People's Democratic Republic of Algeria
Ministry of Higher Education
Mohamed Khider University of Biskra
Faculty of science and Technology
Department of Electrical Engineering

MASTER THESIS

Sciences and Technologies
Electrotechnical Engineering
Renewable Energy

Ref:

Presented and supported by:

Yahia BOUHSI

A Comparative Study Between Scalar Control and Rotor Field-Oriented Control Techniques on Induction Motors

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Signature Favorable opinion of the Jury President

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بسم الله الرحمن الرحيم

Abstract

Electric motors are essential parts of modern technology. Induction motors, especially squirrel cage induction motors (SCIM), are among the most used types since they are strong, easy to use, and can do a lot of different things. However, because these motors don't behave in a straight line, it's hard to regulate them well. This study aims to compare two primary control strategies for SCIM: Scalar Control and Field-Oriented Control (FOC). Scalar Control, although cost-effective and simple, struggles with dynamic performance under varying loads. On the other hand, FOC uses extensive mathematical modeling to give exact control over speed and torque. This makes it suitable for changing conditions, but it costs more in terms of computing power and money. The study uses MATLAB/ SIMULINK simulations to compare the two methods, looking at how well they work, how accurate they are, how stable they are, and how hard they are to execute. Ultimately, this work provides a comprehensive analysis for engineers and researchers, guiding the development of more efficient motor control systems.

Keywords: Squirrel Cage Induction Motor (SCIM), Scalar Control, Field Oriented Control (FOC), Torque Control, Dynamic Performance, Simulation Analysis.

Résumé

Les moteurs électriques sont des composants essentiels de la technologie moderne, et parmi eux, les moteurs asynchrones — en particulier les moteurs asynchrones à cage d'écureuil (SCIM) — sont les plus utilisés en raison de leur durabilité, de leur simplicité et de leur polyvalence opérationnelle. Cependant, leur commande efficace présente des défis en raison de leur comportement non linéaire. Cette étude vise à comparer deux stratégies de commande principales pour les SCIM : la commande scalaire et la commande orientée champ (FOC). La commande scalaire, bien qu'économique et simple, montre des limites en matière de performances dynamiques sous des charges variables. En revanche, la FOC permet un contrôle précis de la vitesse et du couple grâce à un modèle mathématique complexe, ce qui la rend adaptée aux conditions dynamiques, mais avec un coût computationnel et financier plus élevé. La recherche évalue les deux méthodes à l'aide de simulations MATLAB/ SIMULINK, en examinant leur performance, leur précision, leur stabilité et la complexité de leur mise en œuvre. Ce travail fournit finalement une analyse complète à l'intention des ingénieurs et chercheurs, afin de guider le développement de systèmes de commande de moteurs plus efficaces.

Mots-clés : Moteur asynchrone à cage d'écureuil, Commande scalaire, Commande orientée champ, Contrôle du couple, Performance dynamique, Analyse par simulation

الملخص

تُعدّ المحركات الكهربائية من المكونات الأساسية في التكنولوجيا الحديثة، وتُعدّ المحركات الحثية — وخاصة المحركات الحثية ذات القفص السنجابي— (SCIM) من بين أكثرها استخدامًا بفضل متانتها وبساطتها وتعدد استخداماتها التشغيلية. ومع ذلك، فإن التحكم الفعال بهذه المحركات يواجه تحديات بسبب سلوكها غير الخطي. تهدف هذه الدراسة إلى مقارنة استراتيجيتين رئيسيتين للتحكم في محركات :SCIM التحكم السلمي (القياسي) والتحكم الموجه بالمجال .(FOC) فرغم أن التحكم السلمي يتميز بالبساطة وانخفاض التكلفة، إلا أنه يفتقر إلى الأداء الديناميكي الجيد عند تغير الأحمال. بالمقابل، يوفر التحكم الموجه بالمجال دقة عالية في التحكم في السرعة والعزم من خلال نماذج رياضية معقدة، مما يجعله مناسبًا للظروف التشغيلية الديناميكية، لكنه يتطلب موارد حسابية ومالية أكبر. تُقيّم هذه الدراسة الطريقتين من خلال المحاكاة باستعمال MATLAB/ SIMULINK، من حيث الأداء، والدقة، والاستقرار، وتعقيد التنفيذ. وتقدم في النهاية تحليلاً شاملاً يفيد المهندسين والباحثين، ويساعدهم على تطوير أنظمة تحكم أكثر كفاءة للمحركات الكهربائية.

الكلمات المفتاحيةً: المحرك الحثي ذو القفص السنجابي. التحكم السلمي (القياسي)، التحكم الموجه بالمجال، التحكم في العزم، الأداء الديناميكي، التحليل باستخدام المحاكاة

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I hereby express my deepest gratitude to all the staff of Mohamed Khider University of Biskra and the team of the Electrical Engineering Department. They did not hesitate to provide me with all the educational resources contributing to the success of this modest research work.

Thanks to all my teachers for their help from my first day of school until now.

This is a modest thank you to my family. They have been a constant source of encouragement, support, and joy, especially my father, who has always taken care of me from the youngest age until now. May God protect him and prolong his life.

I offer my heartfelt apologies and extend my gratitude to those I may have overlooked!

Dedication

***T**o my dear parents, whose unconditional love and support have been my guiding light.*

***I** am deeply grateful to my family for their unwavering patience and encouragement throughout this journey.*

***T**o my professors and academic mentors, thank you for your wisdom and guidance.*

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***I** am grateful to everyone who had faith in me during my moments of self-doubt.*

***T**his work is a reflection of your influence and inspiration.*

Yahia

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SYMBOLS AND ABBREVIATION S

SYMBOLS

- **Electrical Quantities:**

V: Voltage (supply voltage or stator voltage)
I: Current (stator current or rotor current)
I_s: Stator current
I_r: Rotor current
R_s: Stator resistance
R_r: Rotor resistance
X_s: Stator reactance
X_r: Rotor reactance
Z_s: Stator impedance ($Z_s = R_s + jX_s$)
Z_r: Rotor impedance ($Z_r = R_r + jX_r$)
f: Supply frequency (Hz)
ω: Angular frequency ($\omega = 2\pi f$)
s: Slip (ratio of slip speed to synchronous speed)
E: Induced EMF (electromotive force)

- **Magnetic Quantities:**

B: Magnetic flux density
φ: Magnetic flux
φ_s: Stator magnetic flux
φ_r: Rotor magnetic flux

- **Mechanical Quantities:**

T: Torque (developed torque)
T_{em}: Torque electromagnetic (developed torque)
T_{max}: Maximum torque
T_r: load torque
T_s: Starting torque
N: Rotor speed (RPM)
N_s: Synchronous speed (RPM)
Ω_s: Mechanical angular velocity (rad/s)
ω_s: Synchronous electrical angular velocity (rad/s)

- **Motor Parameters:**

p: Number of poles
L_m: Magnetizing inductance
L_s: Stator inductance
L_r: Rotor inductance
k: Coupling coefficient

- **Efficiency and Performance:**

η: Efficiency of the motor
cosϕ: Power factor

ABBREVIATIONS

IM: Induction Motor
SC: Scalar Control
FOC: field Oriented Control
v/f: Voltage to Frequency Ratio
SCIM: Squirrel Cage Induction Motor
DC: Direct Current
AC: Alternating Current
RMF: Rotating Magnetic Field
PWM: Pulse Width Modulation
DTC: Direct Torque Control
PI: Proportional Integral
VSI: Voltage Source Inverter
RMS: Root Mean Square
IGBTs: Insulated Gate Bipolar Transistors
DSP: Digital Signal Processor
SVM: Space Vector Modulation

GENERAL INTRODUCTION

General introduction

Since the advent of the electric motor, it has become an integral part of everyday life, powering everything from smartphones to airplanes, ships, cars, construction machinery, and even educational tools. In our daily routines, we use various types of motors based on specific needs, locations, and circumstances. However, one particular kind of motor stands out as the most widely used in practical and everyday applications: the induction motor.

Induction motors, especially squirrel cage induction motors (SCIM), are now essential parts of many industrial and commercial applications. These motors are the best choice for many electrical systems since they are simple to build, last a long time, can work in various circumstances, and have better safety regulations than other types. However, controlling the magnetic flux, speed, and torque of these motors presents a significant challenge due to their nonlinear characteristics and complex dynamics. [1]

A lot of approaches, methodologies, research papers, and scientific publications have come out in this sector to help control the behavior, efficiency, speed, and torque of induction motors in different situations. Scalar regulation and Field-Oriented Control (FOC) are two of the most critical ways to regulate induction motors in this situation. Scalar control is one of the earliest ways to regulate induction motors. It changes speed by changing voltage and frequency separately. This method is easy to use and cheap; however, it doesn't work well when the load or speed changes quickly.

Conversely, field-oriented control (FOC), despite being relatively older, continues to be one of the most sophisticated and extensively employed methodologies in this domain. It facilitates the autonomous regulation of the motor's currents—namely, the magnetic and torque components—allowing for accurate control of speed and torque, even in dynamic operating situations. This method uses complicated mathematical changes to tell the difference between the magnetic current and the torque-producing current. This makes it pricier and time-consuming, but it is much better at performance and accuracy. [2]

The objective of this study is to thoroughly compare Scaled Control with Field-Oriented Control in squirrel cage induction motors, focusing on their performance in terms of accuracy, dynamic response, stability, and programming difficulty. In this thesis, Chapter I will provide an overview of squirrel cage induction motors, including their operating principles, electrical and mechanical characteristics, and the challenges associated with their control.

Chapter II will also detail Scaler Control and analyses its performance under various operating conditions. It will discuss the advantages and disadvantages of this technique and present simulation results that demonstrate its effectiveness in controlling this type of motor.

Chapter III will examine Field Orientated Control (FOC), clarifying the mathematical and physical foundations that underpin this technique. This will elucidate how FOC distinguishes between the magnetic current and the torque-generating current, along with the essential mathematical transformations. The performance of this technique will be evaluated through numerical simulations, comparing it to Scalar Control in terms of precision and responsiveness to changes in load and speed.

In the final Chapter, this study seeks to give a complete picture of how to control induction motors with squirrel cages, focusing on the main differences between scalar and field-oriented control. Researchers, engineers, students, and professionals in the field of electrical control systems will find this study to be a helpful reference. It will help them make better and more efficient control systems in the future.

CHAPTER I

THEORY OF SQUIRREL CAGE INDUCTION MOTORS

Chapter I : Theory of squirrel-cage Induction Motors

I.1 Introduction

The study focuses on understanding the physics and electromagnetic phenomena in induction motors, specifically Squirrel Cage Induction Motors (SCIM).

It begins by analyzing SCIM's physical structure and main components, including the rotor and stator. Then, it examines the fundamentals of electromagnetism to clarify how electrical energy is transformed into mechanical energy, which causes the rotor to rotate.

A comprehensive mathematical model of SCIM is developed to represent its electrical, magnetic, and mechanical behavior under dynamic conditions. Park and Clarke transformations are also used in the study to convert electrical quantities from a three-phase system (a-b-c) to a two-phase system (α-β). Through the use of different control strategies, the results improve performance and advance our understanding of SCIM's design and operation.

I.2 Definition

Induction motors are among the most widely used types of electric motors in industrial applications. This popularity can be attributed to their simple design, high efficiency, and low manufacturing and maintenance costs. The operation of induction motors is based on the principle of electromagnetic induction, in which a rotating magnetic field induces currents in the rotor, generating torque that drives the motor.

The squirrel-cage induction motor is the most commonly used type, recognized for its simple construction and high reliability. This motor consists of a stator with copper windings powered by a three-phase alternating current, and a rotor composed of conductive bars arranged in parallel and connected at the ends by rings, giving it a distinctive cage-like appearance. [1]

Below is a description of squirrel-cage induction motors, including their components, fundamental electromagnetic phenomena, and the differential equations that govern their behavior.

I.3 A historical overview of induction motors

The development of induction motors began with **Michael Faraday**'s discovery of the principles of **electromagnetic induction** in **1831**, followed by **James Clerk Maxwell**'s formulation of the laws of electricity in **1860**, laying the foundation for this technology.

By the late 19th century, both **Galileo Ferraris** in **1885** and **Nikola Tesla** in **1886** independently developed induction motor designs. **Ferraris**' design featured a rotor made of a copper cylinder, whereas **Tesla** used a ferromagnetic cylinder with a short-circuited winding. Despite the differences in materials, the fundamental principles of both designs were quite similar. Later, **George Westinghouse** obtained Tesla's patents, enabling him to develop a practical induction motor in **1892**, a model that has retained its core principles despite continuous improvements in performance and design.

In **1896**, **General Electric** and **Westinghouse** signed a cross-licensing agreement for the **squirrel cage** induction motor design. By the beginning of the **20th century**, this design had become a fundamental component of industrial applications. By **1910**, electric trains in Europe began using induction motors, allowing them to achieve speeds exceeding **200 km/h**.

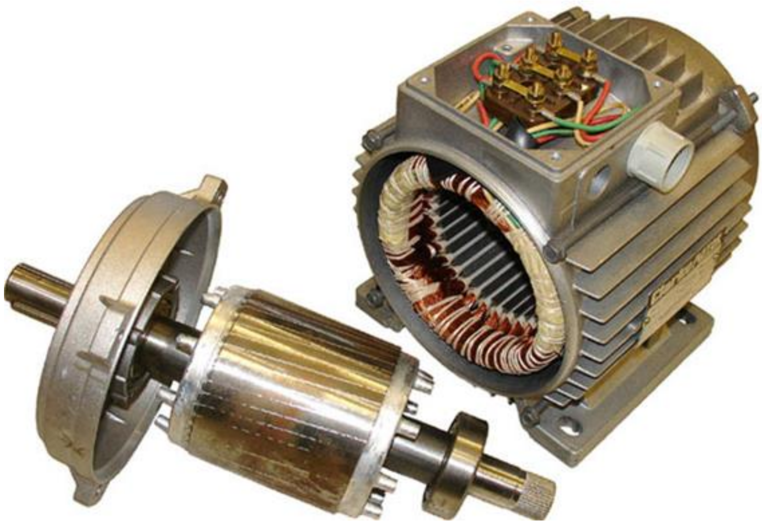
However, **DC motors** developed rapidly, surpassing **induction motors** in industrial and transportation applications for some time. Nonetheless, induction motors regained popularity in 1985 due to advances in power electronics, particularly the development of IGBT-based inverters and Pulse Width Modulation (PWM) techniques, which improved frequency control efficiency and reduced energy losses.

Thanks to these advancements, induction motors continue to play a crucial role in various industries, making them one of the most essential technologies in modern electrical systems.

I.4 Principle of Operation of the Squirrel Cage Induction Motor

I.4.1 Design of the Induction Motor

The induction motor consists of two main parts: **Stator** and **rotor** [2]



I.1: Three-phase induction motor squirrel cage. [3]

I.4.1.1 The stationary part of SCIM (STATOR)

The stator is constructed from multiple thin laminations of aluminum or cast iron, which are precisely punched and tightly clamped together to form a hollow cylindrical structure known as the stator core. This core features evenly spaced slots along its inner periphery. Insulated wire coils are inserted into these slots, and each group of coils, along with the surrounding core, forms an electromagnet (or a pair of poles) when an alternating current (AC) supply is applied. The internal configuration of the stator windings determines the number of poles in an AC induction motor. These windings are directly connected to the power source and are internally constructed in such a way that when powered by alternating current (AC), they generate a revolving magnetic field. This rotating magnetic field is required for the operation of the induction motor because it induces currents in the rotor, allowing the motor to generate torque and rotate. [2]

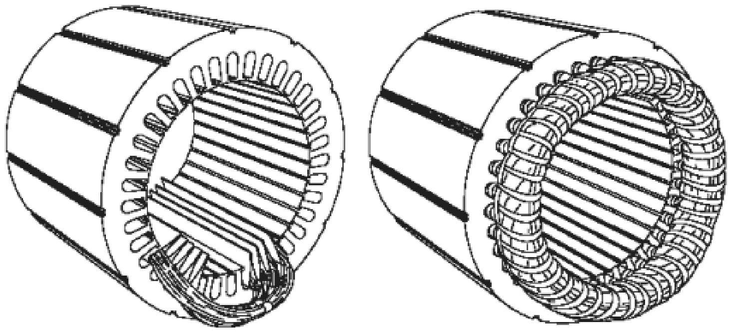


Fig I.2 : A typical stator. [1]

I.4.1.2 The moving part of SCIM (Rotor)

The squirrel cage rotor is constructed from thin steel laminations that are assembled to form a cylindrical core featuring parallel slots cut along its periphery to accommodate bars typically made of aluminum or copper. These bars are joined on both ends by end rings, providing a closed electrical circuit. This basic and sturdy design gives the rotor its distinguishing appearance, like a squirrel cage, thus the name. The rotor is differentiated by the absence of brushes, slip rings, and external electrical connections, making it easy to produce, low-maintenance, and highly reliable. This type of rotor is known for its high starting torque; however, it also draws a significant starting current, making it suitable for large industrial applications. [2]

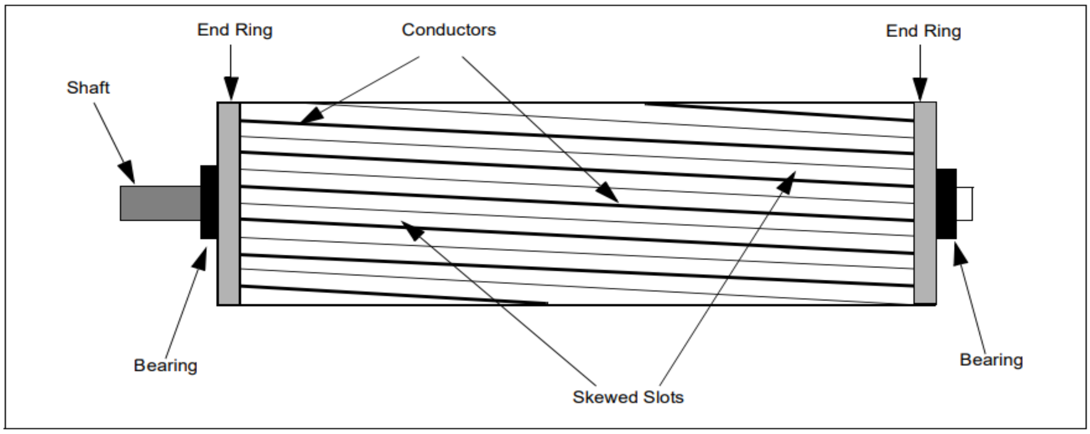


Fig I.3: A typical squirrel cage rotor. [1]

I.4.2 Generation of the Rotating Magnetic Field

When alternating current is applied to three-phase induction motor's stator windings, each phase generates a time-varying magnetic field. Due to the 120-degree phase difference between the three currents, these magnetic fields interact to create a magnetic field that rotates. This revolving field generates currents in the rotor. Which in turn produces torque and converts electrical energy into mechanical energy. The direction of rotation is determined by the sequence of the three electrical phases, while the speed of the rotating field is influenced by the frequency of the alternating current and the number of pole pairs in the motor. [4]

The magnetic fields produced by each phase can be represented as follows:

$$B_A = B_m \sin(\omega t)$$

$$B_B = B_m \sin\left(\omega t - \frac{2\pi}{3}\right)$$

$$B_C = B_m \sin\left(\omega t - \frac{4\pi}{3}\right)$$

Where:

B_A, B_B, B_C are the magnetic fields produced by phases A, B, and C, respectively.

B_m: is the maximum amplitude of the magnetic field.

ω: is the angular frequency of the current ($\omega = 2\pi f$),

where f: is the frequency of the alternating current.

By summing these magnetic fields, a rotating magnetic field with a constant direction and speed is produced. The resultant magnetic field can be expressed as a vector sum:

$$\vec{B} = \overrightarrow{B_A} + \overrightarrow{B_B} + \overrightarrow{B_C} \qquad (I.1)$$

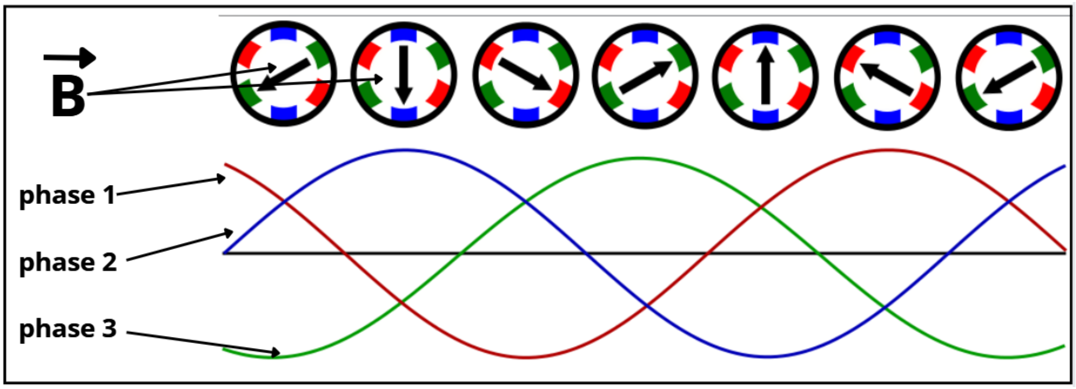


Fig I.4: Rotating Magnetic field (RMF) in SCIM [5]

- **Synchronous Speed (N_s)**

The speed of the rotating magnetic field is known as the synchronous speed (N_s), which depends on the frequency of the alternating current and the number of pole pairs in the motor. The relationship between synchronous speed, frequency (f), and the number of pole pairs (p) is given by:

$$N_s = \frac{60f}{p} \quad (I.2)$$

where:

N_s: is the synchronous speed in revolutions per minute (rpm).

f: is the frequency of the alternating current in hertz (Hz).

p: is the number of pole pairs.

I.4.3 The Effect of Magnetic Field on the Rotor in SCIM

The interaction between the magnetic field of the stator and the rotor is the foundation of the operation of electric motors, which transform electrical energy into mechanical energy using electromagnetic principles. The operation of an induction motor depends on the effect of the stator's magnetic field on the rotor to generate eddy currents and the torque resulting from this interaction.

When a rotating magnetic field is applied to the rotor, it cuts through the conductive bars of the rotor. A change in magnetic flux across a conductor generates an electromotive force (EMF) in accordance with Faraday's law of electromagnetic induction. in the conductor. Faraday's law can be expressed by the following equation: [6]

$$E = -\frac{d\Phi_B}{dt} \tag{I.3}$$

where: $\boldsymbol{E}$: is the induced electromotive force. $\boldsymbol{\Phi_B}$: is the magnetic flux.

In the case of the rotor, the cutting of the conductive bars by the magnetic field generates electric currents in the rotor, known as eddy currents. These currents, in turn, produce a magnetic field in the rotor.

The stator's magnetic field interacts with the magnetic field generated by the currents in the rotor. According to Lorentz's law, this interaction produces a torque that rotates the rotor, thereby converting electrical energy into mechanical energy.

I.4.4 The Slip in SCIM

One of the basic ideas of induction motors is the phenomenon of slip. The rotor must produce induced currents. Assembling Faraday's law of electromagnetic induction, induced currents are created when the rotor speed is lower than the synchronous speed because the magnetic field penetrates the rotor bars. Torque is created when the magnetic field created by these currents interacts with the magnetic field of the stator. [1]

Slip is the relative difference between the synchronous speed (N_s) and the rotor speed (N_r), expressed by the following equation:

$$s = \frac{N_s - N_r}{N_s} \tag{I.4}$$

where:

$\boldsymbol{S}$ **:** is slip. $\boldsymbol{N_s}$: synchronous speed (rpm). $\boldsymbol{N_r}$: rotor speed (rpm).

I.5 Fundamental Electromagnetic Phenomena

I.5.1 Electromagnetic Induction (Faraday's Law)

Assembling Faraday's Law of Electromagnetic Induction, a magnetic field that changes generates an electromotive force (EMF) in a conductor. A squirrel cage induction motor (SCIM) has a rotor made up of short-circuited conductive bars. When the stator's revolving magnetic field passes through the rotor bars, electric currents are generated in them. These currents interact with the revolving magnetic field to generate torque, which causes the motor to rotate. [6]

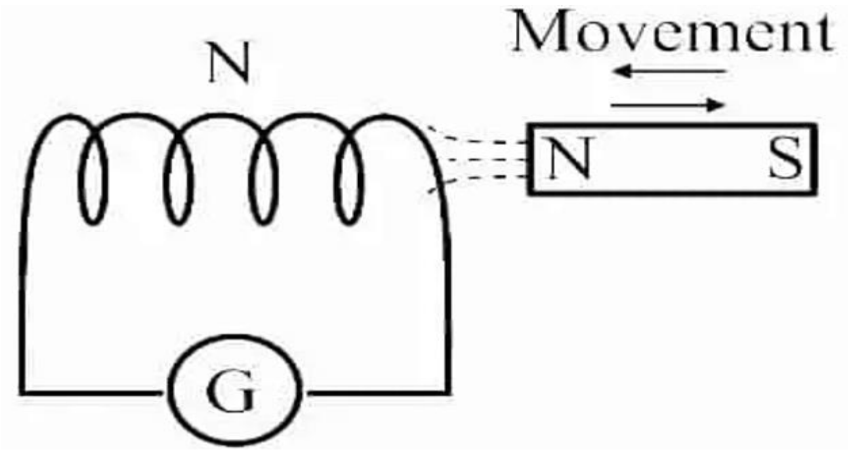


Fig I.5 : Representation of Faraday's law of electromagnetic induction

I.5.2 Lorentz's force Law

When electric currents flow through the rotor bars, these currents interact with the rotating magnetic field of the stator.

According to Lorentz's Law, the force acting on a moving charge (or a current-carrying conductor) in the presence of a magnetic field is given by the equation:

$$F = q(v \times B) \qquad (I.5)$$

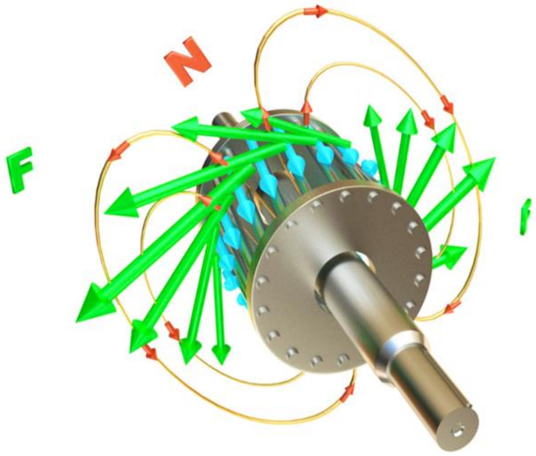


Fig I.6 : Representation of Lorentz force in SCIM. [7]

where**:**

F: is the force exerted**. q :** is the electric charge**. B**: is the magnetic field.

$\boldsymbol{v}$: is the velocity of the charge (or the velocity of the conductor relative to the magnetic field).

In the case of the motor, the equation can be simplified to:

$$F = I(L \times B) \qquad (I.6)$$

where**:**

I : is the electric current in the conductor**. B**: is the magnetic field.

L : is the length of the conductor (the rotor bars).

I.5.3 Lenz's Law

Following Lenz's Law, the induced current in a squirrel cage induction motor (SCIM) flows in the opposite direction as the change in magnetic flux that caused it. This current interacts with the revolving magnetic field to generate torque and keep the motor running smoothly, with slip happening between the rotor speed and the magnetic field. [6]

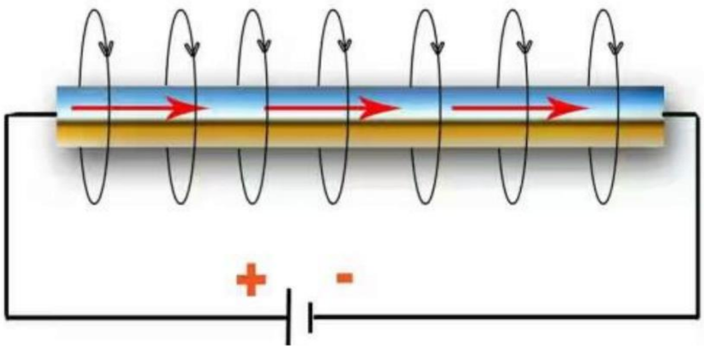


Fig I.7 : Representation Lenz's low [8]

I.6 Torque-Speed Characteristic Analysis of SCIM

I.6.1 Understanding the Torque-Speed Characteristic

The Torque-Speed Characteristic curve of a Three-Phase Induction Motor is a graphical representation that illustrates the relationship between torque and speed, and it is one of the most important aspects for understanding the performance of this type of motor. It helps in selecting the appropriate motor for a specific application and determining whether the motor can start under heavy load. Additionally, it shows the stability of performance under varying speeds and loads, and it is essential in designing speed control systems such as V/f and FOC.

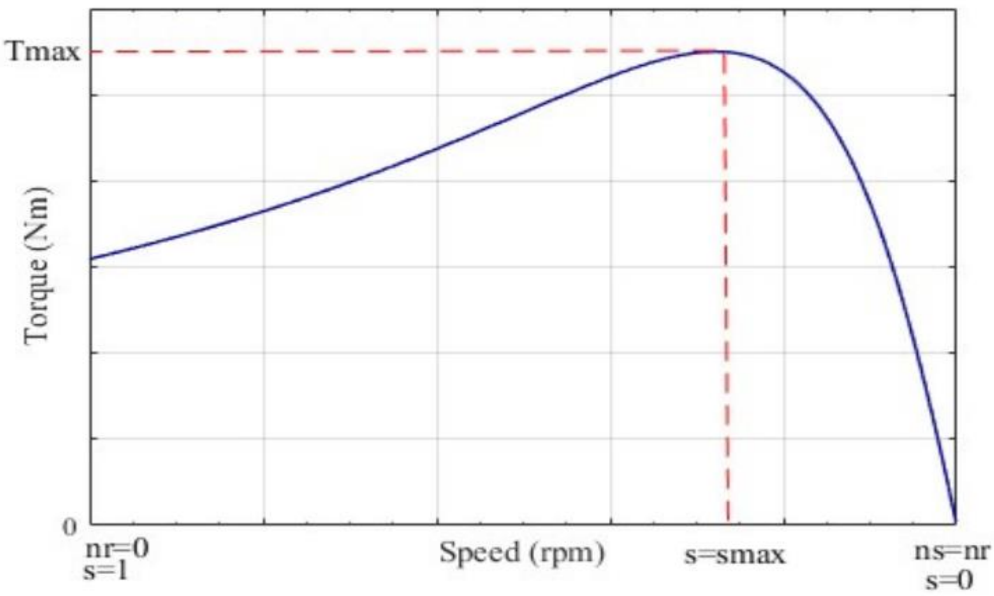


Fig I.8: Speed-torque characteristics of Induction motor [8]

Where:

1. **Horizontal axis** represents speed (typically as a percentage of synchronous speed).
2. **Vertical axis** represents torque.
3. The curve starts at zero speed (startup) and ends at the **synchronous speed (Ns)**.

I.6.2 Key Types of Torque

- **Starting Torque**: The torque produced at the moment of startup.
- **Pull-up Torque**: The minimum torque that appears during acceleration.
- **Breakdown Torque**: The maximum torque the motor can deliver without stalling.
- **Rated Torque**: The torque at which the motor operates under normal conditions (specified on the nameplate).

These torque types can be observed in the main regions of the curve:

- **Start-up Region (Speed = 0):**

Also known as the Locked Rotor Condition. In this region, the starting torque is relatively high (depending on the motor design), and the slip equals 1. The currents are very high at this stage, requiring startup precautions such as using a soft starter.

- **Acceleration Region:**

As the speed increases, the slip gradually decreases. The torque increases rapidly until it reaches its peak value, known as Maximum Torque or Breakdown Torque.

- **A Breakdown Torque:**

This is the highest point on the curve. Beyond this point, if the speed continues to increase and approaches synchronous speed, the torque begins to decline.

- **Near Synchronous Speed (Ns):**

Here, the slip is very small (Slip ≈ 0), and the torque is low because the motor cannot reach the exact synchronous speed (except for synchronous motors), but operates close to it.

I.6.3 Main Factors Affecting the Motor's Torque-Speed Characteristic

- **Voltage and Frequency**: Any variation in voltage or frequency will affect the curve shape.
- **Rotor Design**: The type and construction of rotor bars influence the values of starting and breakdown torque.
- **Motor Temperature**: Affects resistance and thus performance.
- **Mechanical Load**: Determines the operating point on the curve.

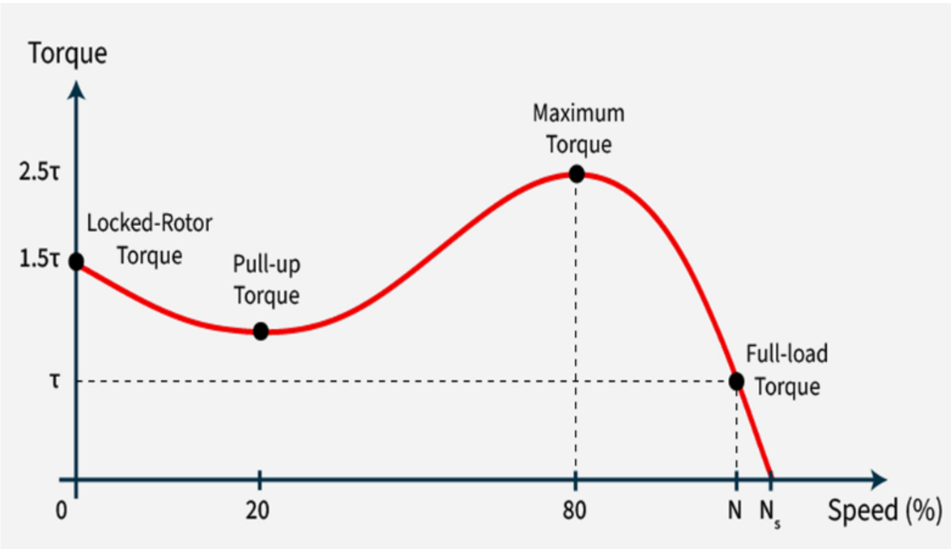


Fig I.9 : the main regions of the Characteristic curve of IM [9]

I.7 Modeling of Squirrel Cage induction motor

I.7.1 Simplifying Assumptions

To properly conduct the modeling of the machine and simplify the presentation of the basic relationships governing the operation and control strategy of the induction motor, the following simplifying assumptions must be adopted:

- **Neglecting saturation**: This allows defining the inductances.
- **Referring the rotor to the stator**: That is, it is assumed that the rotor is three-phase like the stator, and its windings have the same number of turns.
- **Assuming that the stator and rotor windings are bipolar**: And that their phases create sinusoidally distributed fluxes.
- Constant air gap.
- Negligible slot effect.
- Unsaturated magnetic circuit with constant permeability.
- Negligible ferromagnetic losses.
- The influence of skin effect and heating on the characteristics is not taken into account.

These assumptions help simplify the modeling and dynamic analysis of the induction motor.

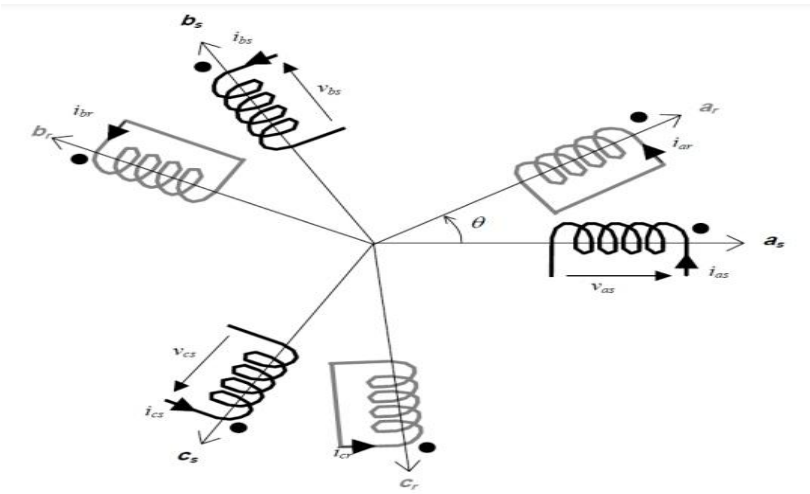


Fig I.10 : Representation of stator and rotor windings of SCIM [9]

I.7.2 Equations of the machine model

The behavior of the motor is fully determined by three main types of equations, which are:

- **Electrical equations**: Describe the relationships between voltage and current in the motor circuits.

- **Magnetic equations**: Express the magnetic interactions between the stator and the rotor.
- **Mechanical equations**: Govern the motion of the motor and the resulting torque.

These equations together form the mathematical model used to understand and analyze the performance of the motor.

Among the consequences of these assumptions, the following can be mentioned:

- Additivity of fluxes.
- Constancy of self-inductances.
- Sinusoidal variation of mutual inductances between stator and rotor windings.

I.7.2.1 Electromagnetic equations

Based on the previous assumptions, the electromagnetic equations of the machine can be written in the following matrix form:

Electromagnetic equations for stator

The stator resistance is the same for all three phases.

$$V_{sa} = R_s I_{sa} + \frac{d\varphi_{sa}}{dt}$$

$$V_{sb} = R_s I_{sb} + \frac{d\varphi_{sb}}{dt}$$

$$V_{sc} = R_s I_{sc} + \frac{d\varphi_{sc}}{dt}$$

In matrix:

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \end{bmatrix} \quad (I.7)$$

In compact form:

$$[V_s]_{a,b,c} = [R_s][I_r]_{a,b,c} + \frac{d}{dt}[\varphi_s]_{a,b,c} \qquad (I.8)$$

- **Electromagnetic equations for rotor:**

The rotor being short-circuited, its voltages are zero. $\emptyset$ φ

$$V_{ra} = 0 = R_r I_{ra} + \frac{d\varphi_{ra}}{dt}$$

$$V_{rb} = 0 = R_r I_{rb} + \frac{d\varphi_{rb}}{dt}$$

$$V_{rc} = 0 = R_r I_{rc} + \frac{d\varphi_{rc}}{dt}$$

In matrix:

$$\begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix} \qquad (I.9)$$

In compact form:

$$[V_r]_{a,b,c} = 0 = [Rr][I_r]_{a,b,c} + \frac{d}{dt}[\varphi_r]_{a,b,c} \qquad (I.10)$$

Where:

Vs : phase voltages at the stator.

Vr : phase voltages at the rotor.

Is: the stator current.

Ir: the rotor current.

φ_s , φ_r: Stator and Rotor Magnetic Flux

I.7.2.2 Magnetic equations

All magnetic fluxes are related to the electric currents inside the machine.

The magnetic equations can be written as:

For the stator: *(I.11)*

$$\begin{bmatrix}\varphi_{as}\\ \varphi_{bs}\\ \varphi_{cs}\end{bmatrix}=\begin{bmatrix}L_s & L_{ss} & L_{ss}\\ L_{ss} & L_s & L_{ss}\\ L_{ss} & L_{ss} & L_s\end{bmatrix}\begin{bmatrix}I_{as}\\ I_{bs}\\ I_{cs}\end{bmatrix}+L_m\begin{bmatrix}\cos(\theta_r) & \cos\left(\theta_r+\frac{2\pi}{3}\right) & \cos\left(\theta_r+\frac{4\pi}{3}\right)\\ \cos\left(\theta_r+\frac{4\pi}{3}\right) & \cos(\theta_r) & \cos\left(\theta_r+\frac{2\pi}{3}\right)\\ \cos\left(\theta_r+\frac{2\pi}{3}\right) & \cos\left(\theta_r+\frac{4\pi}{3}\right) & \cos(\theta_r)\end{bmatrix}\begin{bmatrix}I_{ar}\\ I_{br}\\ I_{cr}\end{bmatrix}$$

In compact form:

$$[\varphi_s]_{a,b,c}=[L_{ss}][I_s]_{a,b,c}+[M_{sr}][I_r]_{a,b,c} \qquad (I.12)$$

For the rotor:

$$\begin{bmatrix}\boldsymbol{\varphi_{ar}}\\ \boldsymbol{\varphi_{br}}\\ \boldsymbol{\varphi_{cr}}\end{bmatrix}=\begin{bmatrix}L_r & L_{rr} & L_{rr}\\ L_{rr} & L_r & L_{rr}\\ L_{rr} & L_{rr} & L_r\end{bmatrix}\begin{bmatrix}I_{ar}\\ I_{br}\\ I_{cr}\end{bmatrix}+L_m\begin{bmatrix}\cos(\theta_r) & \cos\left(\theta_r-\frac{2\pi}{3}\right) & \cos\left(\theta_r+\frac{2\pi}{3}\right)\\ \cos\left(\theta_r+\frac{2\pi}{3}\right) & \cos(\theta_r) & \cos\left(\theta_r-\frac{2\pi}{3}\right)\\ \cos\left(\theta_r-\frac{2\pi}{3}\right) & \cos\left(\theta_r+\frac{2\pi}{3}\right) & \cos(\theta_r)\end{bmatrix}\begin{bmatrix}I_{as}\\ I_{bs}\\ I_{cs}\end{bmatrix}$$

(I.13)

In compact from:

$$[\varphi_r]_{a,b,c}=[L_{rr}][I_r]_{a,b,c}+[M_{rs}][I_s]_{a,b,c} \qquad (I.14)$$

Where:

$$[M_{sr}]=[M_{rs}]^t=L_m\begin{bmatrix}cos\theta & cos\left(\theta+\frac{2\pi}{3}\right) & cos\left(\theta-\frac{2\pi}{3}\right)\\ cos\left(\theta-\frac{2\pi}{3}\right) & cos\theta & cos\left(\theta+\frac{2\pi}{3}\right)\\ cos\left(\theta+\frac{2\pi}{3}\right) & cos\left(\theta-\frac{2\pi}{3}\right) & cos\theta\end{bmatrix} \qquad (I.15)$$

$$[L_S] = \begin{bmatrix} L_s & L_{ss} & L_{ss} \\ L_{ss} & L_s & L_{ss} \\ L_{ss} & L_{ss} & L_s \end{bmatrix} \textit{ Stator winding matrix} \tag{I.16}$$

$$[L_r] = \begin{bmatrix} L_r & L_{rr} & L_{rr} \\ L_{rr} & L_r & L_{rr} \\ L_{rr} & L_{rr} & L_r \end{bmatrix} \textit{ rotor winding matrix} \tag{I.17}$$

Where:

L_s : inductance of a single winding for stator.

L_r : inductance of a single winding for rotor.

L_{ss} : Mutual inductance of coupling between stator windings.

L_{rr} : Mutual inductance of coupling between rotor windings.

L_m : Mutual inductance of coupling between rotor windings.

θ : The angle between the rotor axes and the stator axes.

Electrical equations:

$$[V_{sabc}] = [R_s][I_{sabc}] + \frac{d}{dt}([L_s][I_{sabc}] + [M_{sr}][I_{rabc}]) \tag{I.18}$$

$$[V_{rabc}] = [R_r][I_{rabc}] + \frac{d}{dt}([L_r][I_{rabc}] + [M_{rs}][I_{sabc}]) \tag{I.19}$$

I.7.2.3 Mechanical equations:

Several elements influence the motor's reaction and dynamic behavior, including inertia, torque, and friction. These parameters are critical for creating control systems and assessing motor performance under various operating situations. The mechanical dynamic equation combines all of these components. The mechanical dynamics of the squirrel-cage induction motor can be represented by the mechanical equation below:

$$T_{em} - T_d = J\frac{d\Omega}{dt} + f\Omega \tag{I.20}$$

So:

$$T_{em} - T_d = \frac{J}{p}\frac{d\omega}{dt} + f\,\frac{\omega}{p} \tag{I.21}$$

Cause the electrical angular speed of the rotor is:

$$\omega = p \cdot \Omega \tag{I.22}$$

Where:

J : is the moment of inertia of the motor, [Kgm^2].

f : is coefficient of friction [Nm / rad/s].

Ω : Mechanical angular velocity of the rotor, [rad/s].

ω : Electrical angular velocity of the rotor, [rad/s].

p : The number of pole pairs.

T_{em} : is the electromagnetic torque, [Nm].

T_r : is the mechanical load torque acting on the motor [Nm].

This mechanical equation illustrates that the rotor's angular acceleration is determined by the difference between the electromagnetic torque and the load torque, along with the effects of friction. When the motor reaches a steady-state condition, the electromagnetic torque becomes equal to the sum of the load torque and the friction torque, resulting in a constant angular speed... [10]

I.8 Advantages and Disadvantages of Squirrel Cage Induction Motor

I.8.1 Advantages of Squirrel Cage Induction Motor (SCIM)

1. Uncomplicated and Resilient Design:

- The absence of brushes and commutators means that fewer components are susceptible to wear.

- Endures harsh environments and mechanical strain.

2. Minimal Expense and Upkeep:

- Cost-effective to produce. - It requires less maintenance compared to wound rotor motors.

3. Exceptional Reliability:

- Extended service life attributed to a reduced number of moving components and robust rotor architecture.

4. Autonomous Initiation Capability:

- Initiates immediately upon connection to a power supply, particularly with Direct-On-Line (DOL) or star-delta starters.

5. High Efficiency:

- Exceptional efficiency under medium- to high-load settings.

6. Compact and lightweight:

- The dimensions are reduced for a specific power rating compared to other types.

7. Appropriate for Adverse Conditions:

- Exhibits optimal performance in dusty, humid, and corrosive environments, particularly when adequately enclosed.

I.8.2 Disadvantages of Squirrel Cage Induction Motor

1. Poor speed control (without sophisticated drives):

- The speed is primarily set and depends on the frequency of the supply.
- For exact control, you need Variable Frequency Drives (VFDs) or FOC methods.

2. Low Starting Torque (in standard form):

- Basic SCIMs don't have a lot of beginning torque, but there are high-slip variants that do.

3. High Starting Current:

- It can draw 5–7 times the rated current when it starts up, which may require big starters.

4. No Access to External Rotor:

- The rotor can't be reached for external resistance insertion, unlike wound rotor motors.

5. Less performance when the load is light:

- At low loads, the power factor and efficiency tend to be lower.

I.9 Conclusion

This chapter provided a theoretical overview of squirrel cage induction motors, highlighting its construction, operating principles, and equivalent circuit model. Emphasis was placed on how electromagnetic induction enables torque production without electrical connection to the rotor. The simplicity, robustness, and low maintenance needs of this motor make it widely suitable for industrial applications.

Chapter II

Scalar Control (V/F)- Modeling and Performance Study

Chapter II : Scalar Control (v/f) - Modeling and performance study

II.1 Introduction

This chapter focuses on analyzing selected control techniques for three-phase induction motors within a closed-loop system. It addresses linear scalar control (V/f). The role of the three-phase inverter as a power supply source is also discussed, along with PWM signal generation methods (such as SPWM and Hysteresis PWM) to ensure signal quality.

II.2 Comprehensive Overview of Induction Motors Control

Designing an effective control system for three-phase induction motors requires consideration of several technical factors, including magnetic flux stability, dynamic system response, load variation tolerance, and energy conversion efficiency. A significant factor in the development of electromagnetic torque is magnetic flux, which presents a significant difficulty since torque is directly related to both flux and active current. Meanwhile, speed has an indirect effect on torque. As a result, any change in speed has the potential to upset the torque and create an unstable magnetic flux. it would reduce the dynamic performance of the motor, which is undesirable. [2]

The main objective is to maintain a constant magnetic flux while varying the motor speed, ensuring balanced and accurate torque response, and minimizing losses caused by magnetic saturation or weak magnetization.

Electromagnetic torque in induction motors is directly proportional to both magnetic flux and speed. As a result, variations in speed cause variations in torque, which in turn impact the flux. The employment of sophisticated control techniques, like scalar control (V/f) or (FOC) Control, which seek to decouple these variables and allow separate control of torque and flux, is required due to this high interdependence. [11]

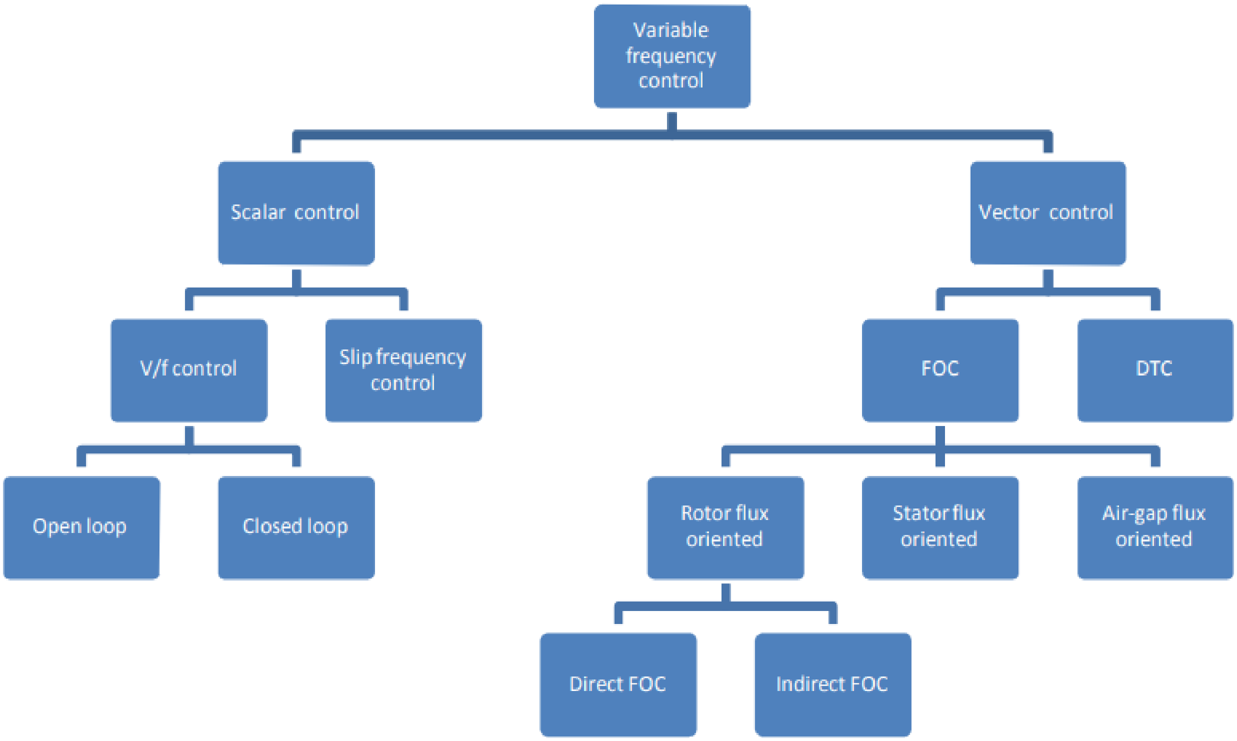


Fig II.1: Representation of control systems in three-phase machine. [12]

II.3 Scalar Control Technique (V/f)

II.3.1 History of Peaceful Control (v/f)

In the 1960s, the voltage-to-frequency ratio control approach, often known as the V/f control technique, began to develop as a straightforward method for managing the speed of induction motors. At that time, more recently developed control methods, such as vector control, were still in the preliminary stages of development.

When power electronics advanced in the 1980s, V/f control became widely used. It was because of its cost and ease of use. As a result, it became an acceptable choice for low-precision control applications, such as fans and pumps.

V/f control is still commonly employed in applications that require straightforward and economical speed control, although more sophisticated control approaches have emerged in recent years.

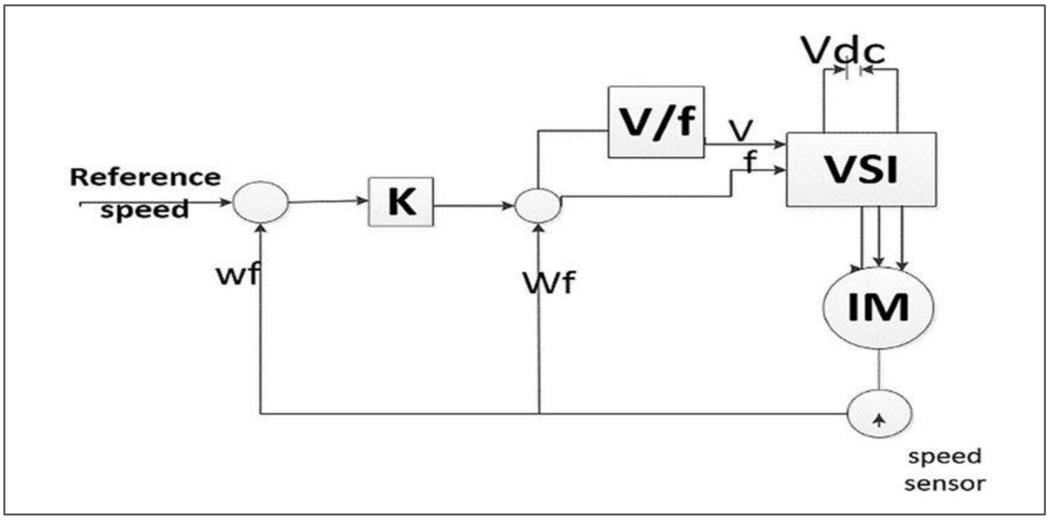


Fig II.2 : Scalar Control Technique (V/f) [13]

II.3.2 The Basic Principle of Scalar Control

Scalar control (V/F control) is considered one of the simplest control techniques for electric motors. This method relies on controlling scalar quantities such as voltage and frequency without considering vector directions or the instantaneous phase of voltages or currents.

One fundamental principle for the proper operation of the induction motor is to maintain a constant magnetic flux in the stator. In induction motors, the magnetic flux is the main factor responsible for generating the electromechanical torque. Any disturbance in maintaining constant flux can lead to undesirable variations in motor performance, such as torque pulsations or increased power consumption. [14]

The motor can efficiently generate the necessary torque without experiencing excessive energy loss or overheating while the magnetic flux is kept constant because its inductive reactance stays within safe bounds. To do this, V/F control systems use an algorithm that maintains a consistent voltage-to-frequency ratio by adjusting the voltage in reaction to frequency changes.

II.3.3 The Relationship Between Voltage and Frequency (V/f)

The scientific basis of the scalar control method is to maintain a constant ratio between the voltage applied to the windings of the induction motor and the electrical frequency supplied to it, meaning that:

$$\Phi \propto \frac{V}{f} \tag{II.1}$$

Where:

Φ: is the magnetic flux in the motor's magnetic circuit.

$\boldsymbol{V}$: is the applied electrical voltage.

$\boldsymbol{f}$: is the electrical frequency.

Maintaining this ratio stabilizes the magnetic flux inside the motor. As long as the frequency stays below a threshold that would diminish excitation, maintaining this flux allows the motor to produce a constant and stable torque at a range of operating speeds.

In order to reduce speed, the frequency must be lowered, which requires a commensurate drop in voltage. Imagine lowering the frequency without lowering the voltage. The motor's temperature will rise as a result of magnetic saturation and an increase in produced currents caused by an excessive increase in magnetic flux. On the other hand, lowering the voltage without correspondingly lowering the frequency will cause the magnetic flux to drop, which will lower the torque that is produced. [8]

II.3.4 Proof of the method for obtaining

$$\overrightarrow{V_s} = R_s I_s + \frac{d\overrightarrow{\varphi_s}}{dt} + j\omega_k \overrightarrow{\varphi_s} \tag{II.2}$$

At high speeds, the voltage drops across the stator becomes very small compared to the total voltage supplied to the motor. Therefore, the voltage drops across the resistance can be neglected, and the equation becomes as follows: [15]

$$\vec{V_s} = \frac{d\vec{\varphi_s}}{dt} + j\omega_k\vec{\varphi_s} \quad (II.3)$$

$$\omega_s = \omega + \omega_k \quad (II.4)$$

$F(d,q) \Rightarrow (\omega_k=0)$	$F(\alpha,\beta) \Rightarrow (\omega_k=\omega_s)$
$\vec{V_s} = \frac{d\varphi_s}{dt}$	$\vec{V_s} = j\omega_s\vec{\varphi_s}$
$\vec{\varphi_s} = \varphi_{max}[\cos(\omega_s t) + j\sin(\omega_s t)]$	
$\vec{V_s} = \omega_s\varphi_{max}[-\sin(\omega_s t) + j\cos(\omega_s t)]$	
$\vec{V_s} = \omega_s\varphi_{max} j[j\sin(\omega_s t) + \cos(\omega_s t)]$	
$\vec{V_s} = j\omega_s\vec{\varphi_s}$	
$\vec{V_s} = j\omega_s\vec{\varphi_s}$	
$V_s = \omega_s\varphi_s \quad \Rightarrow \quad \frac{V_s}{\omega_s} = \varphi_s$	
$\frac{V_s}{\omega_s} = \frac{V_s}{2\pi \cdot F}$	

Example:

$$\frac{V_s}{\omega_s} = \frac{V_s}{2\pi \cdot f} = \varphi_s \Rightarrow \frac{220\sqrt{2}}{2\pi \cdot 50} = \frac{311}{314} \approx 1 = \varphi_s$$

Notes:

- The relationship $\frac{V_s}{\omega_s} = \varphi_s$ holds true in both frames.
- The previous example calculates the flux value for a 220V/50Hz network.

On the other hand: [11]

under steady-state conditions, the equivalent circuit of an induction motor can be modeled as shown in the following figure.

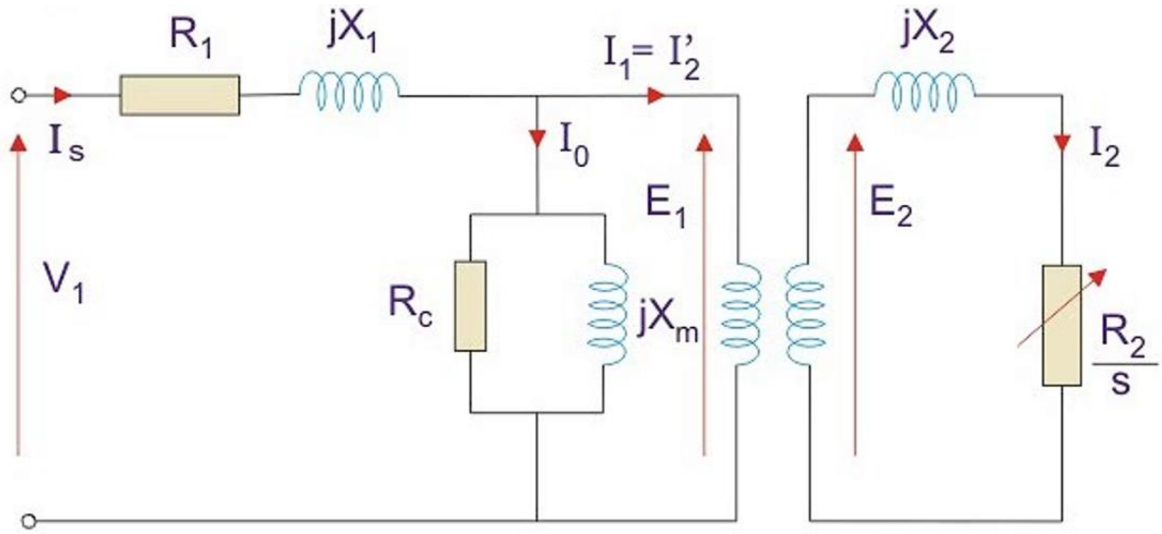


Fig II.3: Representation of induction motor. [16]

When the frequency is changed without changing the voltage, the magnetic flux is affected because:

$$V \approx E = 4.44 \cdot f \cdot N \cdot \Phi \quad (II.5)$$

Where:

$\boldsymbol{E}$: Electromotive force (EMF)

$\boldsymbol{N}$: Number of turns

II.3.5 Constant voltage and variable frequency

Therefore, if the frequency (f) increases without a corresponding increase in voltage (V), the magnetic flux (Φ) will decrease (which weakens the torque). Conversely, if the frequency decreases without reducing the voltage, the magnetic flux (Φ) will increase (which may lead to magnetic saturation).

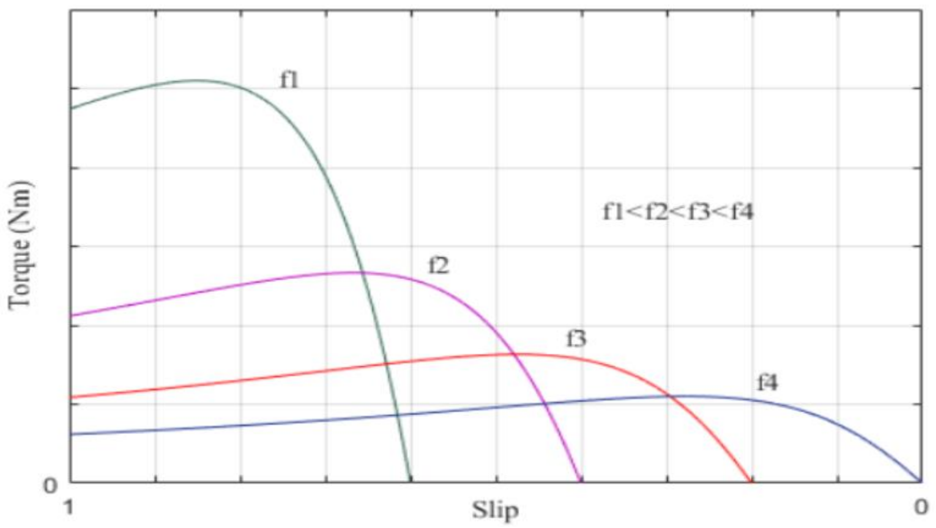


Fig II.4 : Control with V is constant and f is variable. [11]

II.3.6 Constant frequency and variable voltage

If voltage (V) increases while frequency (f) remains constant, then the magnetic flux Φ increases since $\Phi \propto V/f$.

This can cause the motor's magnetic core to enter saturation, leading to excessive magnetizing current, increased core losses, overheating, and reduced efficiency.

If voltage (V) decreases while frequency (f) remains constant, the magnetic flux Φ decreases, resulting in weaker torque production. The motor may become **unable to drive the load effectively**, especially under high-load conditions.

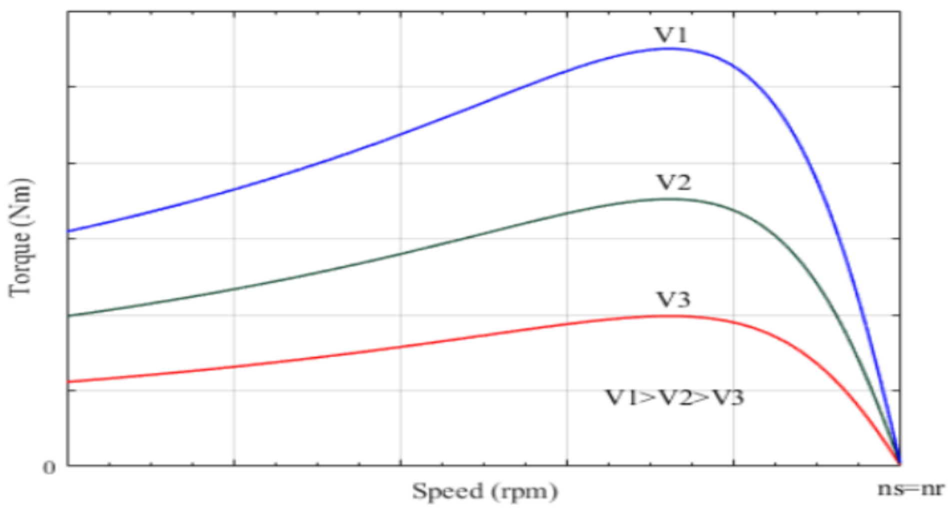


Fig II.5: Control with F is constant and V is variable. [11]

In both cases, deviating from the constant V/f ratio can negatively affect performance which is why keeping V/f constant is a key principle in scalar (V/f) control.

Therefore, the voltage and frequency must be increased or decreased together so that the torque ratio remains unaffected. [17]

Thus, from the previous relationship, there is:

$$V \approx E = 4.44 \cdot f \cdot N \cdot \Phi \tag{II.6}$$

So:

$$V = K.\Phi \tag{II.7}$$

Since the requirement is:

$$\Phi = const \tag{II.8}$$

Therefore, it must be:

$$\frac{V}{F} = const \tag{II.9}$$

If the ratio between f and V is constant, then:

$$\frac{V_1}{F_1} = \frac{V_2}{F_2} = \frac{V_3}{F_3} = \frac{V_4}{F_4} = \ const \tag{II.10}$$

As a result, the mechanical characteristics of the induction motor appear according to each value in such a way that the torque remains constant while the speed changes with the variation of (V, f).

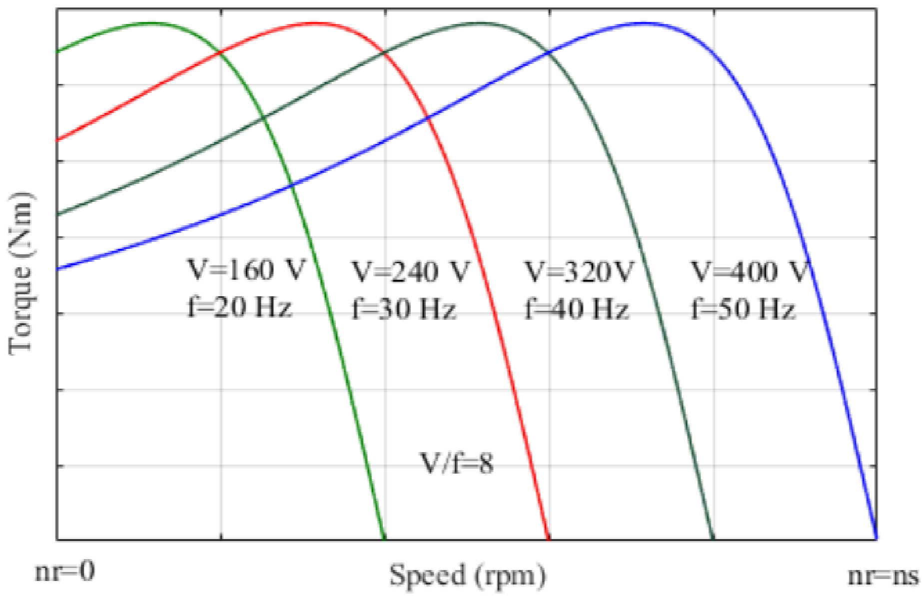


Fig II.6: Control with V/f is variable. [11]

The preceding figure illustrates that the speed transitions smoothly from rest to the rated value. Notwithstanding this exceptional performance, an issue emerges at low speeds, where sustaining maximum torque is unfeasible.

These challenges, particularly in high-dynamic applications or precision control systems, render this sort of control inadequate, as it does not directly regulate motor torque. We have noted that voltage and frequency indirectly influence the torque in this control mechanism.

To improve performance in certain situations, linear or nonlinear adjustments are added to the V/f voltage curves, especially at low speeds, to offset the loss of torque from lower voltage. The voltage equation is subsequently expressed as follows:

$$V_s = k * f + V_0 \qquad (II.11)$$

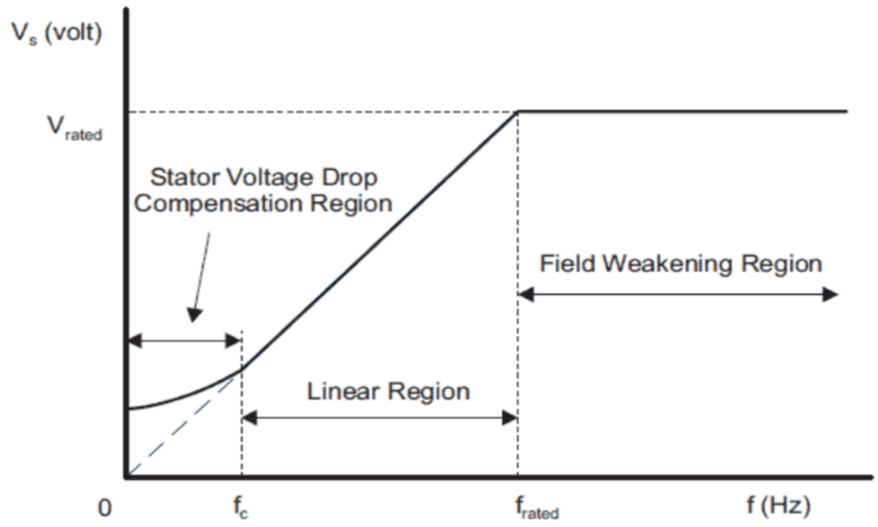


Fig II.7 : Representation of the voltage V0 in the V(f) curve. [18]

II.4 Closed loop

II.4.1 Closed-Loop Operation Mechanism

Since the closed-loop system guarantees speed stability and lessens the effect of fluctuating loads, it is essential for improving the performance of V/F control schemes. The slip phenomenon causes the motor's speed to drop with an added load. At this point, the closed-loop system intervenes by measuring this speed drop using a speed sensor and then comparing the actual speed with the desired reference speed. [19]

The PI controller determines the necessary adjustment and raises the output voltage while keeping the V/F ratio constant if a deviation is found. This process improves system stability by bringing the motor speed back to the intended level and maintaining it near the reference even when operating conditions change.

By automatically compensating for the slip, the system minimizes speed errors under varying load conditions and prevents unwanted oscillations in motor speeds.

II.4.2 Typical Closed-Loop Components

A closed-loop **V/F** control system consists of several key components that work together to ensure accurate control performance: [20]

A. Speed Sensor (Encoder/Tachometer)

A speed sensor such as an encoder or a tachometer is used to continuously measure the actual speed of the motor. The encoder typically sends digital pulses that reflect the number of motor rotations, while the tachometer produces an analog voltage proportional to speed. This data is essential for providing accurate feedback, allowing for a more responsive and stable closed-loop control system.

B. Comparator

The comparator receives the speed reference signal (the desired speed) and compares it with the actual measured value from the sensor. This process generates an "error signal," which represents the difference between the current and desired speeds. This difference is used to adjust the system’s behavior to reach the target speed efficiently.

C. Controller (PI Controller)

The controller (PI) analyzes the error signal and produces a suitable control signal to modify the frequency or voltage delivered to the motor via the inverter. In Proportional-Integral (PI) control, the proportional gain (Kp) provides an immediate response to the error, while the integral gain (Ki) addresses and eliminates steady-state mistakes over time.

D. Inverter

Modifies the output voltage and frequency based on the controller's signal to compensate for any speed deviation.

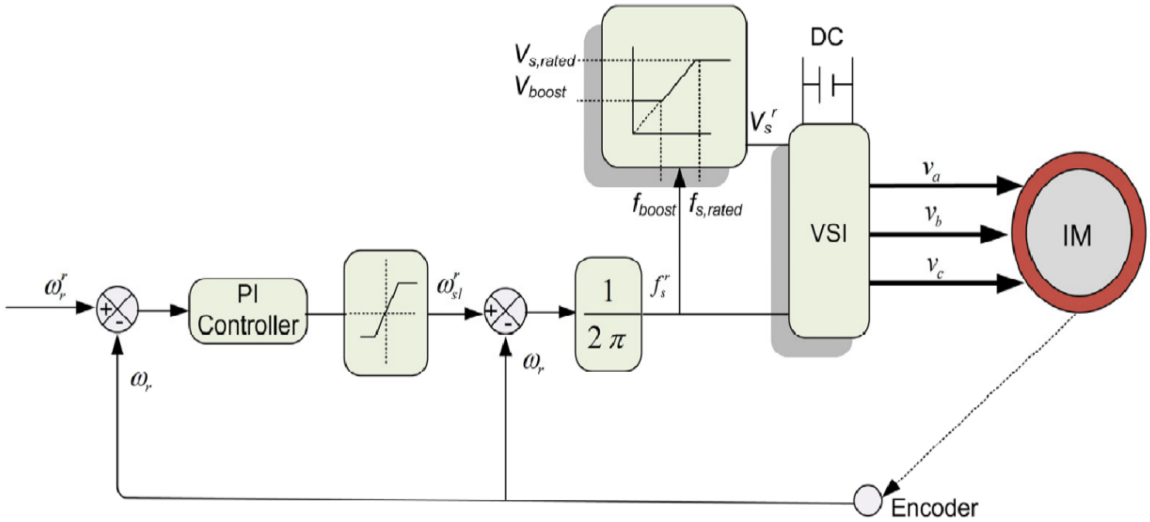


Fig II.8: Closed Loop V/F Control of Three-Phase Induction Motor. [12]

Closed-loop control is essential to improving the motor's dynamic performance in the (V/F) control system, particularly in applications that demand quick and accurate reactions to load or speed variations. This kind of control's primary purpose is to lessen the impact of slip brought on by abrupt variations in mechanical torque. If the motor speed is not controlled as the load changes, it will automatically alter, which could cause vibrations or inaccurate performance. In order to maintain a steady running speed, the controller can continuously modify the output frequency and voltage by employing feedback, which uses sensors to measure the motor's real speed and compare it with the reference speed. This feature increases system efficiency, reduces power consumption, and improves operational reliability, particularly in systems exposed to frequent changes in operating conditions. It also provides a faster and more stable response when the reference signal changes or the load varies, making closed-loop V/F control a suitable choice for medium-accuracy industrial applications.

II.5 A three-phase Voltage Source Inverter (VSI)

II.5.1 Definition

A three-phase voltage source inverter (VSI) is a device that changes and converts a steady direct current (DC) voltage into an alternating current (AC) voltage in three phases, allowing control over its frequency and shape. This type of inverter is the most commonly used for operating three-phase induction motors in motor control systems. [21]

The DC power source for the inverter may come from a battery, fuel cell, solar cell, or any other DC power source. Most industrial applications use a rectifier that takes AC power from the grid and converts it into DC to supply the inverter.

The inverter's output is controlled by adjusting the voltage (rather than directly controlling the current or frequency) using PWM (Pulse Width Modulation).

Fig II.9 : Voltage source Inverter [21]

II.5.2 VSI Components

The inverter consists of the following parts:

- **DC Voltage Source**: Such as batteries or the output of a rectifier.
- **Six Electronic Switches** (S_1 to S_6): Typically, IGBTs or MOSFETs, arranged in a three-phase bridge configuration.
- **Control Circuit**: Responsible for generating switching signals based on PWM algorithms.
- **Filter Circuit**: Usually, an LC filter is used to smooth the pulsed signals into sinusoidal waveforms

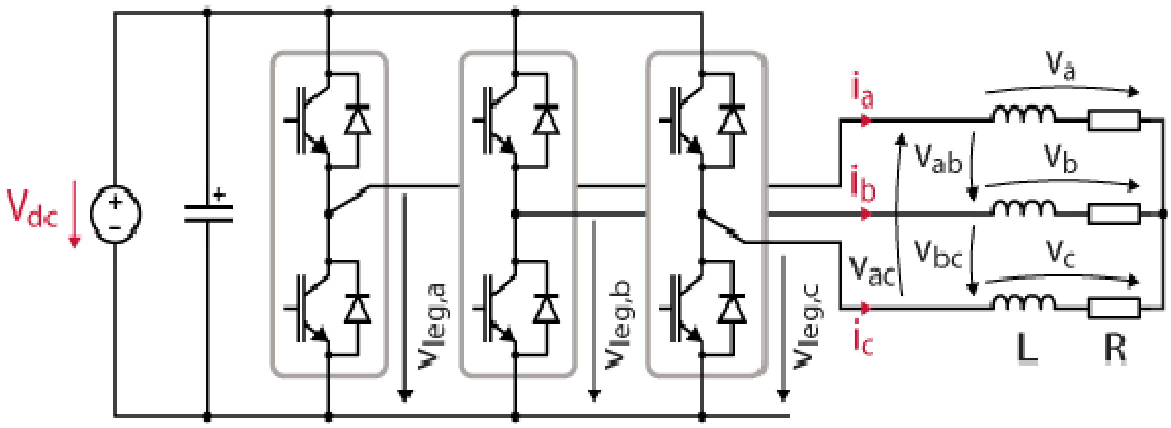


Fig II.10: Topology overview of a three-phase voltage source inverter (VSI).

II.5.3 Operating Principle of a three-phase voltage source inverter (VSI)

The inverter provides an alternating voltage across the three output terminals by turning on and off the power electrical devices. Three couples make up the transistor arrangement:

- (S1, S4) for phase A.
- (S3, S6) for phase B.
- (S5, S2) for phase C.

The 120-degree change between these phases results in a complete 360-degree pulse width cycle. Each set of switches (S1 & S4, S2 & S5, S3 & S6) controls a single phase. The upper switch conducts first to allow current flow, then goes off, while the bottom switch turns on to keep the current flowing. To avoid an internal short circuit, never operate both switches at the same time. The switching pattern creates a three-phase voltage differential.

II.5.4 Inverter Output Voltage Analysis

The output of a three-phase inverter consists of three alternating voltage signals known as phases: Va, Vb, and Vc. These signals are equal in RMS value and are phase-shifted by 120 electrical degrees from each other, forming a balanced three-phase system. Pulse Width Modulation (PWM) technology allows the formation of waveforms close to sinusoidal, which enhances motor performance and reduces losses. These signals are directly fed to induction motors or other three-phase loads, with their frequency and voltage controlled according to operational requirements, especially in V/f and Field Oriented Control (FOC) systems. The output comprises harmonics generated by the modulation process, which can be handled with proper filters. Voltage balance between phases is critical for efficient motor performance and for avoiding issues such as uneven heating or vibration. [22]

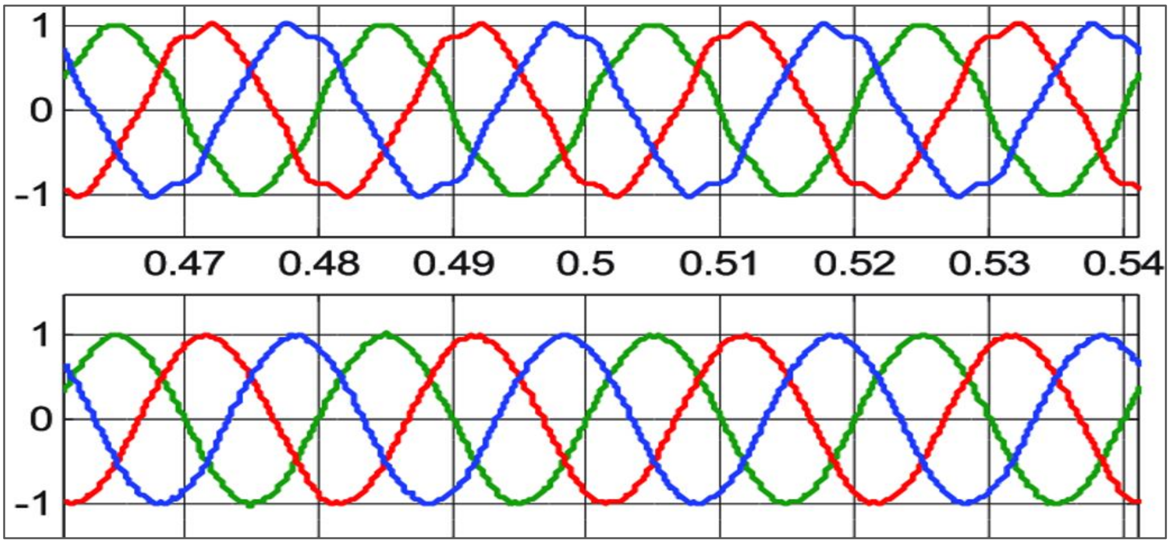


Fig II.11: Inverter Output Voltage Analysis [22]

II.6 Pulse Width Modulation (PWM) Control

II.6.1 Basic Concept

This control technique chops the input DC voltage into a series of square pulses. The width of each pulse is modulated to achieve a desired average output voltage. It includes several methods to generate the square pulse. Among the most well-known methods, we have: [22]

- **Sinusoidal PWM (SPWM)**
  A sinusoidal waveform is used as the reference signal. This technique produces a near-sinusoidal output with low harmonic distortion.

- **Hysteresis PWM**
  This technique is used to control the current by keeping it within upper and lower limits (a hysteresis band). This method is simple and fast to respond, but it produces a variable switching frequency.

II.6.2 Sinusoidal PWM – SPWM

The PWM technique relies on comparing two signals:

- **Reference Wave:** This signal is a three-phase sinusoidal wave (one for each phase: A, B, and C), representing the desired output voltage. The frequency of this wave is proportional to the reference speed of the motor. The maximum voltage of the wave is proportional to the frequency in order to maintain a constant V/f ratio. [23]
- **Carrier Wave:** The carrier wave is a triangular (or sawtooth) waveform with a fixed frequency known as the switching frequency. Its frequency is typically much higher than the reference wave frequency (ranging from 2 kHz to over 20 kHz).

When the two waves (the reference wave and the triangular wave) intersect, control pulses are generated, which are used to switch the transistors in the inverter. The longer the ON time (duty cycle), the higher the average voltage applied to the load.

Every sinusoidal reference wave undergoes comparison with the triangular carrier wave. The upper switch for that phase activates if the sinusoidal wave exceeds the triangular wave. The lower switch activates if the sinusoidal wave is less than or equal to the triangular wave. [22]

This process is repeated at a high frequency for each phase, resulting in pulses with varying widths (variable duty cycle), which are the PWM signals.

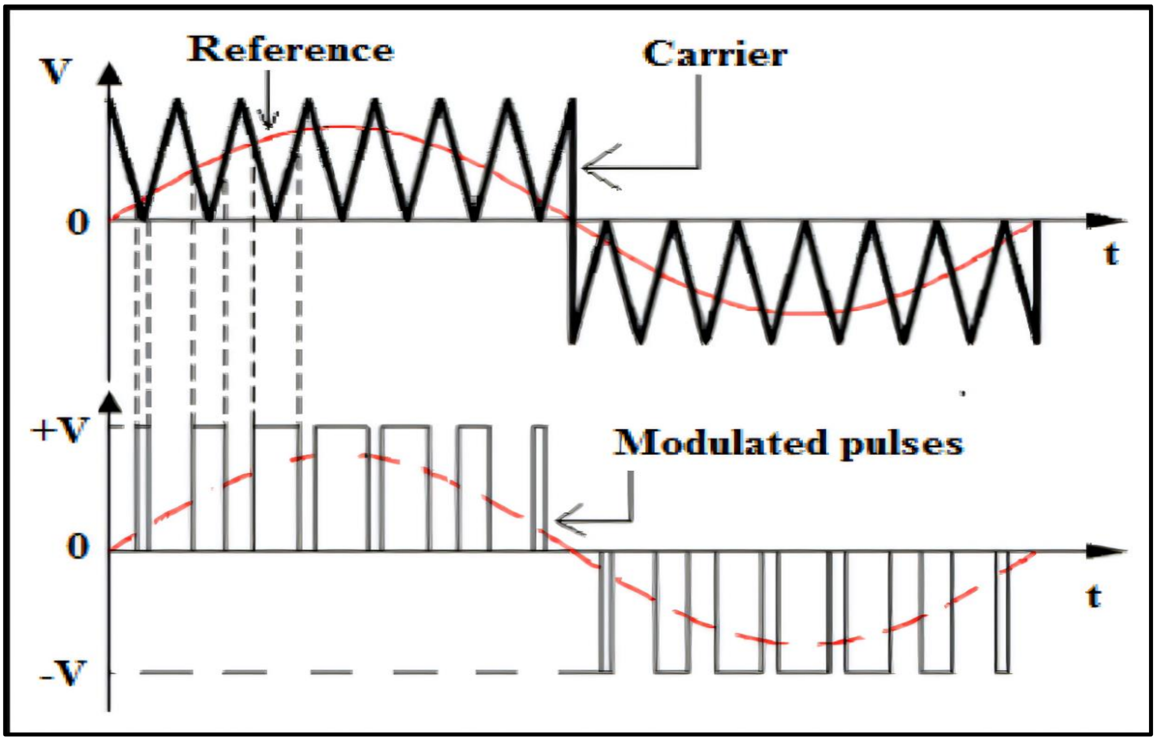


Fig II.12: Sinusoidal PWM control – SPWM [22]

II.6.3 Hysteresis PWM (HPWM)

Hysteresis PWM is a control technique that uses the hysteresis band to regulate the output current or voltage of a three-phase inverter. It compares the reference signal (current) with the actual signal and then switches the transistors (such as IGBTs) on or off to keep the error within a defined range (the hysteresis band). [24]

- If the error exceeds the upper limit of the hysteresis band, the transistors are turned off to reduce the current.
- If the error falls to the lower limit of the hysteresis band, the transistors are turned on to increase the current.

To keep the current within the designated range, we repeat this process at a high frequency. This technique responds quickly to changes, but its switching frequency is not constant.

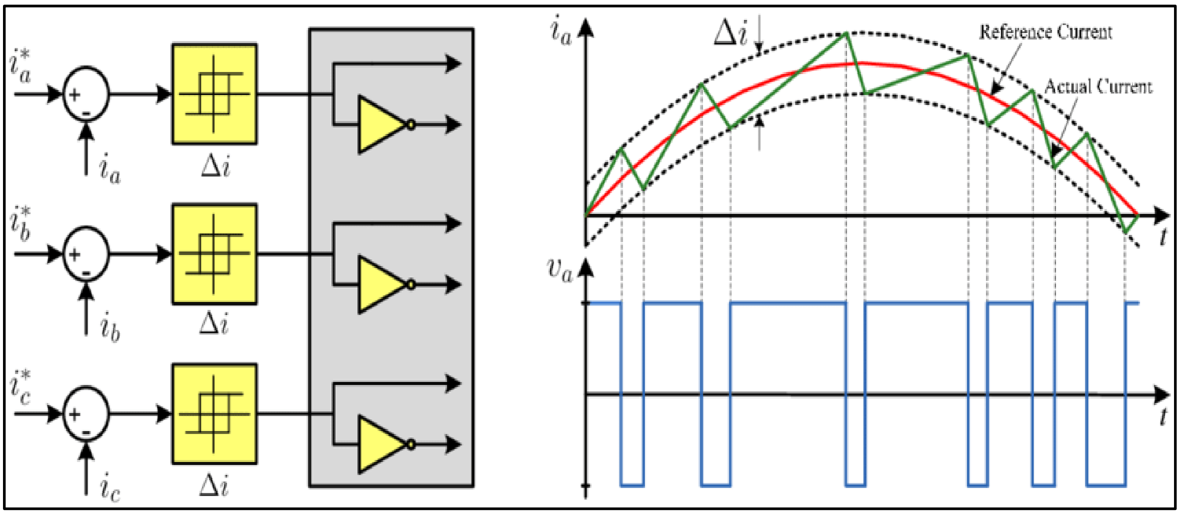


Fig II.13: Control Hysteresis PWM current and switch key logic [24]

II.7 Applications of scalar control (V/f)

Scalar control (especially V/f control) is widely used in applications where simplicity, cost-effectiveness, and steady-state performance are more important than dynamic response or precision. Its main uses include the following domains:

1- **Pumps and Fans:** where smooth speed variation and energy efficiency are needed without precise torque control.
2- **HVAC Systems:** in air handling units and compressors, benefiting from simple and reliable speed control.
3- **Conveyors:** where constant speed operation is adequate and cost-effective control is preferred.
4- **Centrifuges and Mixers:** requiring basic speed regulation without fast transients.
5- **Textile Machinery:** where low to moderate performance is sufficient at varying speeds.
6- **Water Treatment Plants:** for managing motor-driven pumps in a cost-sensitive setup.

II.8 Conclusion

This chapter provided a theoretical overview of the mathematical modeling of an induction motor under scalar control techniques, such as the V/f method. It emphasized the simplicity and ease of implementation of scalar control, while noting its limitations in dynamic performance and precision. The study forms a foundation for understanding how scalar control governs motor behavior through voltage and frequency adjustments without decoupling torque and flux.

Chapter III

Field Oriented Control (FOC)-Modeling and Performance Study

Chapter III : Field Oriented Control (FOC) modeling and performance study

III.1 Introduction

This chapter focuses on the study of controlling three-phase induction motors using the Direct Field-Oriented Control (Direct FOC) technique. It also addresses the transformation from a three-phase system to a two-phase system using Clarke and Park (d-q) transformations. The chapter further discusses the role of the Field Weakening Bloc in reducing the flux component at high speeds. The system relies on the Proportional-Integral (PI) controller to regulate motor currents and speed.

III.2 History of FOC (Field Oriented Control)

Three-phase induction motor control techniques have undergone significant advancements over the past decades, evolving from simple methods to advanced control systems capable of delivering performance comparable to that of DC motors. One of the most important developments in this field is the Field Oriented Control (FOC) technique.

Before the 1970s, induction motor control heavily relied on scalar control methods, particularly the Voltage-to-Frequency (V/f) control technique. While simple and easy to implement, this method lacked dynamic accuracy and did not allow for direct control of torque or flux, which limited its use in industrial applications requiring high precision and fast response.[26]

In the development of Field Oriented Control (FOC) technology, both Friedrich Blaschke and Klaus Hasse played a foundational and pioneering role:

The academic emergence of the FOC concept began in the early 1970s. In 1972, the German engineer and researcher Friedrich Blaschke introduced a new approach to controlling induction motors, later known as Field Oriented Control. The basic idea was to decouple torque and flux variables, similar to what happens in DC motors, by re-representing the stator currents within a revolving reference frame (d-q frame) that was aligned with the rotor's magnetic flux. This idea was innovative because it replaced basic voltage and frequency regulation with dynamic, direct torque control for motor control. [25]

Two years later, in 1974, Klaus Hasse contributed by developing and refining the practical and mathematical application of FOC. He introduced the concept of indirect field-oriented control, which does not require direct measurement of flux or rotor angle but instead uses mathematical models to estimate these values. This advancement significantly contributed to the practical implementation of the technique using the available electronics of that time.

Although promising, technological limitations in CPUs and electronics prevented practical deployment until the early 1980s. The development of transistors, integrated circuits, and microprocessors (including DSPs) permitted the real-time implementation of FOC algorithms, making them suitable for industrial applications requiring great precision and speed.

During the 1990s, the industrial adoption of FOC grew significantly, especially in applications requiring precise control of speed and torque, such as automated production lines, renewable energy systems, and rail transportation. This period also laid the foundation for other techniques like Direct Torque Control (DTC), but FOC remained a preferred choice due to its balanced performance and manageable computational complexity. [25]

Today, FOC is one of the most widely adopted control techniques for three-phase induction motors, praised for its flexibility and high efficiency. It is also being integrated into intelligent control systems supported by predictive control and artificial intelligence, making it an ideal solution for modern industrial systems.

III.3 Comparison of control method between AC IM and DC motor

III.3.1 DC motor

The DC motor consists of a stator and a rotor. The stator produces the electromagnetic flux and is powered by a power source. The rotor is energized through commutator brushes from a separate independent power source, and it generates the torque that drives the mechanical load. [15]

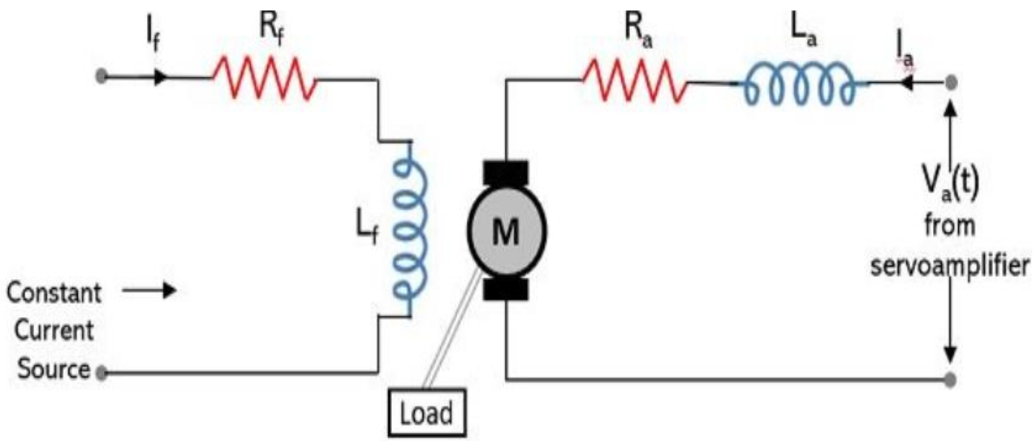


Fig III.1: Representation of a DC Motor with Separate Supply. [26]

There is:

$$V_a = I_a R_a + L_a \frac{dI_a}{dt} + K\varphi\omega \quad (III.1)$$

In the stable state:

$$\frac{dI_a}{dt} = 0 \quad (III.2)$$

So:

$$V_a = I_a R_a + K\varphi\omega \quad (III.3)$$

And:

$$\omega = \frac{V_a - I_a R_a}{k\varphi} \quad (III.4)$$

From the above equation, we conclude that to change the speed of a DC motor, it is sufficient to vary the armature voltage V_a ; the speed will change directly, while the magnetic flux remains constant (which is the desired objective).

Since changing the armature voltage V_a does not affect the magnetic flux, the torque also remains unchanged, as it depends on both the armature current I_a and the magnetic flux. And since the flux is maintained constant, the torque is only affected by the value of I_a, according to the following relation: [15]

$$T_{em} = k\varphi I_a \tag{III.5}$$

Where:

T_{em}: Torque

k: Motor constant

φ: Magnetic flux

I_a: Armature current

The magnetic flux does not change when the armature voltage is varied because magnetic flux (φ) is directly proportional to the excitation current (I_f).

The fundamental mathematical relationship of magnetic flux under magnetic saturation conditions is:

$$\varphi \propto I_f \tag{III.6}$$

III.3.2 Induction motor

The induction motor consists of a fixed part and a moving part, like a direct current motor, but differs in terms of the operating and control principle. (See Chapter I).

The stator is responsible for producing the revolving magnetic flux. When a three-phase voltage is given to an induction motor, a rotating magnetic field is created. Since this field rotates, it cuts through the rotor bars, inducing electric currents in them.

Hence, the name "induction motor" originates from the fact that the rotor currents are caused by the magnetic flux generated by the stator.

Torque is produced by the interaction of the stator's magnetic flux with the rotor's magnetic flux.

In contrast, in a DC motor, the stator and rotor are supplied from independent sources. However, in an induction motor, the rotor currents are generated solely as a result of the interaction between the stator's magnetic flux and the rotor bars. [15]

In summary:

The result is that the rotor supply in a DC motor is independent of the stator supply, whereas in an induction motor, the rotor supply is not independent of the stator.

Additionally, the torque in the induction motor is generated due to the interaction between the rotor flux and the stator flux.

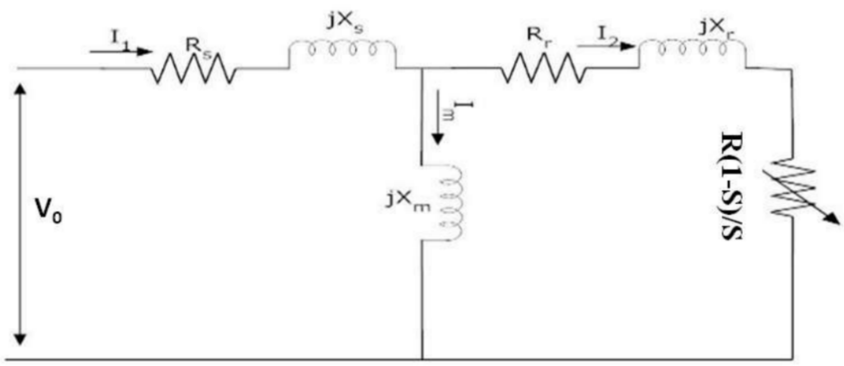


Fig III.2: IM representation with relationship torque, flux, supply. [19]

torque, rotor flux, and stator currents:

$$T_{em} \propto I_r . \varphi \qquad (III.7)$$

Torque and speed:

$$T_{em} = \frac{P}{\Omega} \qquad (III.8)$$

So, what is the problem here?

The key issue in “IM” is that electromagnetic torque is generated by the interaction of the magnetic flux produced by the rotor and that produced by the stator. This interaction causes the torque to be strongly dependent on the rotor flux, implying that any variation in torque has a direct effect on the magnetic flux level. If torque grows uncontrollably, the magnetic flux may reach levels sufficient to cause magnetic saturation in the iron core, resulting in excessive heating of the stator windings and possible insulation damage. In contrast, a considerable decline in torque results in a fall in flux, which may damage the motor's performance or cause it to stop completely. Therefore, precise control of both torque and flux is essential to ensure safe and efficient motor operation.

III.4 Generality of Field-Oriented Control

As is well known, torque in an induction motor is closely linked to magnetic flux, since electromagnetic torque results from the interaction between stator and rotor currents with the magnetic field. However, this direct relationship between torque and flux complicates dynamic control. This is where **Field-Oriented Control (FOC)** becomes essential, as it decouples torque control from magnetic flux, enabling the induction motor to operate similarly to a DC motor. [27]

The **FOC** technique relies on analyzing the motor’s current, voltage, and flux vectors using **Clarke and Park transformations**, which convert the three-phase system into a rotating reference frame (d-q axis). In this system, the direct current component (Id) controls the magnetic flux, while the quadrature current component (Iq) regulates torque, ensuring complete independence between the two. This decoupling allows for a fast, precise dynamic response comparable to DC motor performance while maintaining high efficiency and minimizing speed and torque oscillations.

III.5 The Concept of Operation and Current Decoupling in FOC

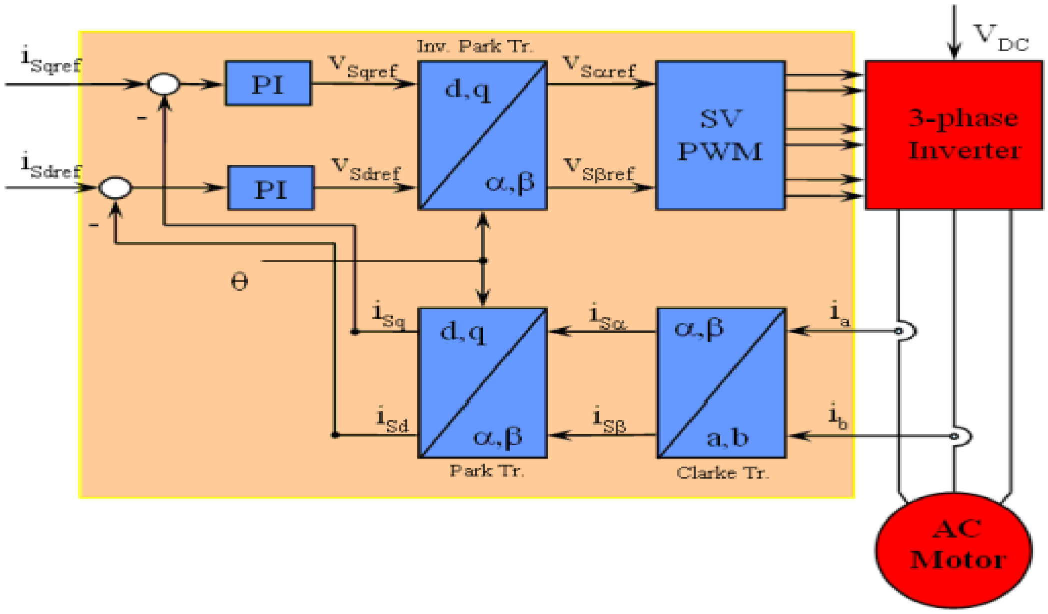


Fig III.3 : Simple scheme of FOC with Clark and park blocs [27]

The decoupling block, highlighted in the previous figure, consists of two essential units: the Clarke and Park transformations, which are used to convert coordinates from one frame to another to simplify current control. The Clarke block transforms the three-phase signals into a two-axis stationary reference frame (α-β) aligned with the stator. Then, the Park block converts these coordinates into a rotating reference frame (d-q) aligned with the rotor flux, allowing for the separation of the current components responsible for flux and torque. These transformations are a fundamental step in implementing field-oriented control (FOC) in AC motor drives. [28]

In three-phase motor control systems, such as induction or synchronous motors, the Clarke Transformation is used to convert three-phase signals (typically currents or voltages) into a two-phase system in the stationary reference frame (α, β), which simplifies digital control and computation. Although there are three signals (I_a, I_b ,I_c), the Clarke transformation requires only two of them because, in a balanced three-phase system, the currents satisfy the relationship:

$$I_a + I_b + I_c = 0 \qquad (III.9)$$

This means that one of the components can be derived from the other two. This approach reduces the number of sensors needed, thereby lowering both cost and system complexity.

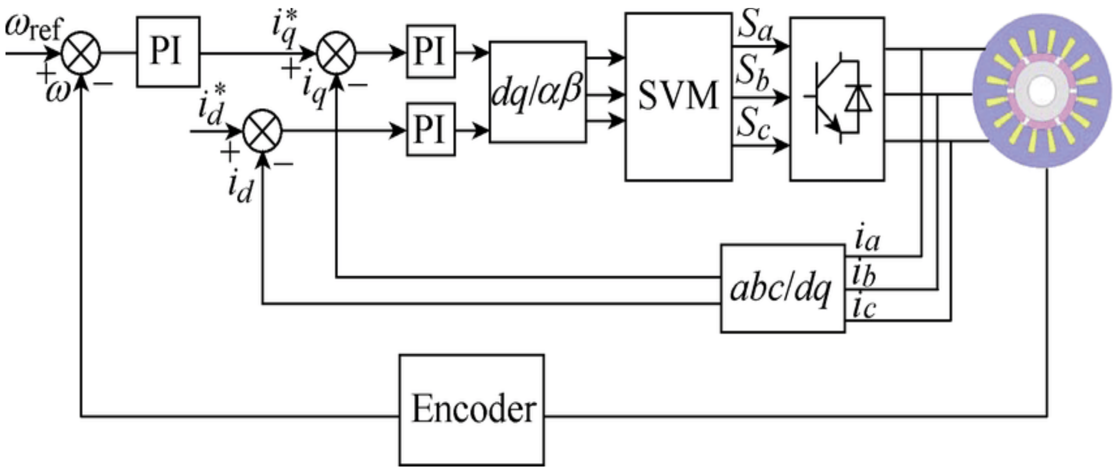


Fig III.4 : Expanded form of Direct Field-Oriented Control (FOC). [29]

This type of control consists of two parts: hardware and software :

III.5.1 Hardware Blocks

These are the physical components of the FOC system: [29]

1- Three-Phase Inverter:

Converts DC voltage into a controlled three-phase AC supply using PWM. It uses IGBTs or MOSFETs and receives gate signals from the SVM block.

2- Squirrel Cage Induction Motor (SCIM):

The target motor being controlled. It has a rugged rotor and is widely used in industrial applications for its durability and simplicity.

III.5.2 Software Blocks

These are algorithmic or computational blocks implemented in a microcontroller, DSP, or FPGA.

1- Clarke Forward Transform Block:

Converts three-phase currents (Ia, Ib, Ic) into a two-axis stationary reference frame (Iα, Iβ).

Used to simplify control and prepare for the Park transform.

2- Park Forward Transform Block:

Converts (Iα, Iβ) into rotating reference frame quantities (Id, Iq) using the estimated rotor angle.

Id: Flux-producing current

Iq: Torque-producing current

3- Angle and Speed Estimator Block:

Estimates the rotor angle (θr) and speed (ωr) based on voltage and current feedback.

In sensorless FOC, this replaces a physical encoder.

Critical for correct d-q frame alignment.

4- PI Control Block:

Contains two PI (Proportional-Integral) controllers:

One for Id (flux control)

One for Iq (torque control)

The outputs are Vd and Vq, the voltage commands in d-q axes.

5- Field Weakening Block:

Allows the motor to operate above its rated speed by reducing the flux (Id current) while limiting the voltage.

Useful in applications requiring extended speed range.

6- Park Inverse Transform Block:

Converts (Vd, Vq) back to (Vα, Vβ) in the stationary frame, aligned with the stator.

7- Space Vector Modulation (SVM) Block:

Converts (Vα, Vβ) into PWM duty cycles to control the inverter switches.

Maximizes voltage utilization and minimizes harmonic distortion.

III.6 Three-Phase to Two-Phase Transformation

When analyzing asynchronous machines (induction motors), dealing with a three-phase system is mathematically challenging. Therefore, mathematical transformations such as the Clarke and the Park transformation are used to simplify the equations and make calculations easier.

The transition from a three-phase system to a two-phase system is a mathematical transformation. This transformation is based on the premise that a two-phase system can equivalently represent the rotating electromagnetic field generated by a three-phase system. This representation enables the examination and analysis of the electrical machine while maintaining essential attributes such as magnetomotive force (MMF) and instantaneous power. It is extensively utilized in contemporary control systems. [28]

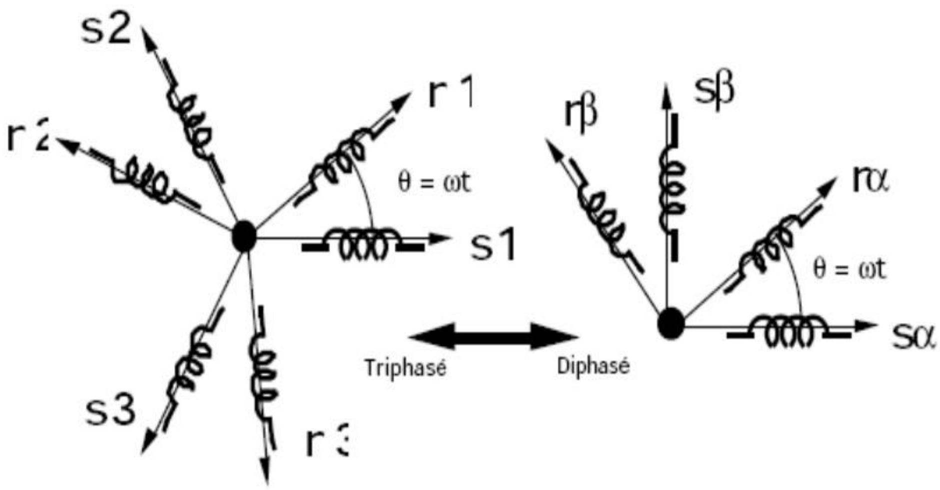


Fig III.5 : transformation three-phase to two-phase system [10]

III.6.1 Purpose of the Transformation

Simplification of Analysis: Converting a three-phase system to a two-phase system reduces the number of variables and equations, making the analysis easier, or design control systems- especially in electrical machines or power electronics.

Preservation of Fundamental Properties: The magnetomotive force (MMF) and instantaneous power are preserved during the transformation.

III.6.2 Concept of the Transformation

In a three-phase system, a rotating magnetic field is generated by three windings spaced 120 degrees apart in space, supplied with currents that are 120 degrees out of phase in time.

In a two-phase system, the same rotating field is created using two orthogonal windings (spaced 90 degrees apart in space), supplied with currents that are 90 degrees out of phase in time.

III.6.3 Assumptions and Conditions of the Transformation

- **Sinusoidal Signals Assumption.**
- **Constant Frequency Assumption.**
- **Steady-State Condition Assumption.**
- **Balanced Three-Phase System Assumption:** Basic Condition: The three-phase system is assumed to be balanced, meaning the voltages or currents in the three phases are equal in magnitude and separated by a phase angle of $\mathbf{120^o}$ or ($\frac{3\pi}{2}$ rad). with The Mathematical Expression: [10]

$$\boldsymbol{f_a + f_b + f_c = 0} \qquad (III.10)$$

Where: $\boldsymbol{f_{a,b,c}}$: Are the electrical quantities (current, voltage...).

III.6.4 Mathematical Steps of that Transformation

The electrical quantities (currents, voltages, magnetic fluxes) are transformed from the three-phase reference frame to a two-phase reference frame using the Clark transform.

III.6.5 Clarke Transformation

The Clarke transformation converts electrical quantities (such as currents or voltages) from a three-phase system (a, b, c) to a two-axis system (α, β) in a stationary reference frame. [2]

Clarke Equation:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \qquad (III.11)$$

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = [Clarke\ Matrix]\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \qquad (III.12)$$

$$[Clarke\ Matrix] = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{III.13}$$

Where:

f_a, f_b, f_c : are the quantities in the three-phase system.

f_α, f_β : the quantities in the two-axis system (stationary reference frame).

f_0 : the zero-sequence component, it's is usually zero in balanced systems.

And:

The quantity f_α is aligned with the a-axis.

The quantity f_β is orthogonal to f_α and represents quadrature component.

The three-phase quantities are projected onto a two-axis plane (α-β), which is stationary in space, as shown in the figure.

III.6.5.1 Park Transformation

The Park transforms converts quantities from a biaxial system (α, β) in a fixed reference frame to a biaxial system (d, q) in a rotating reference frame.

This aims to convert quantities into a rotating frame of reference with the direct axis (d) and the quadratic axis (q) to facilitate control of electric motors. [30]

Park equation:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{III.14}$$

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = [Park\ Matrix] \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{III.15}$$

$$[Park\ Matrix] = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \qquad (III.16)$$

Where:

f_d : Direct-axis component.

f_q : Quadrature-axis component.

θ : is the angle between the fixed axis and the rotating axis.

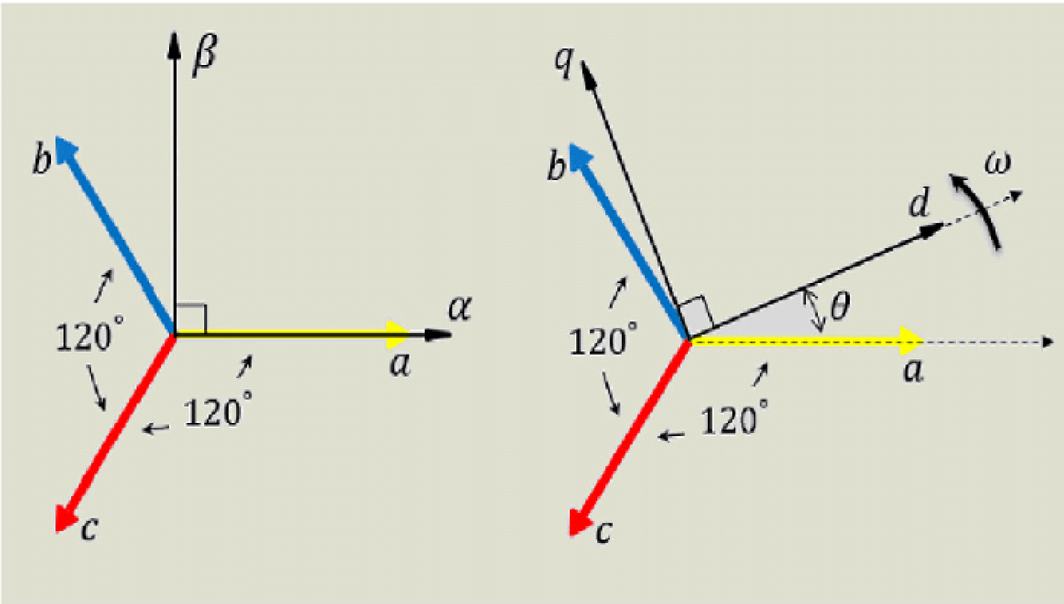


Fig III.6 : Clarke and Park's frame relative to the triangular frame. [31]

III.6.5.2 Direct Park Transformation

Direct Park Transformation Equations is combining Park's equations and Clarke's equations to leverage the properties of both transformations and obtain a moving and rotating biphasic reference frame from (a, **b, c** to **d, q, 0)** directly**.**

Direct Park transforms equations:

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(\theta) & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin(\theta) & -sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (III.17)$$

Where:

$\boldsymbol{f_a, f_b, f_c}$ are the quantities in the three-phase system.

$\boldsymbol{f_d, f_q, f_0}$ are the quantities in the rotating reference frame (d, q, 0).

$\boldsymbol{\theta}$: is the angle between the fixed axis and the rotating axis.

d-axis (Direct Axis): Represents the direct component, typically aligned with the magnetic field.

q-axis (Quadrature Axis): Represents the quadrature component, perpendicular to the magnetic field.

0-axis (Zero Sequence): Represents the zero-sequence component, which is equal in all phases and used in cases of imbalance.

Inverse of direct Park Transform equations:

Inverse Transformation Equations (from **d, q, 0** to **a, b, c**):

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(\theta) & -sin(\theta) & 1 \\ cos\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ cos\left(\theta + \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix}\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} \quad (III.18)$$

This equation is used to transform quantities from the rotating reference frame **(d, q, 0)** back to the three-phase system **(a, b, c)** directly**.**

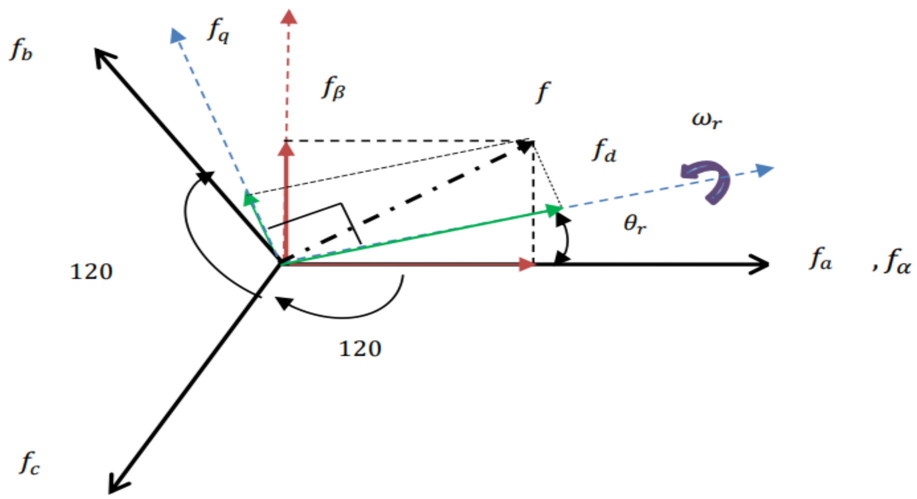


Fig III.7 : (a,b,c) frame and (α, β) clarke and (d, q) park frame's relative. [30]

III.7 SCIM model in the two-axis Park reference frame

III.7.1 Electromagnetic equations in Park reference frame

The dq reference frame forms an electrical angle θ_s with the stationary part (stator) and an electrical angle θ_r with the rotating part (rotor).

The Angles θ_s and θ_r: These are the angles used in Park's transformations, which convert electrical quantities from the stationary to the rotating frame. And to align the quantities between the two axes, this is achieved by linking the angles through the following relationship:

$$\theta_S = \theta + \theta_r \qquad (III.19)$$

After applying the de Park matrix to the voltages, currents and fluxes, the electrical dynamic model of the motor is shown:

$$V_{dq} = [P(\theta)]\left[V_{a,b,c}\right] \qquad (III.20)$$

After calculation:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\varphi_{ds}}{dt} - \frac{d\theta_s}{dt}\varphi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\varphi_{qs}}{dt} + \frac{d\theta_s}{dt}\varphi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d\varphi_{dr}}{dt} - \frac{d\theta_r}{dt}\varphi_{qr} = 0 \\ V_{qr} = R_r I_{qr} + \frac{d\varphi_{qr}}{dt} + \frac{d\theta_r}{dt}\varphi_{dr} = 0 \end{cases} \quad (III.21)$$

Magnetic equations in park:

$$\varphi_{sdq} = [P(\theta_s)][\varphi_{sabc}] \quad (III.22)$$

$$\varphi_{rdq} = [P(\theta_r)][\varphi_{rabc}] \quad (III.23)$$

Magnetic equations in detail:

$$\begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \\ \varphi_{os} \\ \varphi_{dr} \\ \varphi_{qr} \\ \varphi_{or} \end{bmatrix} = \begin{bmatrix} I_s - M_s & 0 & 0 & \frac{3}{2}M_{sr} & 0 & 0 & I_{ds} \\ 0 & I_s - M_s & 0 & 0 & \frac{3}{2}M_{sr} & 0 & I_{qs} \\ 0 & 0 & I_s + 2M_s & 0 & 0 & 0 & I_{os} \\ \frac{3}{2}M_{sr} & 0 & 0 & I_r - M_r & 0 & 0 & I_{dr} \\ 0 & \frac{3}{2}M_{sr} & 0 & 0 & I_r - M_r & 0 & I_{qr} \\ 0 & 0 & 0 & 0 & 0 & I_r + 2M_r & I_{0r} \end{bmatrix} \quad (III.24)$$

Where:

$L_s = I_s - M_s$: Stator cyclic inductance

$L_s = I_s - M_s$: rotor cyclic inductance

$Lm = \frac{3}{2}M_{sr}$: Cyclic mutual inductance between stator and rotor.

After calculation and simplification, it becomes:

$$\begin{bmatrix} \varphi_{ds} \\ \varphi_{qs} \\ \varphi_{dr} \\ \varphi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & Lm & 0 \\ 0 & L_s & 0 & Lm \\ Lm & 0 & L_r & 0 \\ 0 & Lm & 0 & L_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \end{bmatrix} \quad (III.25)$$

III.7.2 Fixed frame of reference relative to the rotating field

Assuming that the dq frame is linked to the rotating field, So the dq frame rotates at the same speed as the rotating field ω_s . If the speed of the dq frame is synchronized with the rotating field, that is mean the Sinusoidal Quantities such as (voltage, current, ...) become constant.

depending on the equation from $\theta_S = \theta + \theta_r$ *(III.19)* there is:

$$\frac{d\theta_s}{dt} = \frac{d\theta}{dt} + \frac{d\theta_r}{dt} \quad (III.26)$$

So:

$$\omega_s = \omega + \omega_{sl} \quad (III.27)$$

$$\omega_{sl} = \omega_s - \omega \quad (III.28)$$

Based on the previous equations, the electrical equations of the motor in d,q frame are written in the form:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega)\varphi_{qr} = 0 \\ V_{qr} = R_r I_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_s - \omega)\varphi_{dr} = 0 \end{cases} \quad (III.29)$$

So:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s . \varphi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s . \varphi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d\varphi_{dr}}{dt} - \omega_{sl} . \varphi_{qr} = 0 \\ V_{qr} = R_r I_{qr} + \frac{d\varphi_{qr}}{dt} + \omega_{sl} . \varphi_{dr} = 0 \end{cases} \quad (III.30)$$

With Magnetic equations in stator and rotor in dq frame (park):

$$\varphi_{ds} = L_s I_{ds} + M I_{dr}$$
$$\varphi_{qs} = L_s I_{qs} + M I_{qr} \qquad (III.31)$$

$$\varphi_{dr} = L_r I_{dr} + M I_{ds} \qquad (III.32)$$
$$\varphi_{qr} = L_r I_{qr} + M I_{qs}$$

Electromagnetic Torque equation:

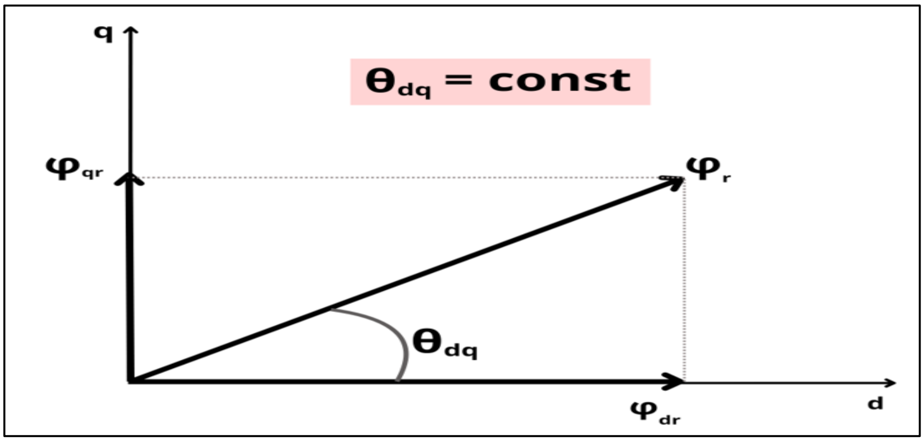
$$T_{em} = P \frac{L_m}{L_r} \left(\varphi_{dr} I_{qs} - \varphi_{qr} I_{ds} \right) \qquad (III.33)$$

III.8 Flux Orientations

III.8.1 Field Orientation Along the d-Axis

The fundamental concept behind achieving decoupled control in an induction motor lies in aligning the motor's magnetic flux. Within the Park (d-q) rotating reference frame, each electrical quantity can be independently represented and managed: [32]

$$\varphi_r = \varphi_{dr} + \varphi_{qr} \qquad (III.34)$$



III.8: flux representation in Park frame (dq)

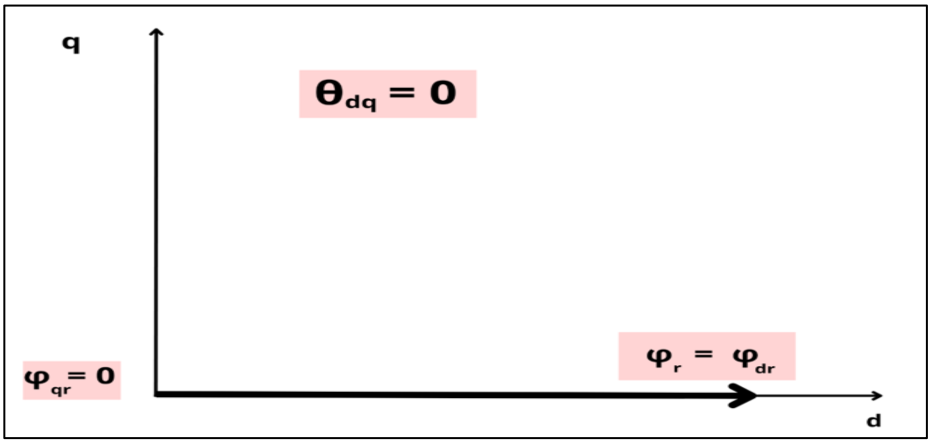
The magnetic flux $\boldsymbol{\varphi_r}$ is composed of the direct axis (d) and the quadrature axis (q), and it deviates from the d-axis by a fixed angle:

$$\theta_{dq} = const$$

The electromagnetic torque equation in this case is as follows:

$$T_{em} = P\frac{L_m}{L_r}\left(\varphi_{dr}I_{qs} - \varphi_{qr}I_{ds}\right) \qquad (III.35)$$

By projecting the flux component φ_r onto the d-axis, the angle θ_{dq} is eliminated, which simplifies the calculations without affecting the motor components, as shown in the following diagram: [32]



III.9: flux representation in Park frame (dq) after the orientation.

Based on the previous diagram, the flux components will be represented according to the following equations:

$$\begin{cases} \varphi_{dr} = \varphi_r \\ \varphi_{qr} = 0 \end{cases} \qquad (III.36)$$

So**:**

$$\theta_{dq} = 0 \qquad (III.37)$$

The electromagnetic torque equation in this case is as follows:

$$T_{em} = P\frac{L_m}{L_r} * \varphi_{dr} * I_{qs} \qquad (III.38)$$

Since the flux is constant, the final equation for the torque is as follows:

$$T_{em} = k * I_{qs} \qquad (III.39)$$

From this, we conclude that the current I_q represents the image of the electromagnetic torque, meaning that in order to change the torque, the I_q current must be changed, and they both vary in the same manner.

On the other hand:

By substituting the value of idr from equation (I.32) into equation (I.30), the second equation of the First-Order Optimality Conditions (FOC) becomes

$$T_r \frac{d\varphi_r}{dt} + \varphi_r = L_m \cdot I_{ds} \tag{III.40}$$

From the previous equation, we conclude that the current I_d is a representation of the electromagnetic flux (I_d is the image of flux); that is, to change the flux, the current I_d must be changed, and both vary in the same manner.

Also:

by rearranging and analyzing the second rotor voltage equation, we arrive at the following result:

$$\omega_{sl} = \frac{L_r \cdot i_{qs}}{T_r \cdot \varphi_r} \tag{III.41}$$

Finally:

Accordingly, the above three equations describe the similarity between the control of the Induction Motor (IM) and the Direct Current (DC) motor through (FOC), which is considered the foundation of this control method :[32]

$$\begin{cases} T_r \frac{d\varphi_r}{dt} + \varphi_r = L_m \cdot i_{ds} \\ C_e = p \frac{L_r}{L_m} \cdot \varphi_r \cdot i_{qs} \\ \omega_{sl} = \frac{L_r \cdot i_{qs}}{T_r \cdot \varphi_r} \end{cases} \tag{III.42}$$

All research works conducted on this subject rely on two main methods. The first is known as the direct method, developed by Friedrich Blaschke (F. Blaschke), while the second is the indirect method, developed by Klaus Hasse (K. Hasse). In this research, we will focus on the direct method for controlling the induction motor.

III.8.2 Direct Field Oriented Control

Based on the previous equations we can control (SCIM) the induction motor using currant or voltage:

In this advanced strategy for controlling induction motors using currant, the flux components on the d and q axes, along with the rotor angular velocity, $(\varphi_{dr}, \varphi_{qr}, \Omega_r)$ are considered as the system's state variables. Meanwhile, the stator currents components on the d and q axes, as well as the slip frequency, $(i_{ds}, i_{qs}, \omega_{sl})$ are used as control inputs that influence the system’s performance and stability. [25]

When controlling using voltage, the state vector remains the same as in the previous method using current, $(\varphi_{dr}, \varphi_{qr}, \Omega_r)$, while the input vector consists of $(v_{ds}, v_{qs}, \omega_s)$.

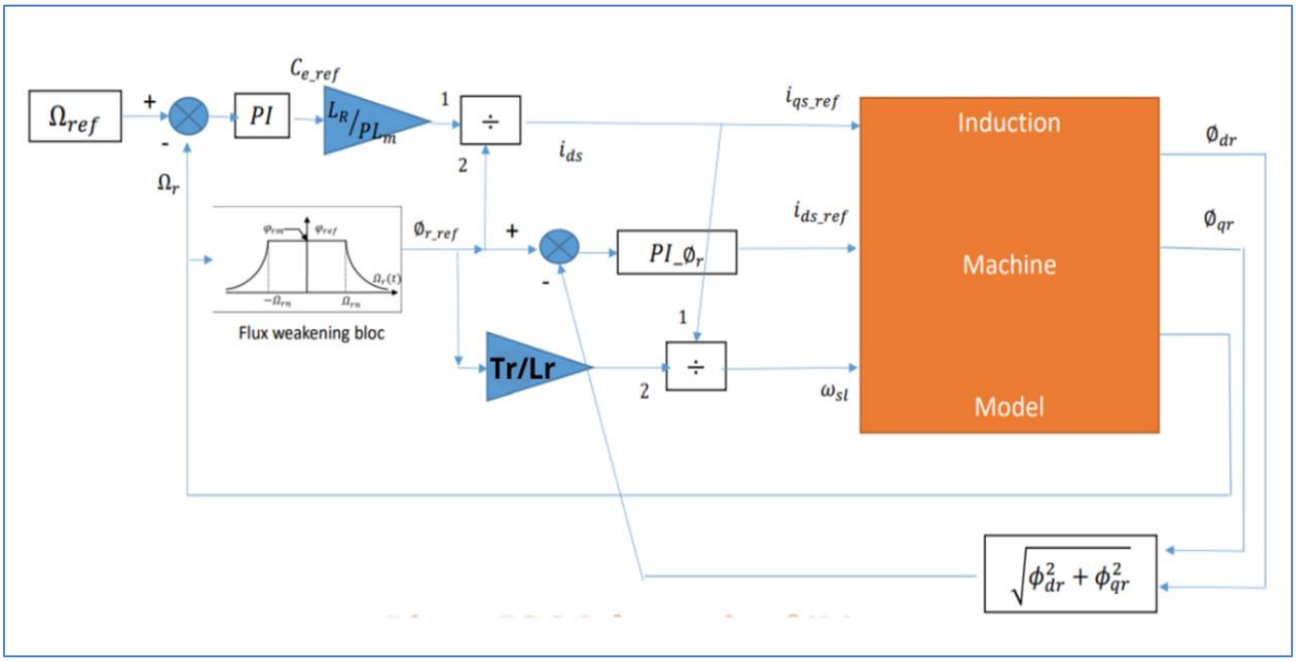
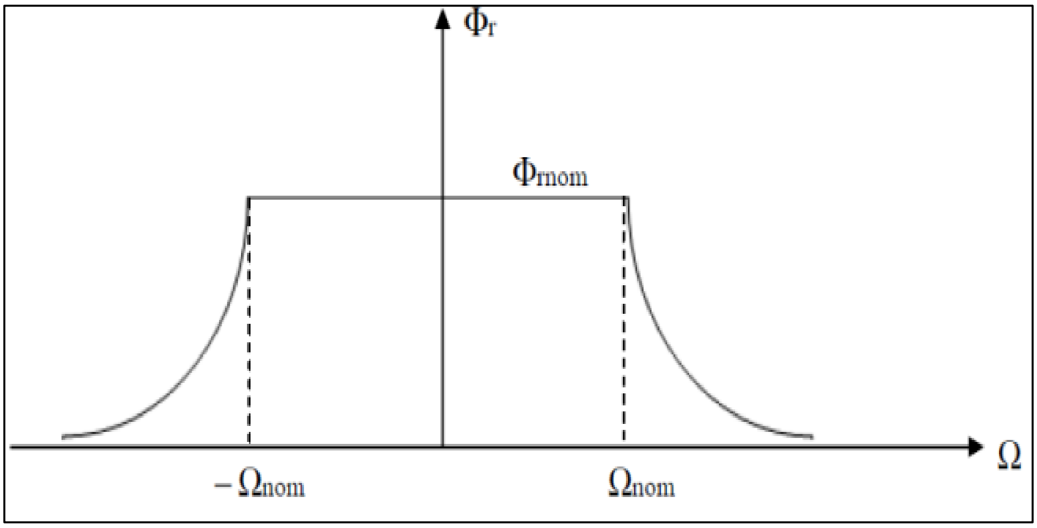


Fig III.10 : Representing system in-outputs Direct FOC Schematic of IM [32]

III.8.3 Field Weakening bloc

In field-oriented control (FOC) systems, the *d*-axis current is used to regulate the magnetic flux within the motor. When the motor reaches its rated speed, further speed increase is limited by the maximum voltage the inverter can supply. To overcome this, the *d*-axis current and, consequently, the magnetic flux is reduced using a technique known as **Field Weakening**. This allows the motor to accelerate beyond its base speed without exceeding the inverter's voltage limit. However, this comes at the cost of reduced torque since torque is directly proportional to magnetic flux. Therefore, field weakening is applied carefully in applications that require high speed but do not demand high torque at those speeds [32]



III.11 : Defluxing block [17]

III.8.4 Design and Implementation of PI Controllers

III.8.4.1 Theoretical Basis of PI Controller

The Proportional-Integral (PI) controller is extensively utilized in industrial applications owing to its simplicity and efficacy in attaining stability. It consists of two main components: the **Proportional (P)** term, which provides an immediate response to the current error, and the **Integral (I)** term, which eliminates steady-state error through time integration. Its mathematical equation is expressed as: [33]

$$u(t) = K_p e(t) + K_i \int e(t)\, dt \tag{III.43}$$

where $e(t)$ represents the error signal, while K_p and K_i are the proportional and integral gains, respectively.

This controller is notable for achieving precise stability while maintaining design simplicity.

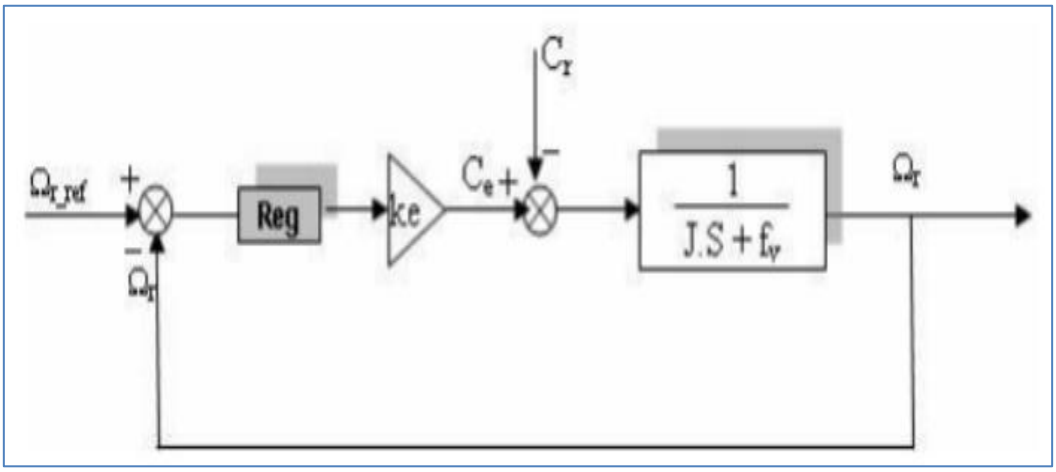


Fig III.12: Speed control loop using PI controller in FOC applied to SCIM [10]

III.8.4.2 Performance of PI in Practical Systems

The PI controller demonstrates high efficiency in medium-speed response applications such as temperature control systems and speed regulation of electric motors. The proportional component improves response speed, while the integral component ensures the elimination of steady-state errors over time. However, it may face limitations in rapidly changing systems, where it can lead to **overshoot** or slow response if its parameters are not properly tuned. [10]

III.8.4.3 Tuning PI Parameters and Applications

The parameters of the PI controller (K_p and K_i) are typically tuned using methods such as **Ziegler-Nichols** or iterative analysis. This controller is preferred for applications that do not require extremely fast responses or that involve measurement noise, as the absence of a derivative component makes it less sensitive to noise compared to PID controllers. It represents an ideal choice for many industrial applications due to its balance between performance and simplicity. [34]

III.9 Applications of Field Oriented Control (FOC)

Field Oriented Control (FOC) is widely used in applications that require high precision and fast dynamic response in controlling the speed and torque of induction and synchronous motors. Its main uses include:

1- **Electric vehicles (Evs):** FOC is used for efficient control of traction motors, offering high performance and energy efficiency.
2- **Industrial robotics and automation:** Ensures precise motion control, especially in robotics arms handling delicate tasks, and CNC machines.
3- **Home Appliances:** such as washing machines and air conditioners, where FOC helps improve energy efficiency and noise reduction**.**
4- **Renewable Energy Systems:** particularly in wind turbine generators to optimize performance under variable wind conditions.
5- **Aerospace and Defense:** for actuators and drones requiring responsive and reliable motor control.
6- **Medical Equipment:** such as precision pumps or surgical robots needing smooth and controlled motion.
7- **Drones (UAVs)**: Allows stable and accurate speed control of multiple motors.

III.10 Conclusion

This chapter explored the mathematical modeling of an induction motor and the principles of Field-Oriented Control (FOC). It highlighted how FOC theory enables independent control of flux and torque by transforming the motor equations into a rotating reference frame. This theoretical foundation is essential for understanding the advantages of FOC in improving the controllability and efficiency of induction motors in various applications.

Chapter IV

SIMULATION RESULTS AND DISCUSSIONS

Chapter IV : Simulation, Results and Discussions

IV.1 Introduction

High-performance control of induction motors has recently piqued the interest of industrial researchers, as the induction motor is the most often used machine. Developments in power electronics have enabled novel control methods. Dynamic numerical simulation is crucial for determining whether the new control design methods are viable and avoiding errors early in simulations before actual implementation. MATLAB/ SIMULINK has proven to be a powerful tool for simulating electrical and mechanical systems because of its simplicity. First, this chapter shows how to use MATLAB/SIMULINK to do a dynamic simulation of an induction motor. Next, we use the scalar control (v/f) method and vector control methods on induction motors. Numerous things may be compared between the two techniques, but the focus is on the speed response, torque response, and other things that are explained below.

IV.2 Mathematical Simulation of the Model Using MATLAB/SIMULINK

In the first part of this thesis, the mathematical representation of the squirrel-cage induction motor (SCIM) was presented. The electrical equations describing the relationships between the motor voltages, currents, and magnetic flux linkages were introduced, along with the mechanical equations governing torque and speed, which were also discussed in the same chapter.

IV.2.1 Simulation of the Clarke and Park Transformations Modeling

We know that induction motors' inductances change over time; thus, we now describe the induction motor using the d-q arbitrary frame transformations (stationary and/or synchronous). When the voltage is unbalanced, or other parameters change, you can see any variable in the motor, making it easy to model the induction motor.

These transformations allow for converting the three-phase model into an equivalent two-phase model, as explained in Chapter Three.

To simplify the modeling of the three-phase induction motor, the Clarke and Park transformations are first applied to convert the signals from the three-phase system (abc) to the stationary d-q reference frame, by substituting θ = 0, since this frame does not rotate. This process is sometimes referred to as the abc to αβ transformation. Subsequently, the signals are transformed from the stationary frame to the synchronous d-q frame, which rotates at the speed of the magnetic field in the air gap, as explained in Chapter Three.

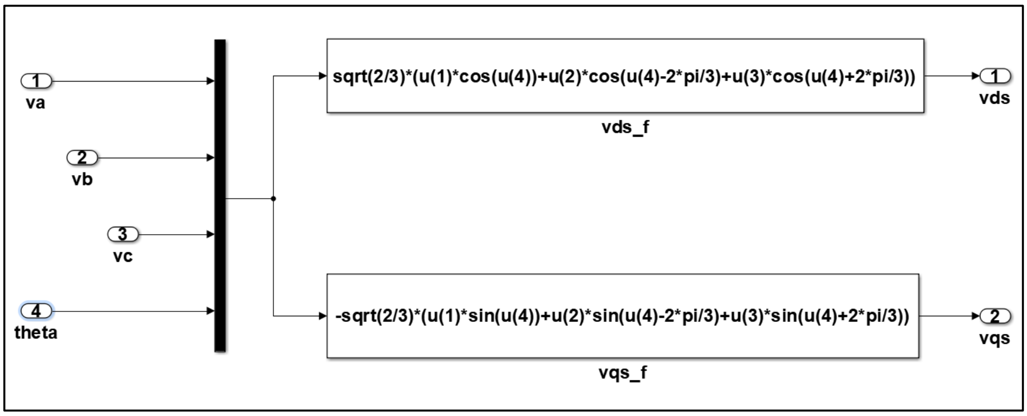


Fig IV.1: Park Transformation Representation in MATLAB/Simulink

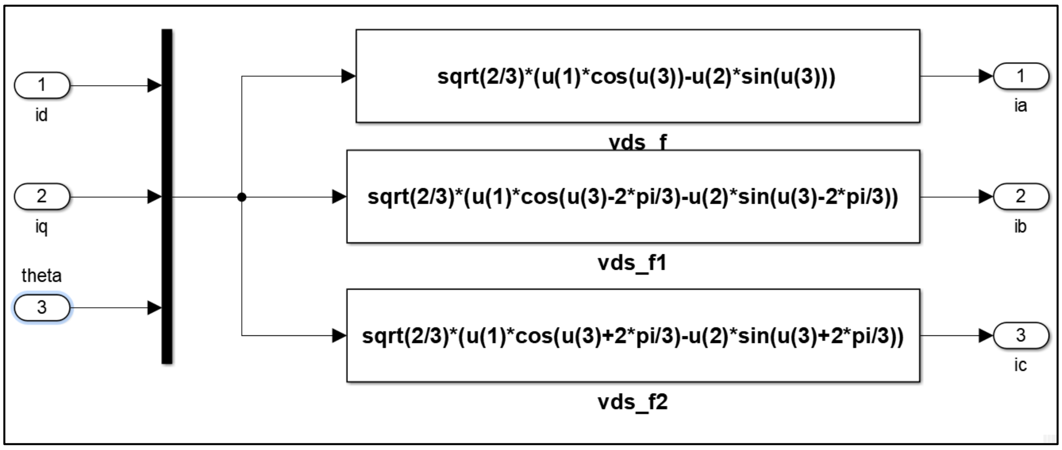


Fig IV.2: Invers Park Transformation Representation in MATLAB/Simulink

IV.2.2 Modeling and Control of the Inverter Using SPWM Technique

IV.2.2.1 SPWM Technique Simulink

The sinusoidal pulse width modulation (SPWM) method produces control signals that regulate the switching of the inverter's power switches. As detailed in Chapter Two, this technology utilizes sinusoidal reference signals and a rapid triangle signal to generate precise pulses that control the switching of electrical components. The simulation model uses these signals to control the voltage and frequency given to the motor, allowing for effective and accurate control methods in the MATLAB/Simulink environment.

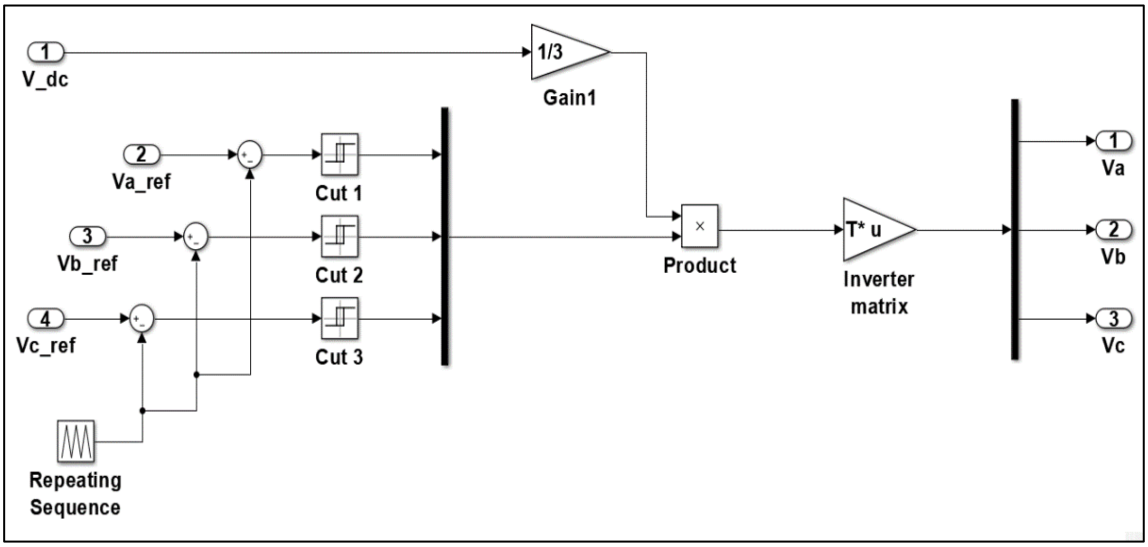


Fig IV.3: Modeling of SPWM Technique (Sinusoidal Pulse Width Modulation)

IV.2.2.2 Three phase voltage inverter Simulink

The three-phase inverter converts electrical energy from direct current (DC) to three-phase alternating current (AC) to supply induction motors. As explained in Chapter Two, this inverter typically consists of six electronic switches arranged in three pairs, each controlled by pulse signals generated using the SPWM technique.

This type of inverter is a fundamental component in simulation models. It allows the generation of alternating voltage waveforms with controllable frequency and amplitude, enabling the study of the motor's response under various operating conditions.

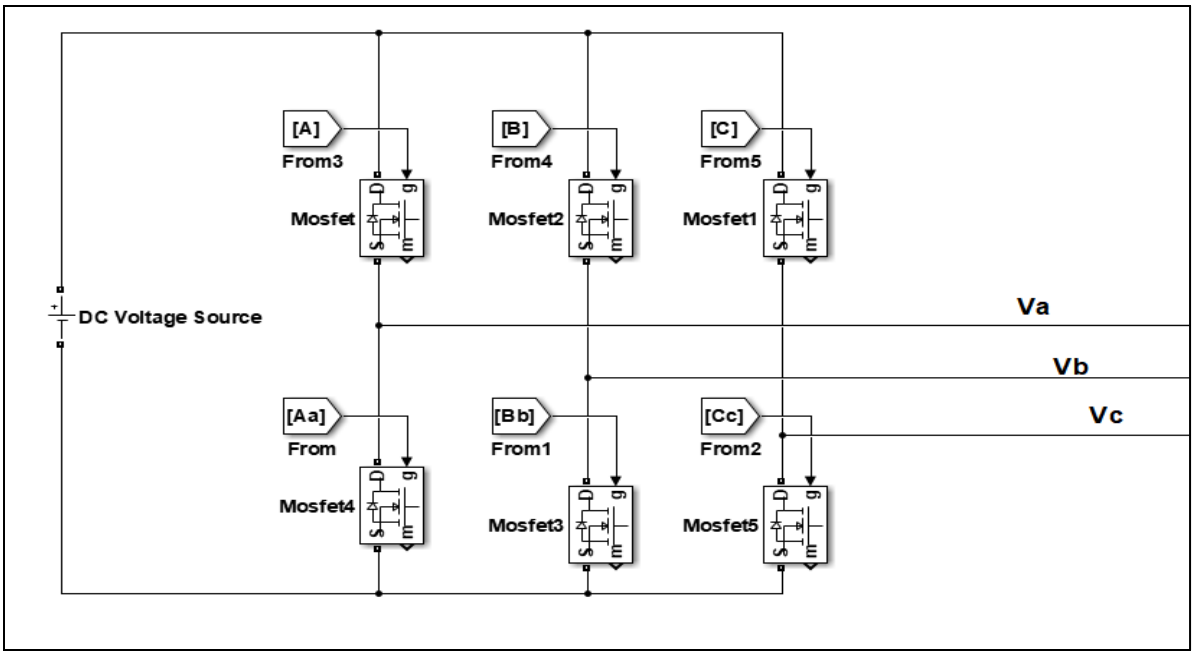


Fig IV.4: Modeling of Three phase in MATLAB/Simulink

IV.2.3 Proportional-Integral (PI) simulation

In industrial control systems, proportional-integral (PI) controllers are often used to govern physical variables like speed or torque. Chapter Three goes into further detail on this form of controller, which has two main parts: a proportional element that deals with the current error and an integral part that adds up past mistakes to make the system more accurate and less likely to deviate from its steady state.

PI controllers are included in the simulation model to manage reference voltage or current signals, whether using control methods like V/f or Field-Oriented Control (FOC). These controllers are set up in the MATLAB/Simulink environment using ready-made control blocks, which makes it easy to adjust control settings and see how they affect system stability and performance.

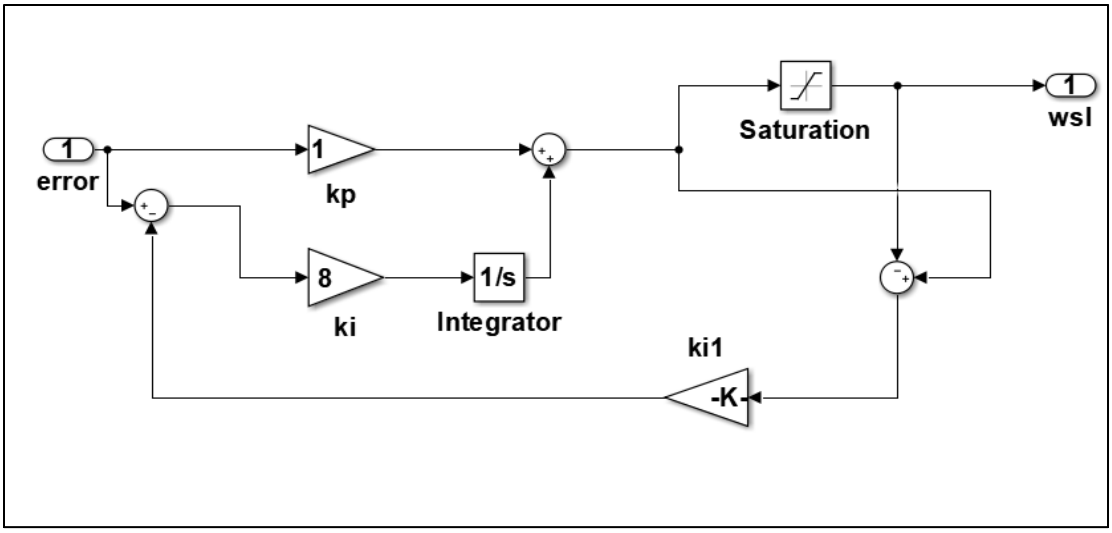


Fig IV.5: Modeling of Proportional-Integral (PI) in MATLAB/Simulink

IV.2.4 Modeling a Three-Phase Induction Motor Using MATLAB/Simulink

The three-phase Squirrel Cage Induction Motor (SCIM) is the focus of our study and simulation due to its simplicity, robustness, and low maintenance requirements. As explained in Chapter One, this type of motor consists of a three-phase stator and a rotor made up of conductive bars connected by short-circuit rings, giving it the characteristic "cage" structure from which it gets its name.

The differential equations in Chapter One represent the motor numerically. These equations describe how currents, voltages, flux connections, and electromagnetic torque change over time. The MATLAB/Simulink software uses this model to see how the motor functions in different conditions. The model lets us see how it changes over time and compare it to the manufacturer's requirements.

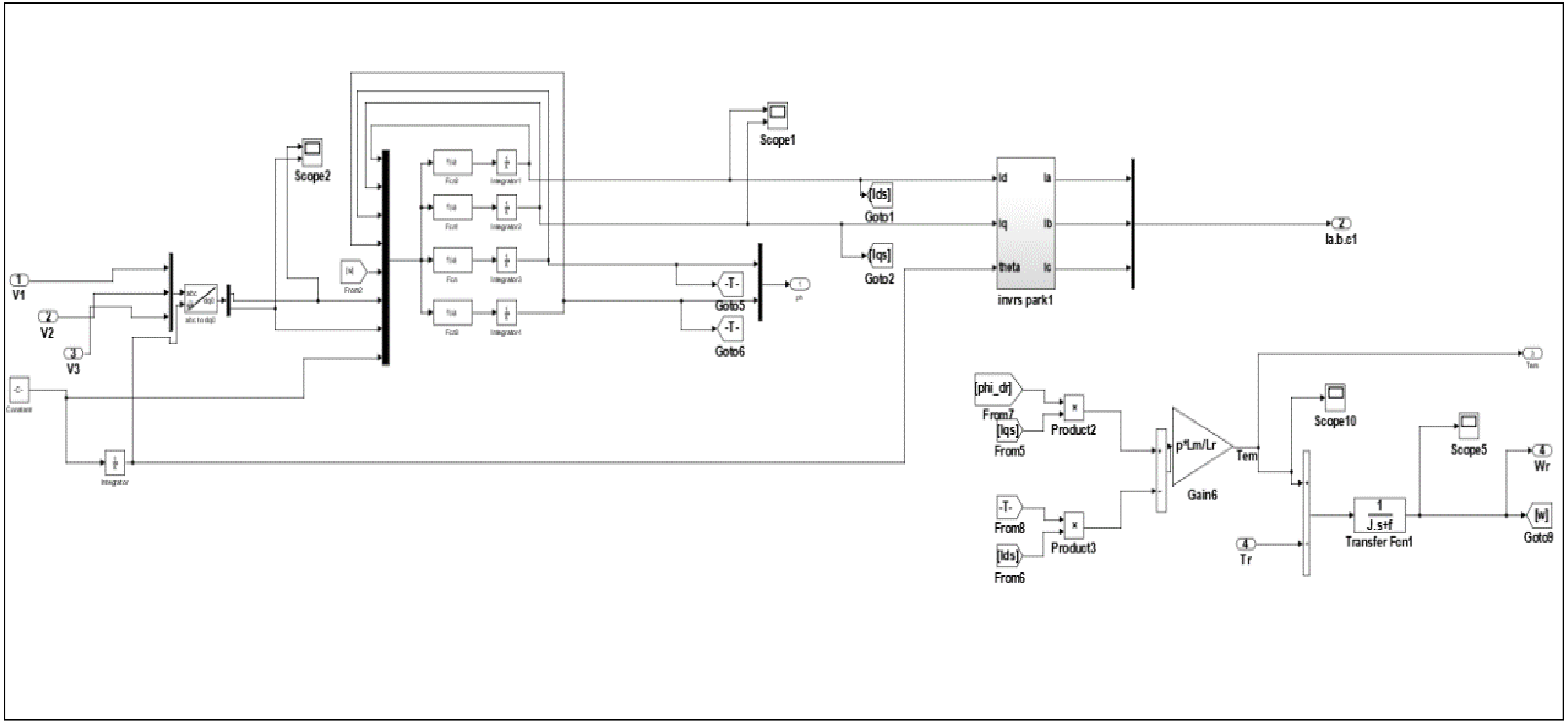


Fig IV.6: Complete SIMULINK model of the Induction Motor

IV.2.4.1 Technical Specifications of a Used Induction Motor

Fig IV.7**:** Electrical and Mechanical Specifications of SCIM

Parameter	**Specifications**
Type	Three-Phase Squirrel Cage Induction Motor
Rated Voltage	380 V (Line) / 220 V (Phase)
Frequency	50 Hz
Number of Poles	4 (p = 2)
Synchronous Speed	1500 RPM
Rated Speed	1420 RPM
Rated Power	1.4 kW
Rated Current	3 A
Power Factor (cosφ)	0.8 – 0.85
Rated Torque (No Friction)	9.41 Nm
Friction Torque	0.18 Nm
Total Torque	9.59 Nm
Moment of Inertia (J)	0.031 kg·m²
Friction Coefficient (f)	0.0012 Nm·s
Stator Resistance (Rs)	4.85 Ω
Rotor Resistance (Rr)	3.805 Ω
Inductances (Ls, Lr, Lm)	0.274 H, 0.274 H, 0.258 H

This model uses MATLAB/Simulink to illustrate how a three-phase induction motor works. The motor gets 380 volts of three-phase power. We test the motor by observing how well it performs with no load and with a load that is less than its rated capacity.

The rated load is applied to the motor shaft with a torque of 9.59 N·m at the time instant *t = 3 seconds*, after the motor has reached a steady-state operation without load. This simulation approach allows for the study of the motor's transient and steady-state responses under changing operating conditions.

The analysis focuses on four main parameters:

a/- Rotor angular speed:

- It measures how fast the rotor spins, usually in RPM or rad/s.
- Slightly lower than synchronous speed due to slip in induction motors.
- Essential for evaluating motor dynamics and load response.

b/- Electromagnetic torque:

- Torque generated by interaction between rotor current and magnetic field.
- Indicates the motor's mechanical power output.
- Key for analyzing motor performance under varying loads

c/- Stator current:

- Current flowing through the stator windings of the motor.
- Directly affects magnetic field strength and torque production.
- Useful for detecting overloads, inefficiencies, and faults.

d/- Magnetic flux:

- Represents the magnetic field linking the stator and rotor.
- Vital for inducing rotor currents and generating torque.
- Its stability ensures efficient motor operation and energy transfer.

This is aimed at understanding the effects of gradual loading on the motor's dynamics and verifying its stability and efficiency in response to various loads.

IV.2.5 Initial dynamic Assessment of Squirrel Cage Induction Motor for Control Technique Comparison

Before comparing the control techniques V/F and FOC, we need to first collect and examine the time-domain curves of important motor variables, such as rotor angular speed, electromagnetic torque, magnetic flux, and stator currents. This first analysis gives us an objective starting point that we can use later to compare the motor's behavior under the same conditions to see how well each control strategy works.

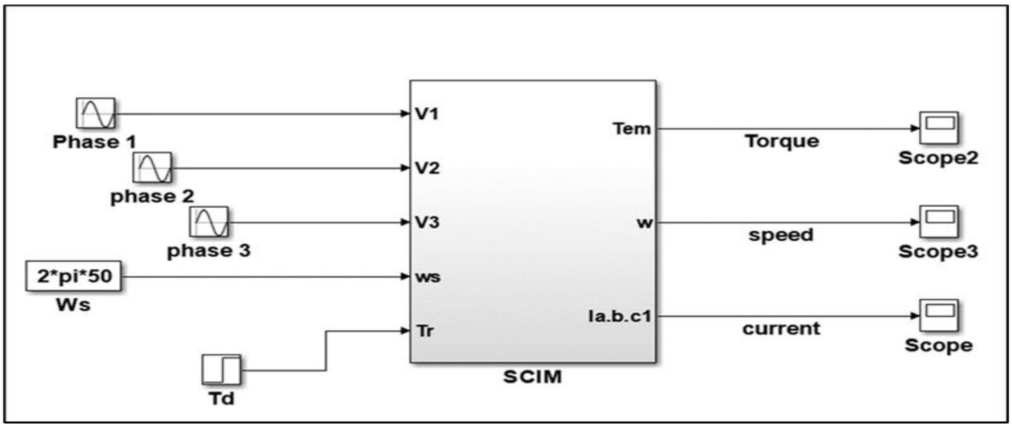


Fig IV.8: Simplified Model of the SCIM (Squirrel Cage Induction Motor)

After connecting the three-phase induction motor to a power source with a rated voltage of 380 V, it is initially run in no-load mode to achieve a steady state. At t=3 seconds, apply a rated load of 9.59 N·m to the motor shaft.

This procedure aims to record and analyze the resulting values of the main variables in both no-load and rated-load conditions, providing an accurate and reliable reference for the comparisons that will be carried out in the subsequent sections of this work.

1. **Rated Speed Curve of the SCIM :**

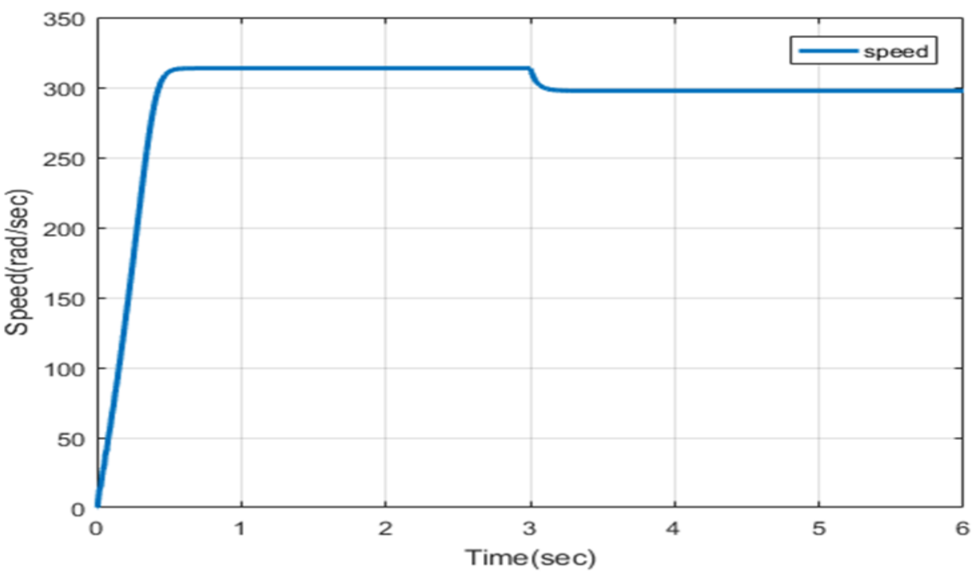


Fig IV.9: SCIM Speed Response Under No-Load and Rated Load Conditions

In the no-load condition, the induction motor's rotor angular speed curve stabilizes at a value very close to the synchronous speed, approximately 313.9 radians per second. This stabilization is due to the low torque demand in this state, which reduces energy losses caused by the load and allows the rotor to approach the rotating magnetic field speed. When the rated load is applied, the torque demand increases to meet the load requirements, causing a higher current draw from the source and resulting in a slip between the rotor speed and synchronous speed. This slip causes the angular speed to decrease and stabilize at a lower value of about 297 radians per second, reflecting the actual operating condition under load and contributing to the balance between the mechanical torque required and the electromagnetic torque produced inside the motor.

2. Rated Electromagnetic Torque in SCIM:

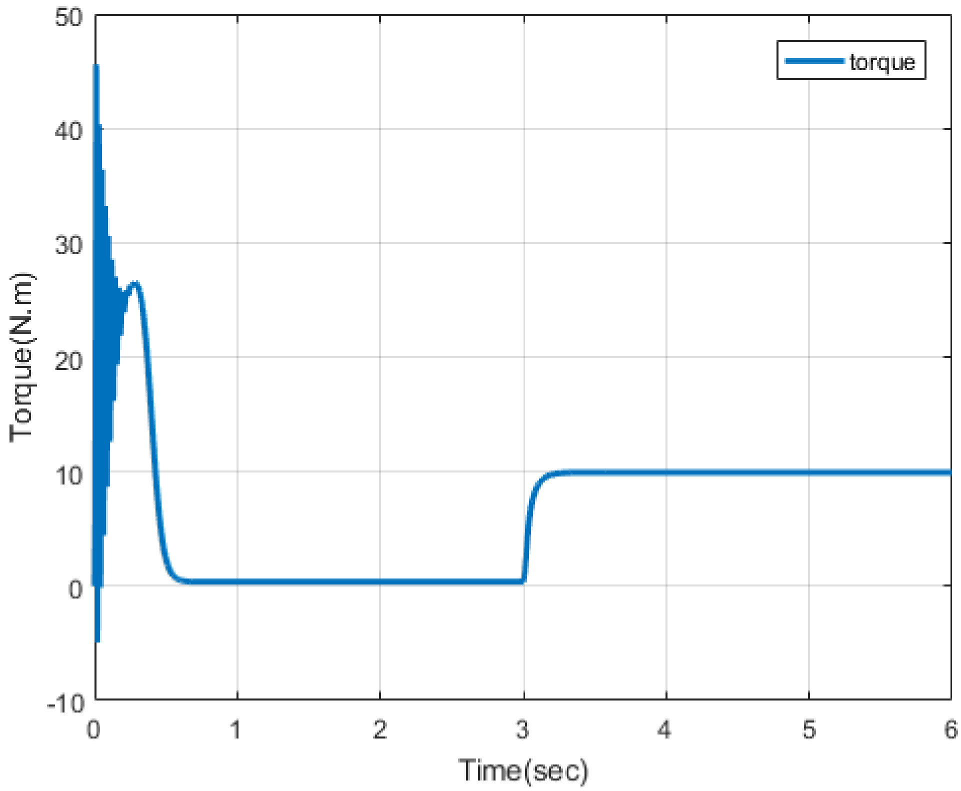


Fig IV.10: SCIM Torque Response Under No-Load and Rated Load Conditions

At startup, the electromagnetic torque curve shows a very high value due to the inrush current. Then, under no-load conditions, the torque gradually decreases to a very low value close to zero. When the rated load is applied, the torque rises and stabilizes at approximately 9.59 Newton meters, with a clear transient response visible in the curve.

The induction motor's torque depends on the difference between the rotor speed and the magnetic field's synchronous speed. At startup, this difference is at its highest, which makes the motor produce more torque. But when the motor runs without a load, the slip goes down a lot, and the torque drops to a very low level that makes up for internal losses. Subsequently, when the motor is subjected to a load, the slip escalates to produce the torque necessary to counterbalance the applied load, thereby stabilizing the torque at the specified value.

3. Rated Electric Current in SCIM:

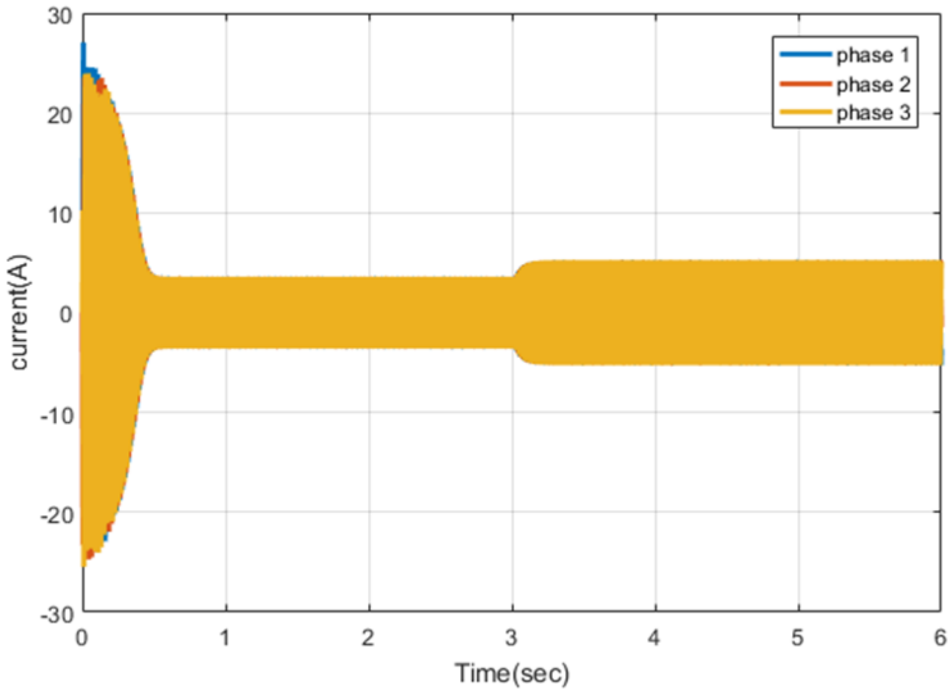


Fig IV.11: SCIM Electric Current Under No-Load and Rated Load Conditions

The current curve exhibits a high value at the startup stage. After stabilizing under no-load conditions, the current gradually decreases to about 3.6 amperes. When the rated load is added, the current goes up to about 5.2 amperes, and the time-domain curve shows a stable pattern after this change.

At startup, no back electromotive force is generated in the rotor, allowing a very high current to flow through the stator windings. Upon reaching steady-state no-load operation, the current reduces to cover only the magnetizing current and losses. When a mechanical load is applied, the total current increases to meet the higher mechanical power demand, reflecting the increased contribution of load current.

These changes serve as evidence of the mathematical model's accuracy in representing the motor's dynamic characteristics and provide a quantitative reference for comparing the motor's behavior when different control techniques are applied later.

The previous simulation results indicated that the performance of this three-phase induction motor under rated operating conditions was highly consistent with the technical specifications provided by the manufacturer. The simulation demonstrated that the final speed stabilized near the nominal value with a low slip, and the drawn current and generated torque matched the nominal specified values within acceptable tolerance limits. This agreement shows that the mathematical model for motor behavior is accurate and that the methods used for modeling and control in the study are trustworthy. Accordingly, the simulation results can be used to analyze the motor's dynamic performance and develop various control strategies.

IV.3 Simulation of V/F and FOC Control Methods using MATLAB/ SIMULINK

In this section, we will model how a three-phase induction motor works using detailed math for two control methods—voltage/frequency (V/f) control and field-oriented control (FOC), which we discussed in chapters two and three. The modeling features electrical and mechanical connections that clearly explain how the motor operates, as well as the ability to switch between stationary and synchronous reference frames as needed.

We used these models to make simulation sets for both strategies in MATLAB/Simulink. The goal was to examine how the motor reacted to different operating conditions, like rapid changes in load or speed reference. The simulations focused on important factors like torque, current, speed, and how well the system worked.

This study looks at the pros and cons of each technique regarding stability, response speed, and control accuracy, allowing for a fair comparison between the two methods to find the best option for high-performance uses.

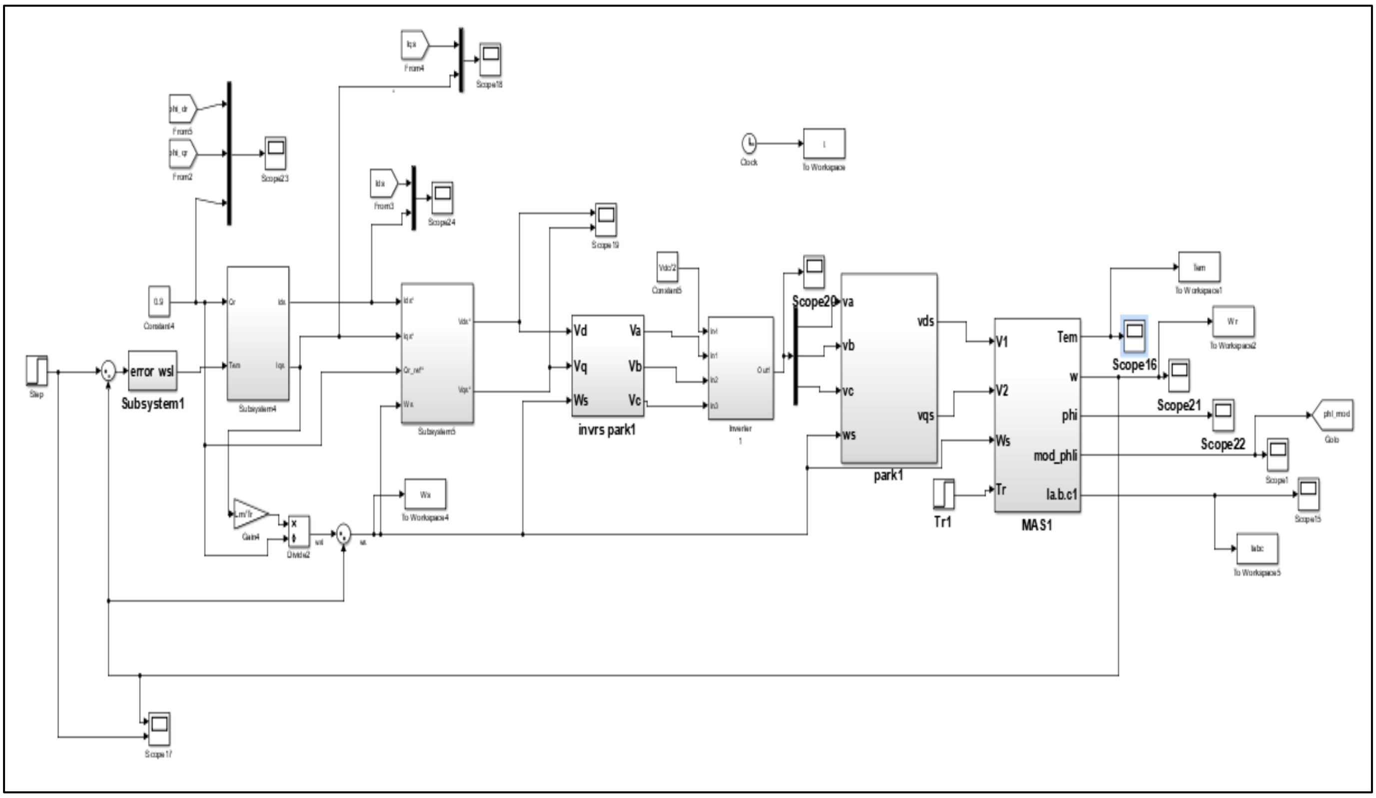


Fig IV.12 : Field Oriented Control SIMULINK.

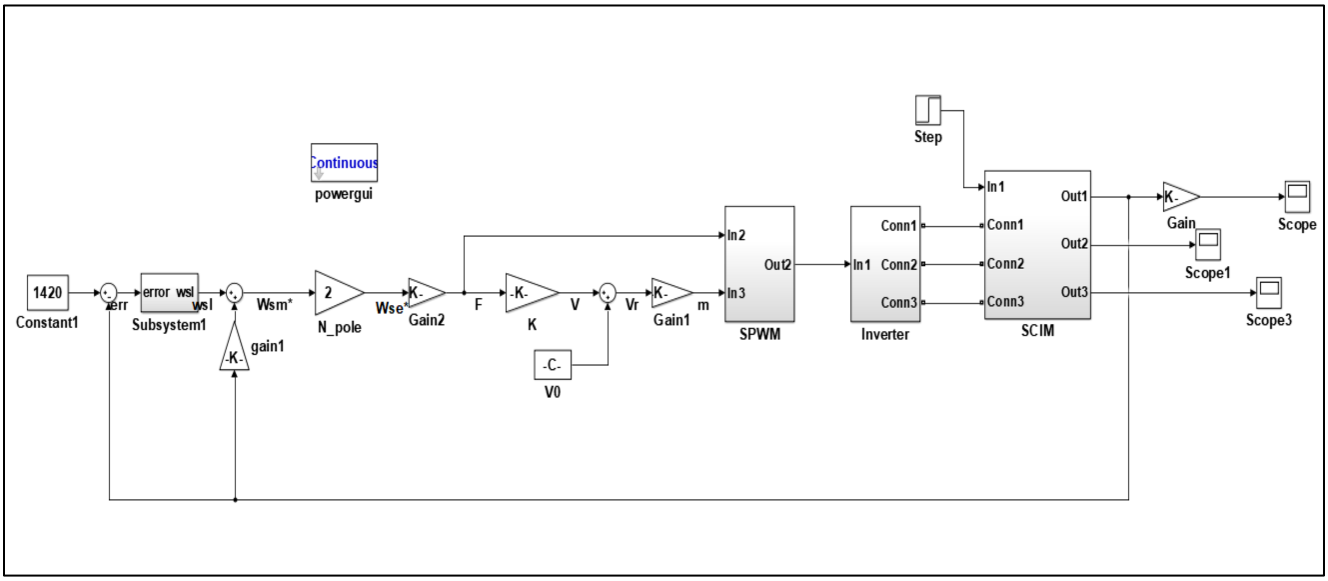
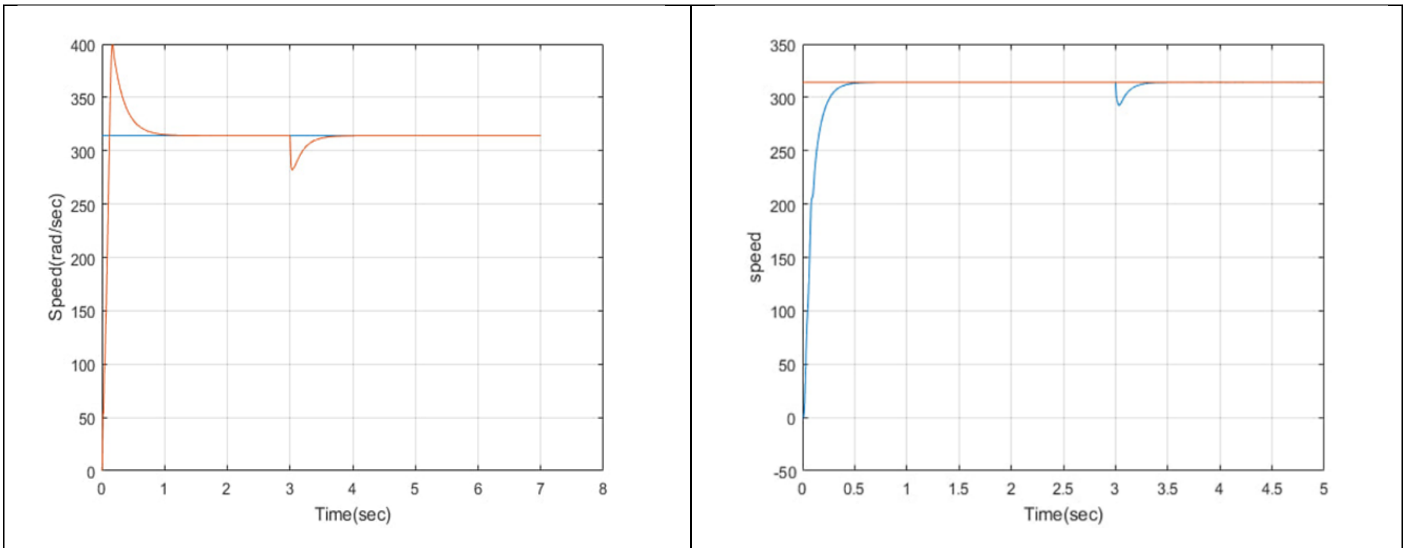


Fig IV.13 : Scalar Control V/F SIMULINK.

IV.3.1 Evaluation and Analysis of Motor Performance Parameters at Steady Speed Under Varying Load

- ***Rotor Speed Curves:***



(a) V/f Control (b) FOC Control

Fig IV.14: Rotor Speed Curves (a) V/f, (b) FOC

During startup, using the Field-Oriented Control (FOC) technique is very fast, with the speed reaching a steady-state value in approximately 0.045 seconds. Similarly, when the rated load is applied, the curve shows a brief transient response that stabilizes in less than 0.03 seconds. Additionally, the decline in speed due to load application is limited, with the speed decreasing only to around 292 rad/s, which indicates a fast and accurate dynamic response. This pattern reflects the effectiveness of FOC in maintaining speed stability and quickly overcoming disturbances, thanks to the dynamic decoupling between torque and flux components.

On the other hand, the speed curve under V/f control reacts much more slowly. It takes around 1.02 seconds to reach a steady state after startup and 0.8 seconds to stabilize after loading an application. Furthermore, the decline in speed when under load is bigger; it goes down to about 278 rad/s instead of 292 rad/s when using Field-Oriented Control (FOC). The large drop shows that V/f control can't quickly adjust to changes in load, leading to lower performance and longer response times because it depends on a basic voltage-to-frequency relationship and doesn't directly control the current components.

- **Electromagnetic Torque Curves:**

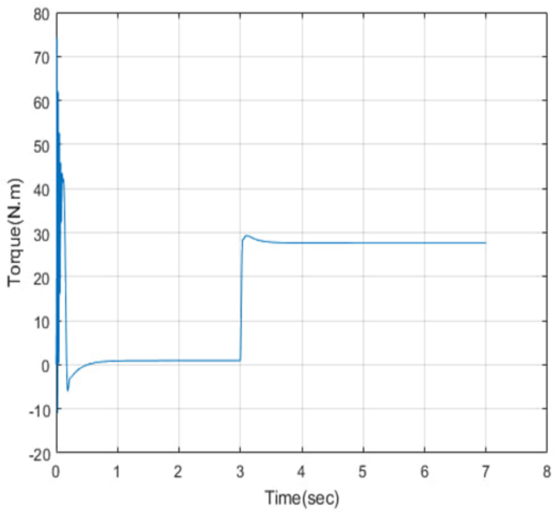
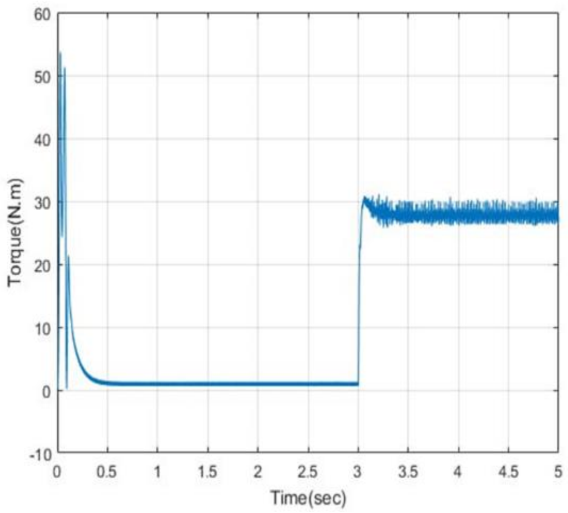
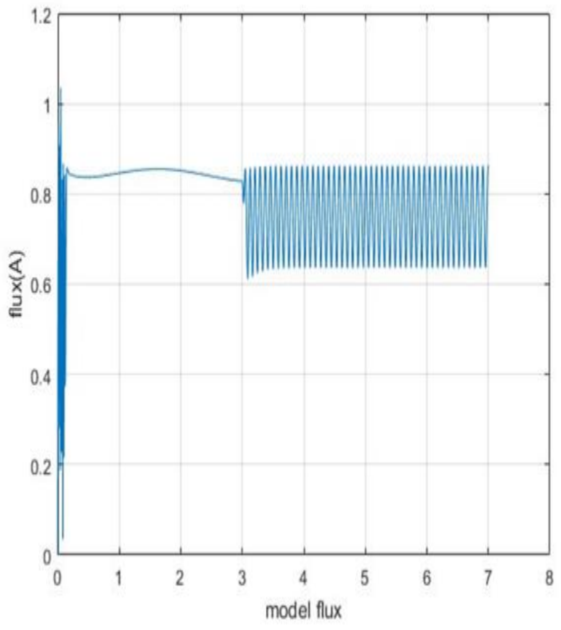
	
(a) V/f control	(b) FOC control

Fig IV.15: Electromagnetic Torque Curves (a) V/f, (b) FOC

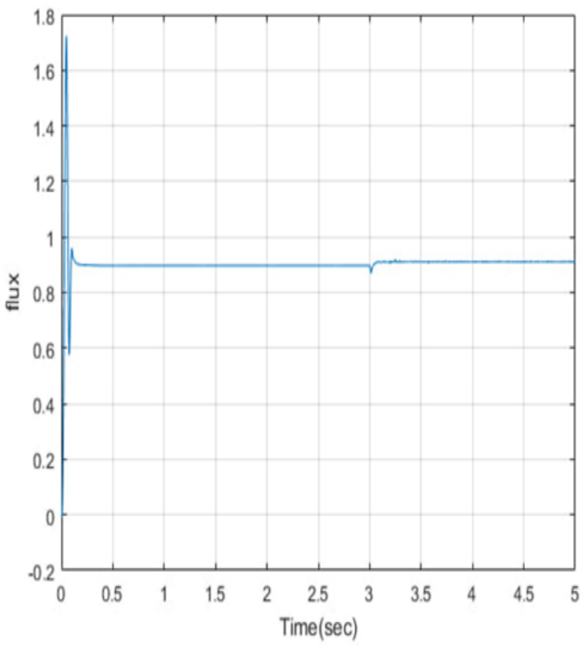
The electromagnetic torque curve shows that the V/f control approach has a high starting torque of roughly 75 N·m. This difference can be explained by not being able to control the current components very well, which causes large inrush currents and, as a result, a higher initial torque. However, the curve demonstrates that transitions aren't smooth as the load varies, with visible oscillations and a relatively slow reaction. Such behavior shows how V/f control can't quickly adjust to sudden changes in how things work.

In contrast, with Field-Oriented Control (FOC), the starting torque is relatively lower at around 55 N·m, yet it is sufficient for efficient motor startup. The torque curve in the FOC case displays a smooth and stable transition from no-load to full-load conditions, with a fast and accurate response and minimal oscillations. This stability is due to FOC's ability to control the torque-producing and magnetizing current components independently.

- **Magnetic Flux Curves:**



(a) V/f Control



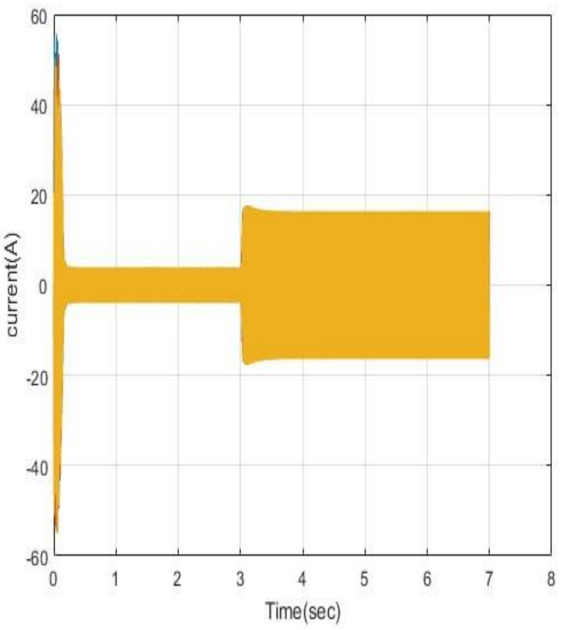
(b) FOC Control

Fig IV.16: Magnetic Flux Curves (a) V/f, (b) FOC

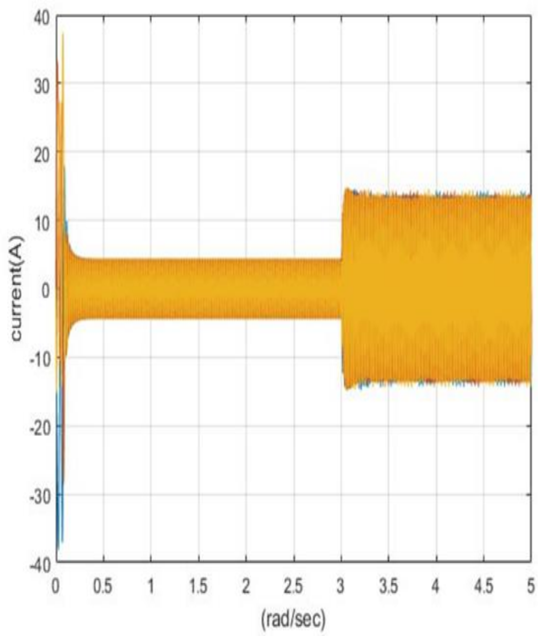
The magnetic flux curve indicates that the field-oriented control (FOC) technique keeps the magnetic flux very stable during operation, whether there is no load or a full load. The curve shows an almost flat line with no distortions, indicating efficient control of the magnetizing current thanks to the dynamic decoupling of current components.

On the other hand, noticeable distortions emerge in the magnetic flux curve under V/f control, particularly when the motor is under load. This issue occurs due to the absence of direct control over the magnetizing current component, leading to undesirable variations in the flux under changing operating conditions. Such behavior negatively affects torque stability and overall motor performance, making this one of the significant drawbacks of this control strategy when compared to FOC.

- **Stator Current Curves:**



(a) V/f Control



(b) FOC Control

Fig IV.17: Stator Current Curves **(a)** V/f, **(b)** FOC

The current waveform shows that the Field-Oriented Control (FOC) technique uses less current while working, staying below about 45 amperes even when fully loaded. This result shows how well FOC uses energy and gets the needed performance with as little current as possible. This reduction is likely because the current components (magnetizing and torque-producing) are controlled precisely and distributed optimally.

When V/f is in charge, on the other hand, the drawn current is much higher, reaching up to 60 amperes under identical conditions. This disparity is because there is no direct control over the current components, which means that too much energy is used to get the right amount of torque. Such behavior is one of the leading indicators of V/f's lower efficiency compared to FOC, especially in applications where energy consumption must be optimized.

IV.3.2 Evaluation and Analysis of Motor Performance Parameters under Constant Load and Varying Speed

- ***Rotor Speed Curves:***

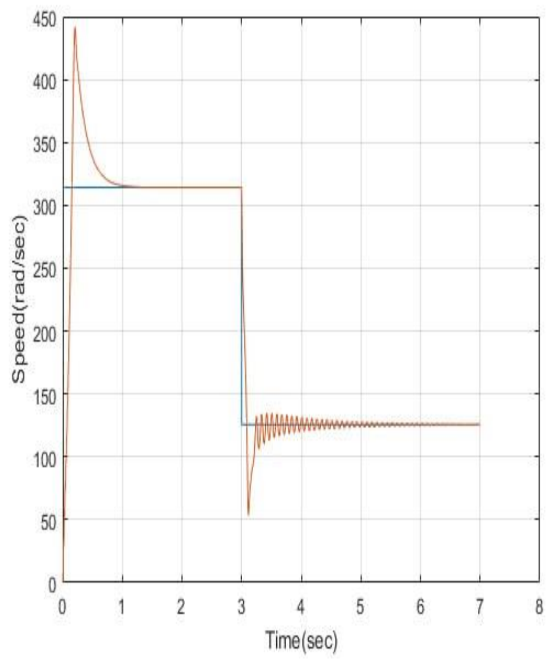
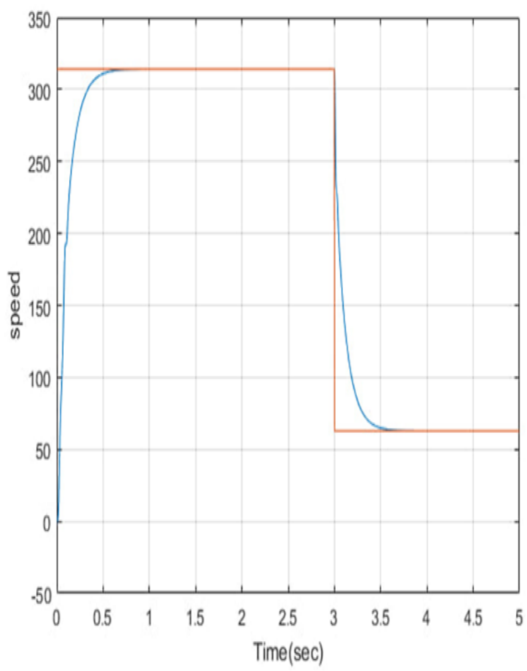
	
(a) V/f Control	(b) FOC Control

Fig IV.18: Rotor Speed Curves (a) V/f, (b) FOC

When we look at the angular speed curve at low speeds, we can see that the Field-Oriented Control (FOC) method gives a smooth and stable response. The curve stays steady without any visible changes or oscillations. FOC can precisely manage the current components, which keeps the motor's performance consistent even at low speeds.

On the other hand, V/f control has stability problems at low speeds, as the speed curve shows clear oscillations and fluctuations. These problems happen because voltage and frequency are less accurate in this operating range, and V/f control can't change the signal exactly to fit the motor's needs. This circumstance makes it harder for things to move smoothly and for the system to stay stable.

- **Electromagnetic Torque Curves:**

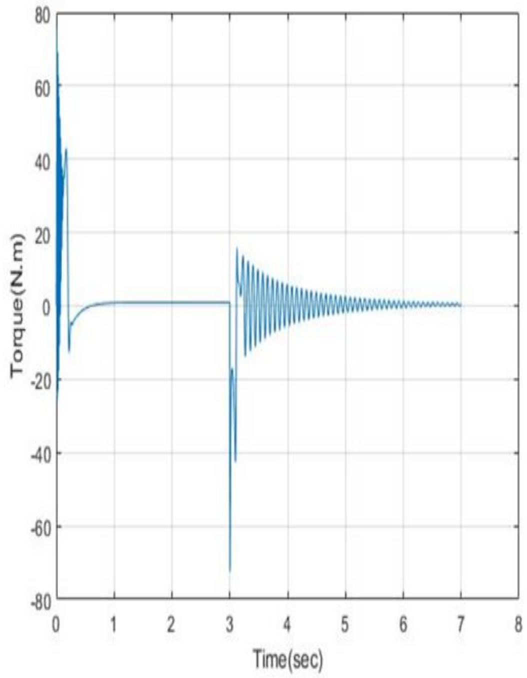
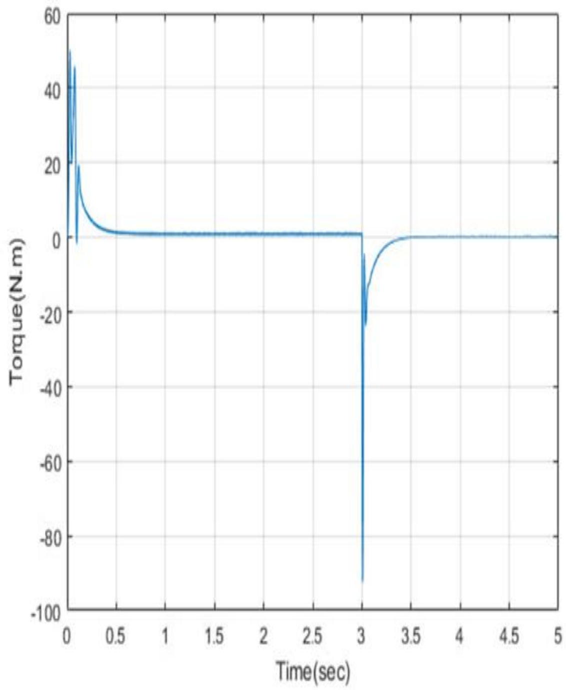
	
(a) V/f control	(b) FOC control

Fig IV.19: Electromagnetic Torque Curves (a) V/f, (b) FOC

The electromagnetic torque curve shows that the Field-Oriented Control (FOC) method keeps the torque stable even when the speed is low. When the load changes and the speed drops temporarily, the system can swiftly recover and stabilize the torque without any visible oscillations. This shows how well FOC can manage torque because it separates the torque and flux components.

In contrast, under V/f control, the torque exhibits clear oscillations and fluctuations at low speeds, making it difficult to quickly stabilize when speed or load changes occur. This is due to the limitations of this technique in directly controlling torque, leading to weaker dynamic performance and unstable response, especially under non-rated operating conditions.

- **Magnetic Flux Curves:**

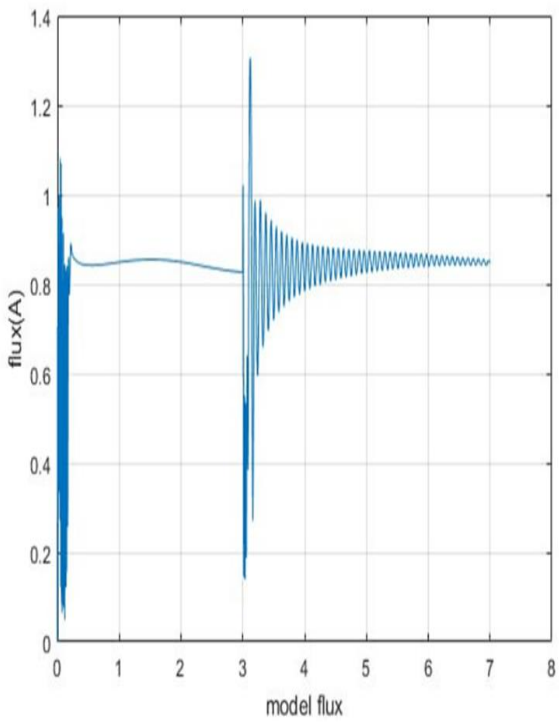
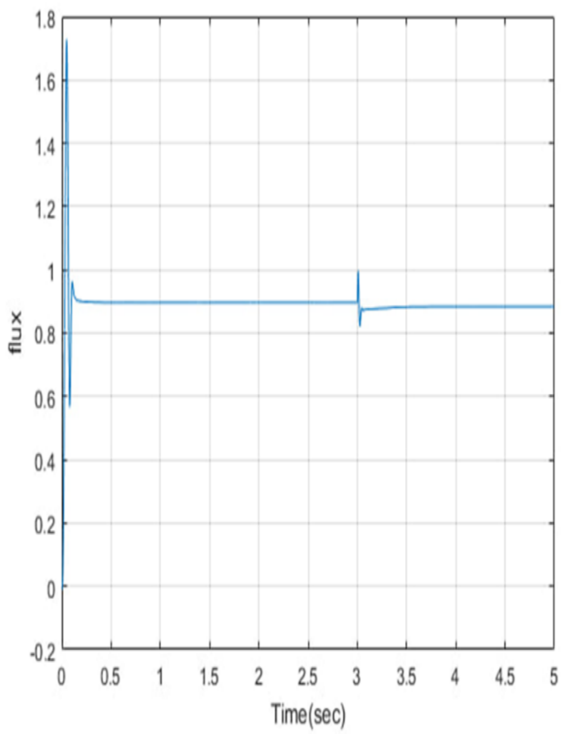
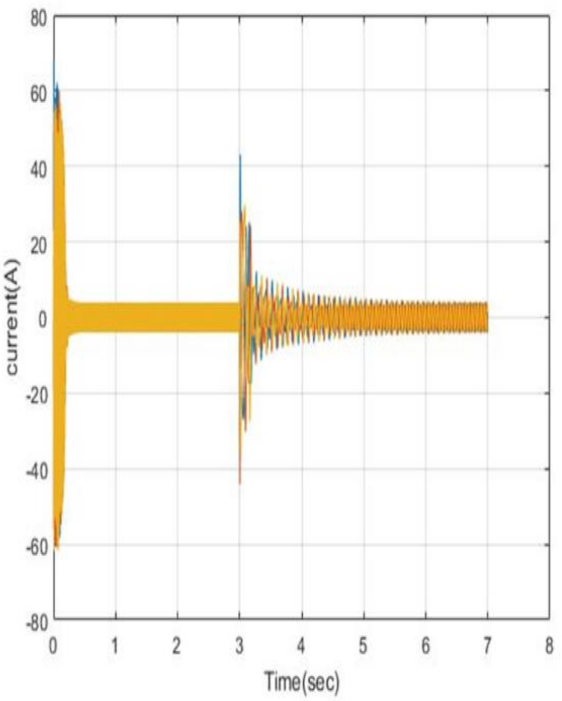
	
(a) V/f Control	(b) FOC Control

Fig IV.20: Magnetic Flux Curves (a) V/f, (b) FOC

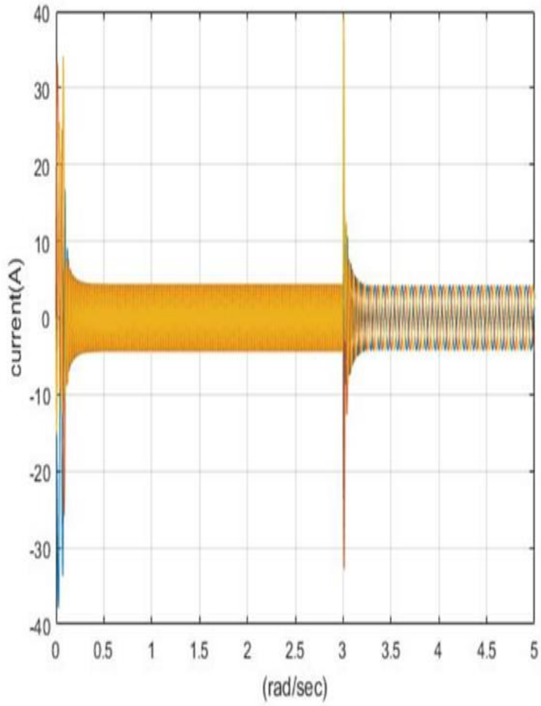
The magnetic flux remains stable and consistent over time when using Field-Oriented Control (FOC), both during steady-state operation and in response to changes in speed or load. This reflects the precise control over the magnetizing current, which is decoupled from the torque-producing component, allowing the flux to remain unaffected by dynamic conditions.

On the other hand, in V/f control, the flux curve shows disturbances and oscillations, especially after operating at low speeds. These fluctuations are due to the lack of direct regulation of the magnetizing current, which causes the flux to vary unintentionally under changing conditions. This results in degraded torque performance and contributes to the instability of the overall motor operation.

- **Stator Current Curves:**



(a) V/f Control



(b) FOC Control

Fig IV.21: Stator Current Curves (a) V/f, (b) FOC

The starting current in V/f control can reach a peak of about 60 A, which is very high and can put a lot of stress on the motor and power supply parts. This spike happens because there isn't enough precise control when the motor starts up. The voltage-to-frequency ratio is applied evenly without any feedback from how the motor is actually doing.

Field-oriented control (FOC), on the other hand, has a much lower starting current of about 40 A and stays steadier during both the startup and running phases. This result shows that FOC works well to change the current components in real time to meet the motor's needs. This method makes the system more efficient and puts less stress on the electrical system.

IV.3.3 dynamic decoupling In FOC technique:

The Field-Oriented Control (FOC) method splits the electric current into two parts: Ids, which makes the magnetic flux, and Iqs, which makes the torque. As we talked about in Chapter III, this dynamic decoupling lets you regulate each part separately. For example, you can stabilize the magnetic flux curve by managing IDs, and you can change the torque curve as needed using Iqs without one influencing the other.

This method provides excellent flexibility and significantly improves the **motor's dynamic response**, especially under varying conditions or during sudden load changes. It also helps reduce torque ripples and maintain performance stability.

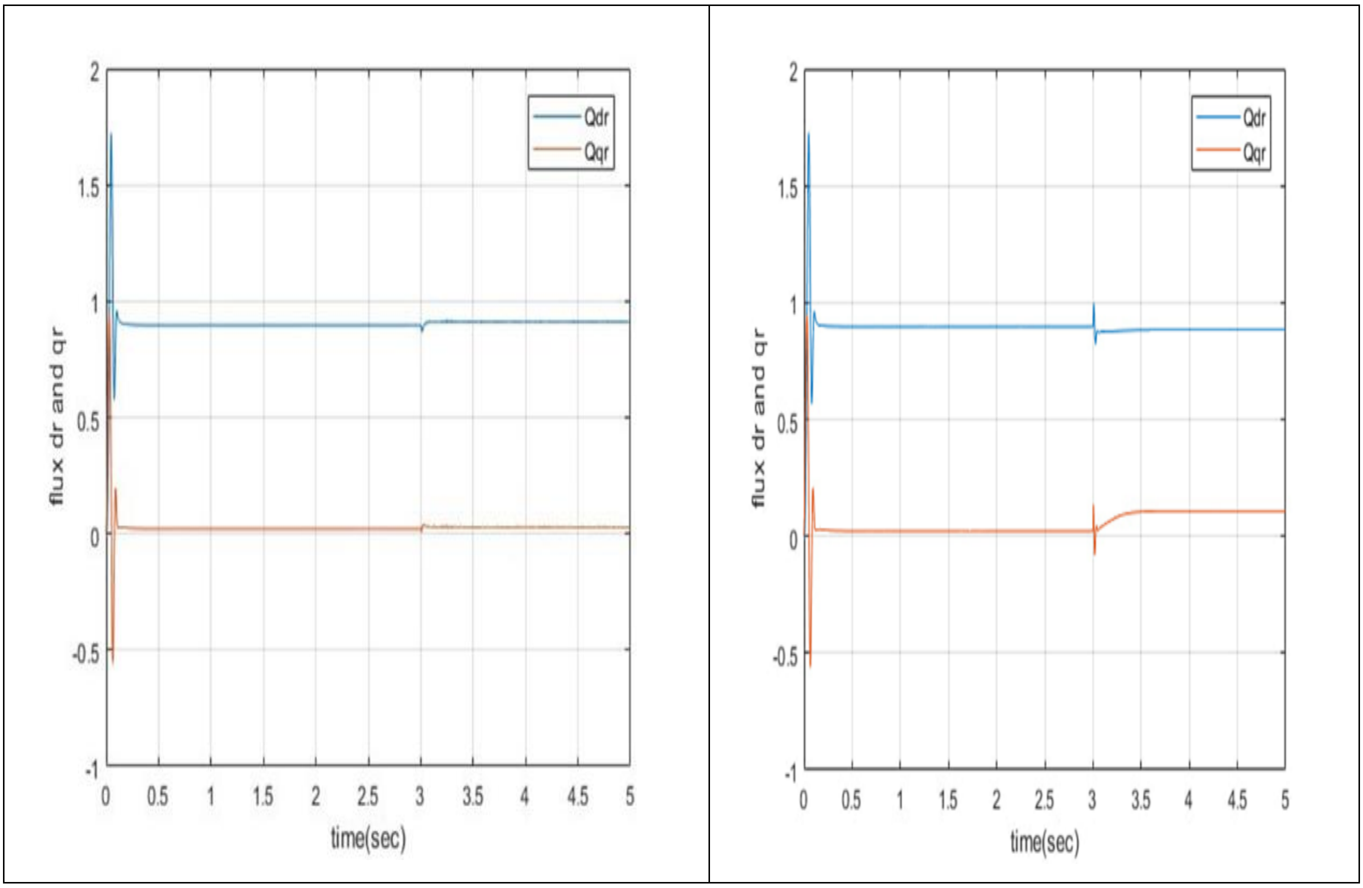


Fig IV.22: Separated Components of the Flux Curves: Qdr and Qqr

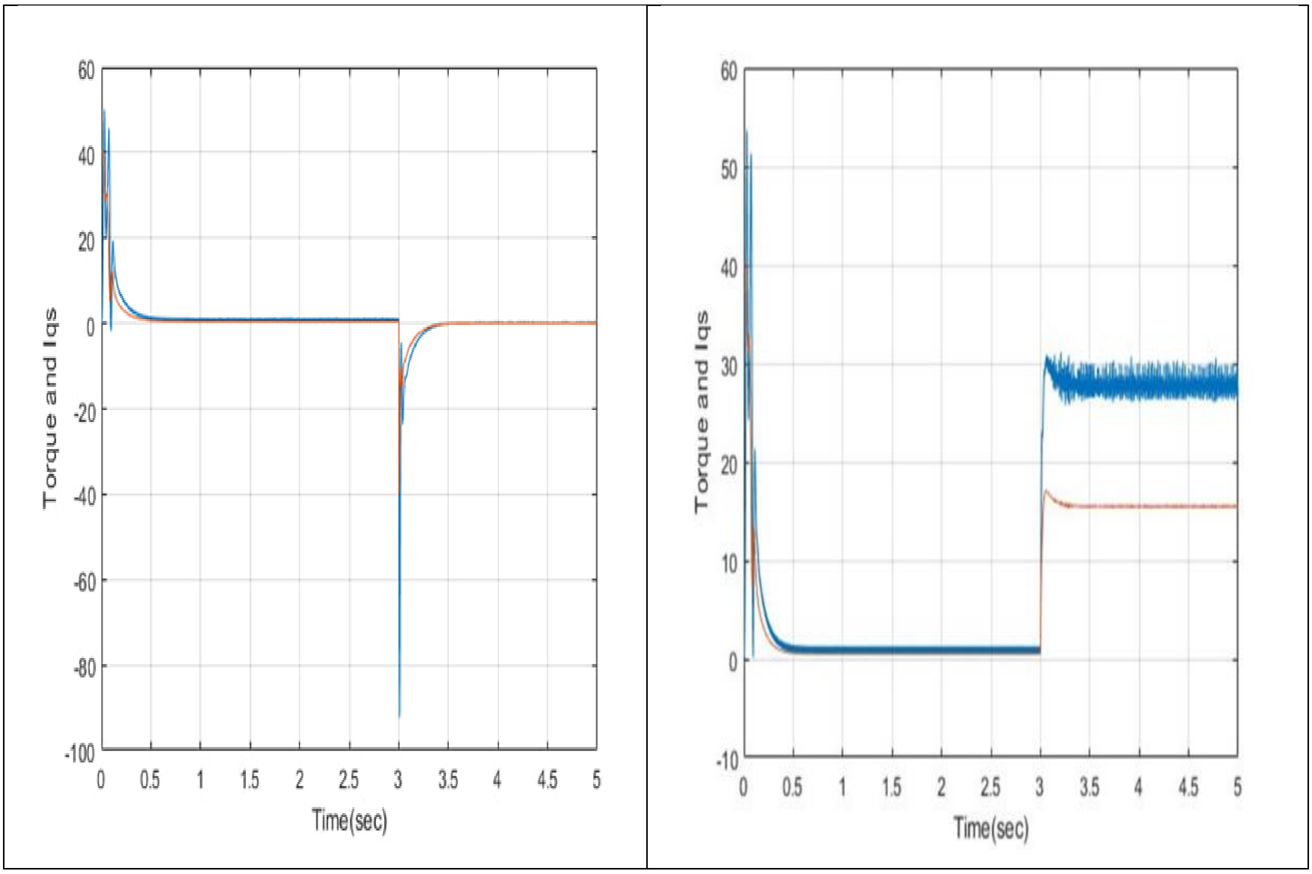


Fig IV.23: Torque Curve (Tem) and Current Curve (Ids)

By observing the electromagnetic torque curve (Tem) and the Ids current curve, it is evident that the torque closely follows the variations in Ids, both in increasing and decreasing phases. This is because the Ids current represents the primary component responsible for generating the magnetic flux inside the motor, which in turn is the fundamental factor in producing electromagnetic torque.

Therefore, any change in Ids is directly reflected in the value of Tem, making the Ids curve effectively a mirror of the torque behavior in real-time. This highlights the strong relationship between the magnetizing current component and the generated torque in the FOC control scheme.

IV.4 A comparative Analysis table of Scalar Control and Rotor Field-Oriented Control: Key Differences and Performance Aspects

Parameters	**V/f (Closed Loop)**	**FOC (Closed Loop)**	**Advantage**
Dynamic Response	Relatively slow	Fast and precise	**FOC**
Torque Stability	Unstable with flux changes	Stable due to decoupling	**FOC**
Initial Cost	Low	High	**V/f**
Energy Efficiency	Moderate	High	**FOC**
Maintenance	Simple	Complex and requires expertise	**V/f**
Implementation Complexity	Simple	High	**V/f**
Long-Term Efficiency & Sustainability	Limited	Excellent	**FOC**
Speed and Torque Control Accuracy	Low	High	**FOC**
Load Change Response	Slow	Fast	**FOC**
Application Flexibility	Limited	Broad	**FOC**

Conclusion

This chapter shows that field-oriented control (FOC) offers better control of torque and speed, as well as quick responses in different situations, such as when loads change or at low speeds. FOC can isolate the components of magnetizing and torque-producing currents and manage them independently. This feature enhances the system's stability and efficiency over time, mitigates losses, and bolsters overall stability.

V/f control, on the other hand, is quick to set up and use. Therefore, it's an excellent choice for applications with steady and straightforward operating needs. It doesn't need expensive hardware or fast processors, which makes it easier to keep up and costs less. However, its performance becomes limited at low speeds or during sudden load variations, where a slow response and oscillations in torque and speed are observed due to the lack of separation between current components and the influence of flux variations on torque.

Based on the above, the choice of an appropriate control strategy should depend on the nature and complexity of the industrial application. When high precision, rapid response, and adaptability to changing conditions are required, FOC is the ideal choice despite its higher cost. However, for simpler systems that do not require high accuracy, V/f remains a practical and economical alternative, with awareness of its limitations in dynamic environments.

General Conclusion and Futuer Work

GENERAL CONCLUSION AND FUTUER WORK

IV.5 General Conclusion

This work provided a thorough comparison of scalar control (voltage/frequency or V/f control) and field-oriented control (FOC) for induction motor drives. These two ways of controlling the motor's torque and speed are completely unique. Each has its pros and cons, as well as situations where it works best.

Scalar Control, or V/f control, works by keeping the voltage-to-frequency ratio the same so that the magnetic flux in the motor stays about the same. This technology is easy to use, doesn't need much feedback, and is commonly employed in industrial settings where low cost, easy setup, and modest performance are acceptable. Scalar Control has particular problems with dynamic performance, though, because it is open-loop or very slightly closed-loop. Scalar control can't separate torque and flux, which makes response times slower, speed tracking less accurate, and torque control worse, especially when the load changes or the conditions change. Even with these problems, its simplicity makes it ideal for low-performance tasks like fans, pumps, and HVAC systems where precise control isn't necessary.

Conversely, Field-Oriented Control (FOC) offers a more advanced and dynamic methodology by isolating the torque and flux-generating elements of the stator current via coordinate transformation into a rotating reference frame. This technique simulates the control attributes of a DC motor, providing autonomous regulation of torque and flux, enabling the motor to react swiftly and precisely to variations in speed or load. FOC works better because it responds quickly, has less torque ripple, runs smoothly, and is more efficient. It works exceptionally well for high-performance tasks like robotics, electric vehicles, elevators, and precision manufacturing systems where speed and accuracy are critical. FOC has benefits, but it also makes it harder to put into action. To figure out the rotor's position or speed, you need many sensors or complex estimating methods, as well as a lot of computing power for the transformations and control loops that are required. Furthermore, to get the best performance, control parameters need to be carefully tuned, which might be hard for people who aren't experts or systems that don't cost a lot.

During the MATLAB/Simulink-based simulation-based comparison, it was clear that FOC always did better than Scalar Control when the speed reference changed quickly or the load changed. FOC was able to keep its stability better, settle down faster, and respond to torque more consistently. Scalar Control, on the other hand, fell behind, especially when there was a lot of demand or sudden changes.

Both approaches struggle to perform well in unusual situations, such as when the voltage drops or the power goes out. Scalar Control might keep working even when there are small problems, but it won't be able to keep the right speed or torque. FOC is better in normal settings, but it could become unstable or less reliable if the supply voltage drops below the level needed for correct flux estimation. This experiment shows how important protection mechanisms and high-quality power supplies are in FOC systems.

In conclusion, this study indicates that no one control mechanism is better than all the others. You should choose between scalar control and field-oriented control based on the demands of the application, weighing performance needs against system complexity, cost, and the amount of work needed to implement it. Scalar Control is still a good and valuable option for applications that have consistent load circumstances and don't need to change too often. Field-oriented control, on the other hand, is the apparent choice when high accuracy, quick response time, and efficiency are most important. This is because it is worth the extra expense and complexity that come with implementing it.

IV.6 Recommended Future Work

Future research in this area should include a more comprehensive analysis comparing the two significant methods. Numerous potentials persist for more exploration and development:

Future work could include implementing both control techniques on real-time embedded devices like DSPs or FPGAs. This would allow testing performance in real-world situations, taking into account the effects of hardware limits and sensor errors.

Adding more advanced control methods to the study, including Direct Torque Control (DTC), Model Predictive Control (MPC), or controllers based on artificial intelligence (like fuzzy logic or neural networks), could give us a better idea of the trade-offs in performance.

A complete analysis of how both control techniques respond to different kinds of electrical and mechanical faults, such as broken rotor bars, voltage drops, and phase loss, may reveal more about the system's reliability and strength.

Analyzing and comparing how energy-efficient the two approaches are under different load levels and how they affect the motor's heating and cooling needs should help designers who care about energy use.

Future studies may investigate sensor-less implementations of FOC, where rotor position or speed is predicted instead of measured. This could lower costs and simplify the system while maintaining good performance.

Learning how these control tactics work when the induction motor gets power from changing sources like solar inverters or is part of innovative grid systems will make them more useful in modern, eco-friendly systems.

Focusing on adaptive or self-tuning control algorithms that can automatically improve performance parameters in both V/f and FOC systems could make them more useful in changing situations.

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الجمهورية الجزائرية الديمقراطية الشعبية
PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
MOHAMED KHIDER UNIVERSITY OF BISKRA
FACULTY OF SCIENCES AND TECHNOLOGY
VICE DEAN IN CHARGE OF STUDIES AND ISSUES RELATED TO STUDENTS
Réf. : /2024

وزارة التعليم العالي والبحث العلمي
جامعة محمد خيضر - بسكرة
كلية العلوم و التكنولوجيا
نيابة العمادة المكلفة بالدراسات والمسائل المرتبطة بالطلبة
المرجع : /ن.ع.م.د.م.م.ط/2024

بسكرة في :

السيد : مدير مؤسسة (Agrodiv)
المركب الصناعي والتجاري_ تزليزة_ولاية تيميمون

الموضوع: إجراء تربص

في اطار تكوين في طور الماستر 2 تخصص : الطاقات المتجددة في الكهروتقني قسم : الهندسة الكهربائية

للطالب(ة) : BOUHSI YAHIA

عنوان المذكرة : A Comparative Study Between (Scalar Control) and (Rotor Field Oriented Control) Techniques in Squirrel Cage Induction Motors in industrial environments.

تحت اشراف الأستاذ : بوستة عبير

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Réf. : /2024 — المرجع : /ن.ع.م.د.م.م.ط/2024

اتفاقية تربص

بين

المؤسسة الجامعية: **جامعة محمد خيضر بسكرة** ممثلة من طرف : **غضبان حاتم عميد كلية العلوم والتكنولوجيا**

و

المؤسسة / الادارة المستقبلة **موسسة (Agrodiv) المركب الصناعي والتجاري_ تزليزة_ولاية تيميمون** ممثلة من طرف مدير المؤسسة.

المادة الاولى: أحكام عامة

تخضع هذه الاتفاقية لأحكام المادة 6 من المرسوم التنفيذي رقم 13-306 المؤرخ في 24 شوال عام 1413 الموافق 31 غشت سنة 2013 ، و المتضمن تنظيم التربصات الميدانية و في الوسط المهني لفائدة الطلبة و المتعلق بطبيعة التربصات الميدانية و في الوسط المهني لفائدة الطلبة و تقييمها و مراقبتها.

المادة 2: موضوع الاتفاقية

تهدف هذه الاتفاقية الى تحديد اطار تنظيم و سير التربصات الميدانية و في الوسط المهني لفائدة طلبة قسم **الهندسة** الكهربائية كلية العلوم و التكنولوجيا جامعة محمد خيضر بسكرة

يخص التربص الطالب (ة) المسجل (ة) لنيل شهادة الماستر في **تخصص: الطاقات المتجددة**

للطالب (ة) : **Bouhsi Yahia** المزداد(ة) بتاريخ: بـ **21/05/1999** بـ **تينركوك_ تيميمون**

المادة 3: أهداف التربص

يهدف التربص التكويني الى السماح للطالب بتطبيق معارفه النظرية والمنهجية التي تحصل عليها خلال تربصه و إنجاز مشروع نهاية الدراسة بتحضير مذكرة.

يهدف التربص إلى تحضير الطالب للحياة المهنية. ويندرج التربص ضمن المسار البيداغوجي للطالب وهو إجباري للحصول على شهادة الثانية ماستر

المادة 4: مواضيع التربصات و تنظيم العمل

تترك مواضيع التربصات وكذا مخططات عمل المتربصين والاهداف المرجوة من التربصات لتقدير المشرفين على التربصات وتحدد حسب برنامج الدراسات وموضوع نهاية الدراسة المصادق عليه من طرف المشرف الأستاذ الباحث للمؤسسة الجامعية بموافقة الهيئات البيداغوجية لكلية العلوم والتكنولوجيا جامعة محمد خيضر بسكرة والهيئات المعنية بالتكفل بالتربصات في مؤسسة أو إدارة الاستقبال.

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الجمهورية الجزائرية الديمقراطية الشعبية
PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH — وزارة التعليم العالي والبحث العلمي
MOHAMED KHIDER UNIVERSITY OF BISKRA — جامعة محمد خيضر - بسكرة
FACULTY OF SCIENCES AND TECHNOLOGY — كلية العلوم و التكنولوجيا
VICE DEAN IN CHARGE OF STUDIES AND ISSUES RELATED TO STUDENTS — نيابة العمادة المكلفة بالدراسات والمسائل المرتبطة بالطلبة

Réf. : /2024 — المرجع : /ن.ع.م.د.م.م.ط/2024

المادة 5: تعيين المؤطرين ومسؤولي التربصات

تعين المؤسسة الجامعية أستاذا باحثا مؤطرا للتربص وهو : **بوستة عبير** وتعين المؤسسة المستقبلة مسؤولا للتربص.

تعيين الاطارات التقنية (مسؤولو التربص) المكلفة بمتابعة المتربصين من طرف. المؤسسة المستقبلة ويجب أن يكونوا متحصلين على شهادة مهندس دولة أو ما يعادلها على الاقل وذوي خبرة.

يوضع ا لمتربص خلال تواجده في أماكن التربص تحت السلطة السلمية لمسؤول التربص المعين .

يجب على ا لمتربص خلال تواجده في أماكن التربص الاحترام التام لأحكام النظام الداخلي للمؤسسة أو الإدارة المستقبلة و المصلحة التي ألحق بها.

المادة 6: الكيفيات العملية لسير التربص

- **مدة التربصات:**
- فترة التربص من **19/12/2024** إلى **02/01/2025**.
- **المادة 7:** شروط مختلفة

-التغطية الاجتماعية للمتربص:

تضمن المؤسسة الجامعية التغطية الاجتماعية عند وقوع حادث بسبب أوبمناسبة التربص في المؤسسة ، تقع مسؤولية التصريح بحادث العمل على عاتق المؤسسة أو الإدارة التي يتم فيها التربص.

يجب على الإدارة أو المؤسسة المستقبلة أن ترسل إلى المؤسسة الجامعية التي ينتمي إليها المتربص دون تأخير، نسخة من التصريح بحادث العمل ا لمرسل إلى هيكل الضمان الاجتماعي المختص.

المادة 8: سريان الاتفاقية

تسري هذه الاتفاقية ابتداء من تاريخ توقيعها من الطرفين.

بسكرة في : ....
عميد الكلية

عميد كلية العلوم و التكنولوجيا
أ.د واغضبان حاتم

رأي المؤسسة المستقبلة

Amine ABDELMALEK
Directeur du Complexe

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