained stable operation, with negligible impact on speed and flux, and only a slight increase in current amplitude. These observations highlight the robustness and adaptability of the proposed control strategy against system uncertainties and nonlinearities.

Overall, the Fuzzy PD+I control structure successfully combines fast dynamic response, precise speed tracking, and high robustness, offering a reliable and efficient approach for advanced control of Doubly-Fed Induction Machines. Compared with conventional PI and Fuzzy PI controllers, the proposed Fuzzy PD+I method achieves superior performance in terms of transient response, disturbance rejection, and steady-state precision, making it a promising solution for modern high-performance electric drive systems.

III.8 Conclusion

In this chapter, the design, implementation, and performance evaluation of the intelligent control strategy Fuzzy PD+I have been comprehensively presented and applied to the Doubly-Fed Induction Machine (DFIM). The DFIM represents a key component in modern renewable energy systems, particularly in variable-speed wind turbine applications, due to its high efficiency, wide operational speed range, and superior dynamic characteristics. The proposed Fuzzy PD+I controller was designed to address one of the most critical challenges in DFIM operation, namely achieving precise and robust speed control under variable load and parameter conditions. While conventional PI or fuzzy PI controllers often suffer from limitations such as slower transient response, overshoot, or inability to completely eliminate steady-state error, the Fuzzy PD+I strategy provides an enhanced and balanced solution that combines the adaptive nonlinear response of fuzzy logic with the stability and accuracy of integral action. The controller structure demonstrated a remarkable ability to adapt dynamically to different operating conditions, where the fuzzy inference mechanism based on the speed error and its rate of change enabled smoother transitions, reduced oscillations, minimized overshoot, and improved overall stability, especially during sudden changes in load torque or reference speed. The integral term effectively compensated steady-state deviations, ensuring precise speed tracking and zero steady-state error. Simulation results confirmed that the Fuzzy PD+I control strategy significantly enhances both dynamic performance and steady-state precision, outperforming conventional PI and fuzzy PI methods. Its adaptive nonlinear behavior enables faster convergence, improved disturbance rejection, and better robustness against parameter variations. Therefore, the Fuzzy PD+I controller can be considered a reliable and efficient control approach for modern electric drive systems, especially in renewable energy applications that demand fast response, high stability, and adaptability, highlighting its potential as a scalable solution for intelligent, high-performance electrical machines operating under real-world dynamic conditions.

General Conclusion

In the contemporary era of continuous industrial progress and the growing reliance on electric machines for high-precision and mission-critical applications, the demand for advanced control strategies capable of managing nonlinear and dynamic system behaviour has become increasingly vital. Among various electrical machines, the Doubly-Fed Induction Machine (DFIM) stands out for its unique capability to regulate power flow in both directions, ensuring high flexibility and efficiency in speed and torque control[1]. This makes the DFIM a prime candidate for use in renewable energy conversion systems, particularly wind turbines, as well as in modern variable-speed electric drives. However, the control of the DFIM remains a challenging task due to its nonlinear characteristics, parameter sensitivity, and coupling between electrical and mechanical variables, which often lead to degraded performance when operating under disturbances or parameter variations[3]. To address these issues, this study proposes the development of an intelligent hybrid control strategy based on the Fuzzy PD+I controller, designed to enhance both the transient and steady-state performance of the machine. The research begins with the mathematical modeling of the DFIM, describing its electrical and mechanical dynamics through differential equations in the d–q reference frame. Using Park’s transformation, the machine equations are reformulated to facilitate the design of an efficient control algorithm. The implementation of vector control ensures the decoupling of torque and flux components, thereby improving control accuracy and system responsiveness[14]. The central concept of this work lies in the integration of fuzzy logic with the classical PD+I control structure. The fuzzy PD component provides adaptive nonlinear control based on the instantaneous error and its derivative, enhancing the dynamic response and minimizing overshoot, while the integral term guarantees the elimination of steady-state error, ensuring accurate tracking of the reference speed even under external disturbances and parameter uncertainties. This hybrid design combines the adaptability of fuzzy reasoning with the stability of integral action, resulting in a more robust and flexible control system. Simulation results confirm the effectiveness and robustness of the proposed Fuzzy PD+I controller, as the DFIM achieves precise speed tracking with rapid transient response, reduced settling time, and minimal overshoot. The control signals exhibit smooth variations, demonstrating improved system stability and reduced oscillations during sudden changes in load torque or reference speed. Additionally, the controller shows strong resistance to variations in machine parameters such as stator and rotor resistances, proving its reliability under real-world conditions. The results also highlight its superiority over conventional PI and Fuzzy PI controllers in terms of response speed, stability, steady-state precision, and robustness, confirming its potential as an intelligent and efficient control approach for advanced electric drive systems[30]. This study provides a significant contribution to the field of intelligent control of electric machines, emphasizing the benefits of

combining classical control theory with fuzzy logic techniques, and opens perspectives for future research through the integration of adaptive or neural-fuzzy mechanisms to further enhance the controller's learning capability and adaptability toward more autonomous and intelligent energy conversion systems.

References

-
- [1] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and S. D. Pekarek, *Analysis of Electric Machinery and Drive Systems*, 3rd ed., Wiley-IEEE Press, 2013.
- [2] W. Leonhard, *Control of Electrical Drives*, 3rd ed., Springer, 2001.
- [3] I. Boldea and S. A. Nasar, *Electric Drives*, CRC Press, 2005.
- [4] P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994.
- [5] P. Vas, *Sensorless Vector and Direct Torque Control*, Oxford University Press, 1998.
- [6] B. K. Bose, *Modern Power Electronics and AC Drives*, Prentice Hall, 2002.
- [7] P. C. Krause and C. H. Thomas, "Simulation of Symmetrical Induction Machinery," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-84, no. 11, pp. 1038–1053, 1965.
- [8] M. H. Rashid, *Power Electronics: Circuits, Devices, and Applications*, 4th ed., Pearson, 2017.
- [9] R. Peña, J. C. Clare, and G. M. Asher, "Doubly Fed Induction Generator Using Back-to-Back PWM Converters and Its Application to Variable-Speed Wind-Energy Generation," *IEE Proc. Electric Power Applications*, vol. 143, no. 3, pp. 231–241, 1996.
- [10] G. Abad, J. Lopez, M. A. Rodriguez, L. Marroyo, and G. Iwanski, *Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation*, Wiley-IEEE Press, 2011.
- [11] A. Tapia, G. Tapia, J. X. Ostolaza, and A. Susperregui, "Modeling and Control of a Wind Turbine Driven Doubly Fed Induction Generator," *IEEE Transactions on Energy Conversion*, vol. 18, no. 2, pp. 194–204, 2003.
- [12] A. D. Hansen and G. Michalke, "Multi-pole Permanent Magnet Synchronous Generator Wind Turbines' Grid Support Capability in Faulted Power Systems," *Renewable Energy*, vol. 32, no. 9, pp. 1594–1610, 2007.
- [13] F. Blaschke, "The Principle of Field Orientation Applied to the New Transvector Closed-Loop Control System for Rotating-Field Machines," *Siemens Review*, vol. 34, no. 3, pp. 217–220, 1972.
- [14] L. Xu and P. Wang, "Dynamic Modeling and Control of DFIG-Based Wind Turbines Under Unbalanced Network Conditions," *IEEE Transactions on Power Systems*, vol. 22, no. 1, pp. 314–323, 2005.
- [15] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications*, Wiley-IEEE Press, 2010.
- [16] F. Blaschke, "The principle of field orientation as applied to the new transvector closed loop control system for rotating field machines," *Siemens Review*, vol. 34, no. 3, pp. 217–220, 1972.
- [17] K. Hasse, "On the dynamic behavior of the asynchronous machine with field-oriented control," *Archiv für Elektrotechnik*, vol. 55, no. 7, pp. 436–441, 1973.
- [18] D. W. Novotny and T. A. Lipo, *Vector Control and Dynamics of AC Drives*, Oxford University Press, 1996.

- [19] J. Holtz, "Sensorless control of induction motor drives," *Proceedings of the IEEE*, vol. 90, no. 8, pp. 1359–1394, 2002.
- [20] R. Krishnan, *Electric Motor Drives: Modeling, Analysis, and Control*, Prentice Hall, 2001.
- [21] C. Schauder, "Adaptive speed identification for vector control of induction motors without rotational transducers," *IEEE Transactions on Industry Applications*, vol. 28, no. 5, pp. 1054–1061, 1992.
- [22] M. Depenbrock, "Direct Self-Control (DSC) of Inverter-Fed Induction Machine," *IEEE Transactions on Power Electronics*, vol. 3, no. 4, pp. 420–429, 1988.
- [23] R. Marino, P. Tomei, and C. M. Verrelli, *Induction Motor Control Design*, Springer, 2010.
- [24] Z. Xu and L. Xu, "Modeling and control of doubly fed induction generator wind turbines," *IEEE Transactions on Energy Conversion*, vol. 20, no. 2, pp. 398–405, 2005.
- [25] A. K. Jain and V. T. Ranganathan, "Modeling and field oriented control of doubly fed induction generators," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1821–1828, 2008.
- [26] S. Muller, M. Deicke, and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Industry Applications Magazine*, vol. 8, no. 3, pp. 26–33, 2002.
- [27] G. Abad, M. A. Rodríguez, L. Marroyo, and G. Iwanski, *Power Electronics and Control of Doubly Fed Induction Machine Systems*, Wiley-IEEE Press, 2011.
- [28] S. Morimoto, Y. Takeda, and T. Hirasu, "Vector control of induction motor without shaft encoder," *IEEE Transactions on Industry Applications*, vol. 28, no. 3, pp. 553–559, 1992.
- [29] J. Hu and B. Wu, "Model predictive direct torque control of induction motor drives with discrete space-vector modulation," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 2443–2453, 2009.
- [30] E. H. Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant," *Proceedings of the Institution of Electrical Engineers*, vol. 121, no. 12, pp. 1585–1588, 1974.
- [31] T. Takagi and M. Sugeno, "Fuzzy identification of systems and its applications to modeling and control," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. SMC-15, no. 1, pp. 116–132, 1985.
- [32] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, 1965.
- [33] K. M. Passino and S. Yurkovich, *Fuzzy Control*, Addison-Wesley Longman, 1998.
- [34] C. C. Lee, "Fuzzy logic in control systems: Fuzzy logic controller—Part I & II," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 20, no. 2, pp. 404–435, 1990.
- [35] B. Kosko, *Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence*, Prentice Hall, 1992.

- [36] M. Sugeno and G. T. Kang, "Structure identification of fuzzy model," *Fuzzy Sets and Systems*, vol. 28, pp. 15–33, 1988.
- [37] J.-S. R. Jang, C.-T. Sun, and E. Mizutani, *Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence*, Prentice Hall, 1997.
- [38] C. C. Hang, K. J. Åström, and W. K. Ho, "Refinements of the Ziegler–Nichols tuning formula," *IEEE Proceedings D - Control Theory and Applications*, vol. 138, no. 2, pp. 111–118, 1991.
- [39] M. Mudi and S. Pal, "A robust self-tuning scheme for PI- and PD-type fuzzy controllers," *IEEE Transactions on Fuzzy Systems*, vol. 7, no. 1, pp. 2–16, 1999.
- [40] H. Ying, *Fuzzy Control and Modeling: Analytical Foundations and Applications*, IEEE Press, 2000.
- [41] H. X. Li and S. K. Tso, "Quantitative design and analysis of fuzzy proportional–derivative control," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 4, pp. 779–784, 1999.
- [42] S. Elmas, S. Bayrak, and I. M. Colak, "Adaptive fuzzy logic controller for speed control of induction motor," *Expert Systems with Applications*, vol. 37, no. 7, pp. 5560–5568, 2010.
- [43] A. Belkaid, L. Chrifi-Alaoui, and M. Bendib, "Fuzzy adaptive PD+I controller for speed control of DFIG-based wind turbine," *International Journal of Electrical Power & Energy Systems*, vol. 117, 105704, 2020.
- [44] J. Zhao, H. Yu, and W. Zhang, "Hybrid intelligent control of induction motor using fuzzy PD+I strategy," *ISA Transactions*, vol. 75, pp. 131–141, 2018.
- [45] B. I. Saeed and B. Mehrdadi, "Zero overshoot and fast transient response using a fuzzy logic controller," in *Proceedings of the 17th International Conference on Automation and Computing (ICAC 2011)*, IEEE, London, UK, pp. 116–120, 2012..

Appendix

Parameters of the Doubly-Fed Induction Machine (DFIM)

C.1 Nominal Parameters

$$P_n = 4 \text{ KW}$$

Nominal Power

$$v/U = 220 \text{ 380V} - 50\text{Hz}$$

Nominal Voltage

$$i/I = 15/8.6\text{A.}$$

Nominal Current

$$\Omega_n = 1440 \text{ tr/min}$$

Nominal Speed

$$P = 2$$

Number of Pole Pairs

C.2 Electrical Parameters

$$R_s = 1.2 \Omega$$

Stator Resistance

$$R_r = 1.8 \Omega$$

rotor Resistance

$$L_s = 0.1554 \text{ H}$$

Stator Inductance

$$L_r = 0.1568 \text{ H}$$

rotor Inductance

$$M = 0.15 \text{ H}$$

Mutual Inductance

C.3 Mechanical Parameters

$$j = 0.2 \text{ Kg.m}^2$$

Moment of Inertia

$$f = 0.001 \text{ N.m.s/rd.}$$

Friction Coefficient.

**Thesis submitted in partial fulfillment of the requirements for the Master 2
degree in Science in automatic and systems**

Topic :

speed control of doubly-fed induction machine
using a fuzzy PD+I controller

By : MOKHTARI mohamed

Abstract:

This work presents a fuzzy PD+I control strategy for the speed control of a Doubly-Fed Induction Machine (DFIM). The controller combines the fast response of a PD structure with the steady-state precision of an integral action, enhanced by fuzzy logic adaptation. Simulation results in MATLAB/Simulink show improved speed tracking, reduced overshoot, and better robustness compared to the conventional PI controller.

Keywords: DFIM, Fuzzy PD+I, Fuzzy Logic, Speed Control, Vector Control

Résumé:

Ce travail présente une stratégie de commande floue PD+I pour la régulation de la vitesse d'une Machine Asynchrone à Double Alimentation (MADA). Le contrôleur combine la réponse rapide de la structure PD avec la précision en régime permanent de l'action intégrale, améliorée par l'adaptation de la logique floue. Les résultats de simulation sous MATLAB/Simulink montrent une meilleure poursuite de vitesse, une réduction du dépassement et une robustesse accrue par rapport au régulateur PI conventionnel.

Mots-clés : MADA, Commande floue PD+I, Logique floue, Commande de vitesse, Commande vectorielle

الملخص :

يقدم هذا العمل إستراتيجية تحكم ضبابي PD+I للتحكم في سرعة الآلة غير المتزامنة ذات التغذية المزدوجة (MADA). يجمع المتحكم بين الاستجابة السريعة لبنية PD والدقة في الحالة المستقرة للمركبة التكاملية (I)، مع تعزيز الأداء من خلال خاصية التكيف في المنطق الضبابي. أظهرت نتائج المحاكاة باستخدام MATLAB/Simulink تحسناً ملحوظاً في تتبع السرعة، وتقليل التجاوز، وزيادة المتانة مقارنةً بالمتحكم التقليدي PI.

الكلمات المفتاحية: MADA، التحكم الضبابي، المتحكم PD+I، التحكم في السرعة، التحكم المتجهي.