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Design and Simulation of an IFOC Based Solar Water Pumping System with MPPT Control

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Dedication

The journey was not easy, nor was the dream within immediate reach. Yet, by the grace of Allah, perseverance, and determination, we have finally reached this important milestone.

We dedicate this humble work to our beloved parents, whose endless sacrifices, support, and prayers have been the foundation of our success. Their encouragement and guidance have inspired us throughout this journey.

We also extend our sincere gratitude to our families, friends, classmates, and everyone who supported us, encouraged us, or contributed in any way to the completion of this work.

To all of you, we dedicate this achievement with deep appreciation and respect. Without the blessings of Allah and your unwavering support, this success would not have been possible.

Thanks and Appreciation

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and enabled us to accomplish this work.

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for accepting to evaluate this modest work and for enriching it with their valuable academic

remarks.

Abstract

This work presents the modeling and simulation of a standalone solar-powered water pumping system. The proposed system consists of a photovoltaic (PV) array, a DC-DC boost converter, a voltage source inverter (VSI), a three-phase induction motor, and a centrifugal pump.

To maximize the utilization of solar energy, a Maximum Power Point Tracking (MPPT) technique based on the Perturb and Observe (P&O) algorithm is implemented. In addition, an Indirect Field Oriented Control (IFOC) strategy is employed to ensure accurate control of the speed and torque of the induction motor. The overall system is modeled and simulated using MATLAB/Simulink.

Simulation results demonstrate the effectiveness of the proposed control strategies in improving energy utilization, ensuring stable operation, and enhancing the dynamic performance of the water pumping system. The obtained results confirm the suitability of the proposed solution for water pumping applications in remote and off-grid areas.

Keywords: Photovoltaic system, Solar Water Pumping, Induction Motor, MATLAB/Simulink.

الملخص

يتناول هذا العمل نمذجة ومحاكاة نظام مستقل لضخ المياه يعمل بالطاقة الشمسية الكهروضوئية. يتكون النظام من مولد شمسي، ومحول رافع للجهد (Boost)، وعاكس جهد (VSI)، ومحرك حثي ثلاثي الطور، ومضخة طرد مركزي. تم اعتماد تقنية تتبع نقطة القدرة العظمى (MPPT) المعتمدة على خوارزمية الاضطراب والملاحظة (P&O) لتعظيم القدرة المستخرجة من المصفوفة الشمسية، كما تم استخدام تقنية التحكم غير المباشر الموجه بالمجال (IFOC) للتحكم في سرعة وعزم المحرك. أظهرت نتائج المحاكاة باستخدام MATLAB/Simulink فعالية النظام المقترح وكفاءته في تطبيقات ضخ المياه بالمناطق النائية.

الكلمات المفتاحية : الطاقة الشمسية الكهروضوئية، ضخ المياه الشمسي، المحرك الحثي

. MATLAB/Simulink

Résumé

Ce travail porte sur la modélisation et la simulation d'un système de pompage d'eau autonome alimenté par un générateur photovoltaïque. Le système est constitué d'un convertisseur DC-DC Boost, d'un onduleur VSI, d'un moteur asynchrone triphasé et d'une pompe centrifuge. Afin d'optimiser l'exploitation de l'énergie solaire, une commande MPPT basée sur l'algorithme Perturb and Observe (P&O) est adoptée. Le moteur est contrôlé par la stratégie Indirect Field Oriented Control (IFOC), garantissant une bonne régulation de la vitesse et du couple. Les résultats obtenus sous MATLAB/Simulink confirment l'efficacité du système proposé pour les applications de pompage dans les zones isolées.

Mots-clés : Système photovoltaïque, Pompage d'eau, Moteur asynchrone, Convertisseur Boost.

List of Abbreviations

PV	Photovoltaic
DC	Direct current
AC	Alternating current
MPPT	Maximum Power Point Tracking
Voc	Open-circuit voltage
Isc	Short-circuit current
Vmpp	Voltage at maximum point
P&O	Perturbation and Observation Algorithm
VSI	Voltage Source Inverter
PI	Proportional Integral
PWM	Pulse Width Modulation
IM	Induction Machine

Table of contents

<i>Dedication</i>	I
<i>Thanks and Appreciation</i>	II
Abstract.....	III
List of Abbreviations.....	IV
Table of contents.....	V
List of Figures.....	IX
List of Tables.....	XI
General Introduction	I
CHAPTER I: General Overview of Photovoltaic Pumping Systems	2
I.1.Introduction.....	3
I.2.Solar Radiation.....	3
I.3. Types of Solar Radiation.....	3
I.3.1. Direct Solar Radiation.....	3
I.3.2. Diffuse Solar Radiation.....	3
I.3.3. Reflected Solar Radiation.....	4
I.3.4. Global Solar Radiation.....	4
I.4. Solar Energy.....	4
I.4.1. Photovoltaic solar energy.....	5
I.4.1.1. The photovoltaic effect.....	5
I.5. Photovoltaic cells.....	6
I.5.1. Operating Principle of Photovoltaic Cells.....	7
I.6. Different types of photovoltaic cells.....	8
I.6.1. Mono crystalline cells.....	8
I.6.2. Polycrystalline cells.....	8
I.6.3. Amorphous silicon cells.....	9
I.6.4. Comparison of different technologies.....	10
I.7. Photovoltaic modules.....	10
I.7.1. Role of the PV solar module.....	11
I.8. Connection of photovoltaic modules.....	11
I.8.1. Series connection.....	11
I.8.2. Parallel Connection.....	11

I.8.3. Mixed connection (Series – Parallel)	12
I.9. photovoltaic system	12
I.9.1. Autonomous systems	13
I.9.2. Grid-connected systems	13
I.9.3. Hybrid systems	14
I.10. Power electronic converters	15
I.10.1. DC-DC converters	15
I.10.2. DC-DC Converters for Solar Energy Systems	15
I.10.3. types of DC-DC converters	16
I.11. Advantages and disadvantages of a photovoltaic system	16
I.11.1. Advantages	16
I.11.2. disadvantages	16
I.12. What constitutes a photovoltaic pumping system	16
I.13. Photovoltaic Pumping Systems	17
Figure I.18: General configuration of a photovoltaic pumping system	17
I.13.1. Autonomous Photovoltaic Systems	17
I.13.2. Grid-connected photovoltaic systems	18
I.14. Electrochemical energy storage system	19
I.14.1. Operating Principle of a Battery	19
I.14.2. Battery Characteristics	19
I.14.3. The different types of batteries	20
I.14.3.1. Lead or lead-acid batteries	20
I.14.3.2. Nickel-cadmium batteries	20
I.14.3.3. Les batteries au nickel-zinc	20
I.14.3.4. Sodium–nickel chloride batteries	21
I.14.3.5. Lithium-ion batteries	21
I.14.3.6. Lithium-ion polymer batteries	21
I.14.3.7. Metal hydride batteries	21
I.15. Pumping subsystem	22
I.15.1. Pumps	22
I.15.1.1. The different types of pumps	22
I.15.1.2. Positive displacement pump	23
I.15.1.3. Centrifugal pump	23
I.15.1.4. Structure of a centrifugal pump	23
I.16. Motors	24

I.16.1. Direct Current Motor	24
I.16.2. Synchronous motors	24
I.16.3. Asynchronous motors	24
I.17. Conclusion	25
CHAPTER II : Modeling of Photovoltaic Pumping System	26
II.1.Introduction	27
II.2. Photovoltaic generator modeling	27
II.2.1. Parameters of a photovoltaic cell	27
II.2.1.1. Short-circuit current I_{sc}	27
II.2.1.2.Open-circuit voltage	27
II.2.1.3. Maximum power	28
II.2.1.4.Efficiency	28
II.2.1.5. Fill Factor	28
II.2.2. Electrical Model of a Photovoltaic Generator	28
II.2.2.1. Single-Diode Model	28
II.2.3.Effect of Irradiance	31
II.2.4.Effect of Temperature	32
II.3.1. Principle of operation	32
II.3.2. Equivalent mathematical model	33
II.3.3. Conversion and yield report	34
II.4. Step-down converter (Buck converter)	34
II.4.1. Principle of operation	34
II.4.2. Equivalent Mathematical model	35
II.4.3. Conversion and yield report	36
II.5. Buck-Boost Converter	36
II.5.1. Principle of operation	37
II.5.2. Conversion and yield report	38
II.6. Modeling of the Asynchronous Machine (Induction Machine)	39
II.6.1.Simplifying Assumptions	39
II.6.2.Equivalent Mathematical model of IM	39
II.7. Modeling of the Centrifugal Pump	41
II.8. Conclusion	42
CHAPTER III : Control of Photovoltaic Pumping System	43
III.1.Introduction	44
III.2. Control of the Photovoltaic Pumping System	44

III.2.1.MPPT Control (Maximum Power Point Tracking)	44
III.2.1.1. Perturb and Observe (P&O) Method	44
III.2.2. Inverter Control	48
III.2.2.1. Current Control Using Hysteresis Regulators	48
III.3. Field-Oriented Control	49
III.3.1 Flux Orientation Selection	49
III.3.2. Types of Vector Control	49
III.3.2.1 Direct Vector Control	50
III.3.2.2 Indirect Vector Control	50
III.4. Principle of Vector Control	50
III.4.1. Input–Output Decoupling	51
III.4.2. Basic Block Diagram of Vector Control	53
III.5. Regulation	54
III.5.1. Controller Design	54
III.5.2. Characteristics of Controllers	55
III.5.3. Calculation of regulators	55
III.5.3.a. Speed Controller	55
III.5.3.b. Flux Controller	56
III.6. Conclusion	57
CHAPTER IV: Simulation of Photovoltaic Pumping System	58
IV.1.Introduction	59
IV.2.System under processing	59
IV.3. System Description	60
IV.4. Simulation Results	61
IV.5. Conclusion	70
General Conclusion	71
List of References	74
Appendices	81

List of Figures

Figure I.1: Components of Solar Radiation.....	4
Figure I.2: Solar spectrum.....	5
Figure I.3: Working Principle of the Photovoltaic Effect.....	6
Figure I.4: A photovoltaic cell.....	7
Figure I.5: Principle of Photovoltaic Cells.....	8
Figure I.6: Monocrystalline cells.....	8
Figure I.7: Polycrystalline cells.....	9
Figure I.8: Amorphous silicon cells.....	9
Figure I.9: Composition of a photovoltaic (PV) solar module.....	10
Figure I.10: Series connection of solar cells.....	11
Figure I.11: Parallel connection of photovoltaic cells.....	12
Figure I.12: Parallel and series connection of photovoltaic cells.....	12
Figure I.13: Autonomous photovoltaic installation.....	13
Figure I.14: Diagram of a grid-connected photovoltaic installation.....	14
Figure I.15: Autonomous hybrid photovoltaic installation.....	14
Figure I.16: Symbol of a DC-DC converter.....	15
Figure I.17: Principle of DC–DC Converter Voltage Regulation.....	16
Figure I.19 : Schematic diagram of a standalone system without electrochemical storage.....	18
Figure I.20: Components of a Centrifugal Pump.....	23
Figure II.1: Equivalent circuit of the single-diode model.....	29
Figure II.2: I–V and P–V curves for different irradiance levels.....	32
Figure II.3: I–V and P–V curves for different irradiance levels.....	32
Figure II.4: Basic diagram of a Boost converter.....	33
Figure II.5: Equivalent circuit diagram of the boost chopper when $t \in [0; \alpha, T_s]$	33
Figure II.6: Equivalent circuit of a boost chopper when $t \in [\alpha, T_s; T_s]$	34
Figure II.7: Shape of the conversion ratio as a function of the duty cycle.....	34
Figure II.9 : Principle diagram of a Buck converter.....	34
Figure II.10: Equivalent circuit diagram of the series chopper when $t \in [0, \alpha T_s]$	35
Figure II.11: the conversion ratio $M(d)$ of a series chopper (DC-DC converter).....	36
Figure II.12: Buck-Boost Converter.....	36
Figure II.13: Equivalent circuit of a Buck-Boost converter when $t \in [0, \alpha T_s]$	37
Figure II.14: Equivalent circuit of a Buck-Boost converter when $t \in [\alpha T_s, T_s]$	37
Figure II.15: Conversion ratio as a function of the duty cycle.....	38
Figure II.16: Representative diagram of a three-phase inverter.....	38

Figure III.1: Operating characteristic of the P&O method.....	45
Figure III.2: Flowchart of the P&O Method.....	46
Figure III.3: Divergence of the P&O Method.....	47
Figure III.4: Principle of Hysteresis Current Control.....	48
Figure III.5: Flux Orientation (Rotor, Stator, and Air-Gap Flux).....	49
Figure III.6: Principle of decoupling control of the Induction Motor (IM).....	51
Figure III.7: Reconstruction of the V_{sd} and V_{sq} Voltages.....	52
Figure III.8: Decoupled control expressions of rotor flux and the electromagnetic torque.....	53
Figure III.9: Basic Block Diagram of Vector Control.....	54
Figure III.10: Block Diagram of the PI Control.....	54
Figure III.11: Block Diagram of Speed Control.....	55
Figure III.12: Functional Block Diagram of the Flux Controller.....	56
Figure IV.1: Block Diagram of the Photovoltaic Water Pumping System.....	59
Figure IV.2: Solar Irradiance Variation Profile.....	61
Figure IV.3: Dynamic Response of Photovoltaic Current.....	61
Figure IV.4: Dynamic Response of Photovoltaic Power.....	62
Figure IV.5: Dynamic Response of Duty Cycle.....	62
Figure IV.6: Dynamic Response of Boost Converter Current.....	63
Figure IV.7: Dynamic Response of the Boost Converter Output Voltage.....	63
Figure IV.8: Dynamic Response of Boost Converter Power.....	64
Figure IV.9: Motor Direct and Quadrature Voltage Response.....	64
Figure IV.10: Dynamic Response of Direct and Quadrature Currents.....	65
Figure IV.11: Induction Motor Three-Phase Voltages.....	65
Figure IV.12: Induction Motor Three-Phase Currents.....	66
Figure IV.13: Dynamic Response of Electromagnetic Torque.....	66
Figure IV.14: Dynamic Response of Motor Speed.....	67
Figure IV.15: Dynamic Response of Mechanical Power.....	67
Figure IV.16: Dynamic Response of Pump Load Torque.....	68
Figure IV. 17: Dynamic Response of Pump Power (P_{pump}).....	69
Figure IV.18: Dynamic Response of Hydraulic Head (H).....	69
Figure IV.19: Dynamic Response of Pump Water Flow Rate.....	70

List of Tables

Table I.1.: Comparison of different cell technologies.....	10
Table III.1: Principle of the P&O Algorithm.....	46

General Introduction

General Introduction:

Since the widespread use of electricity, global energy consumption has continuously increased. At the same time, the environmental impact of fossil fuels, together with the depletion of conventional energy resources, has encouraged the development of renewable and sustainable energy sources. Among these resources, photovoltaic (PV) solar energy has emerged as one of the most promising alternatives due to its availability, environmental friendliness, and suitability for remote areas .[1]

One of the most important applications of photovoltaic energy is water pumping, particularly in isolated rural regions where access to the electrical grid is limited but solar irradiance is abundant. Photovoltaic water pumping systems are commonly used for domestic water supply, livestock watering, and small-scale irrigation. These systems generally consist of a photovoltaic generator, a DC–DC power converter, a voltage source inverter, an electric motor, and a hydraulic pump.[2]

The present work deals with the modeling and simulation of a photovoltaic water pumping system with hydraulic storage. The proposed system aims to ensure efficient energy conversion, maximum power extraction from the photovoltaic generator, and reliable control of the induction motor driving the centrifugal pump under varying environmental conditions. This dissertation is organized into four chapters as follows:

Chapter One introduces the basic concepts of photovoltaic solar energy and photovoltaic water pumping systems, together with the operating principles and characteristics of their main components.

Chapter Two presents the mathematical modeling of the different components of the proposed system, including the photovoltaic generator, DC–DC converters, the Voltage Source Inverter (VSI), the three-phase induction motor, and the centrifugal pump.

Chapter Three describes the control strategies implemented in this work. It focuses on the Maximum Power Point Tracking (MPPT) algorithm used to maximize the extracted photovoltaic power and the Indirect Field-Oriented Control (IFOC) technique adopted for the induction motor.

Chapter Four presents and discusses the simulation results obtained using MATLAB/Simulink. The dynamic performance of the proposed photovoltaic water pumping system is evaluated under different operating conditions to verify the effectiveness of the adopted control strategy.

CHAPTER I: General Overview of Photovoltaic Pumping Systems

I.1.Introduction

Solar energy represents an alternative to conventional fossil fuels. It is a renewable energy source that depends on the sun and is considered inexhaustible. It is also a clean and environmentally friendly source of energy due to its low carbon dioxide (CO₂) emissions. Through solar panels or solar thermal power plants, solar radiation can be converted into electrical or thermal energy. [1].

Photovoltaic solar energy consists of the direct conversion of solar radiation into electrical energy using photovoltaic panels composed of solar cells. This energy is used in various applications, among which solar water pumping systems are particularly important. These systems use the electricity generated by photovoltaic panels to operate water pumps, providing an economical and environmentally sustainable solution for water supply, especially in remote areas.

In this chapter, a general overview of photovoltaic solar energy and its importance is presented, starting from the solar cell and extending to the photovoltaic system and its applications in solar water pumping systems.

I.2.Solar Radiation

The energy that reaches the ground is less than 1354 W/m² (the solar constant) because part of the solar radiation is absorbed by the atmosphere (about 15%) and re-emitted in all directions in the form of diffuse radiation. The atmosphere also reflects a portion of the solar radiation back into space (about 6%). Thus, the global radiation at ground level is the sum of direct radiation and diffuse radiation. The energy received by a surface depends on several factors such as the season, altitude, weather conditions, terrain, pollution, the orientation of the surface, etc. At ground level, several components are distinguished [1].

I.3. Types of Solar Radiation

I.3.1. Direct Solar Radiation

It is received directly from the sun, without being scattered by the atmosphere. It is the difference between global radiation and diffuse radiation [2].

I.3.2. Diffuse Solar Radiation

It consists of light scattered by the atmosphere (air, cloudiness, aerosols). Scattering is the phenomenon that divides a parallel beam into a multitude of beams spreading in all directions. In the sky, air molecules, water droplets (clouds), and dust particles all contribute to this dispersion of the sun's rays. Therefore, it mainly depends on weather conditions [3].

I.3.3. Reflected Solar Radiation

It is the radiation that is reflected by the ground or by objects located on its surface. This albedo can be significant when the ground is particularly reflective (such as water, snow, etc.) [4].

I.3.4. Global Solar Radiation

On a horizontal surface: It is the total solar radiation coming from the sun that reaches a horizontal surface on planet Earth. This therefore includes the vertical component of direct solar radiation as well as diffuse solar radiation.

On an inclined surface: Global radiation on an inclined surface corresponds to the sum of direct, diffuse, and reflected radiation [2].

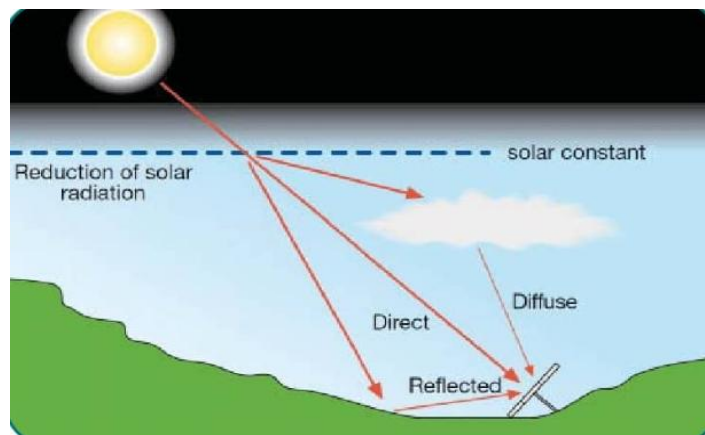


Figure I.1: Components of Solar Radiation

I.4. Solar Energy

The Sun irreversibly transforms every second 564 million tons of hydrogen into 560 million tons of helium. The Sun therefore loses 4 million tons, which are dispersed in the form of radiation. The energy emitted by the Sun each second is therefore about 3.85×10^{26} W. However, only a very small fraction of this power is received by the Earth because of the small solid angle under which our planet is seen from the Sun: approximately two billion times less. This still gives a considerable value (about 1.9×10^{17} W)..

The solar energy received per unit area perpendicular to the Sun's rays, at a Sun–Earth distance equal to its average value, is called the solar constant, which is estimated at $1,367 \text{ W}\cdot\text{m}^{-2}$ [5] [6].

Albert Einstein, while working on the photoelectric effect, discovered that light does not only have a wave nature, but that its energy is also carried by particles called photons. The energy of a photon is given by the relation:

$$E = h.c^2 \dots\dots\dots (I.1)$$

h : Planck's constant.

c : the speed of light.

Thus, the shorter the wavelength, the greater the energy of the photon [7]. The Sun emits electromagnetic radiation (Figure I.2) within a wavelength band ranging from 0.22 to 10 microns (μm) [8].

The energy associated with this solar radiation is approximately distributed as follows:

- ❖ 9% in the ultraviolet band ($< 0.4 \mu\text{m}$).
- ❖ 47% in the visible band (0.4 to $0.8 \mu\text{m}$).
- ❖ 44% in the infrared band ($> 0.8 \mu\text{m}$).

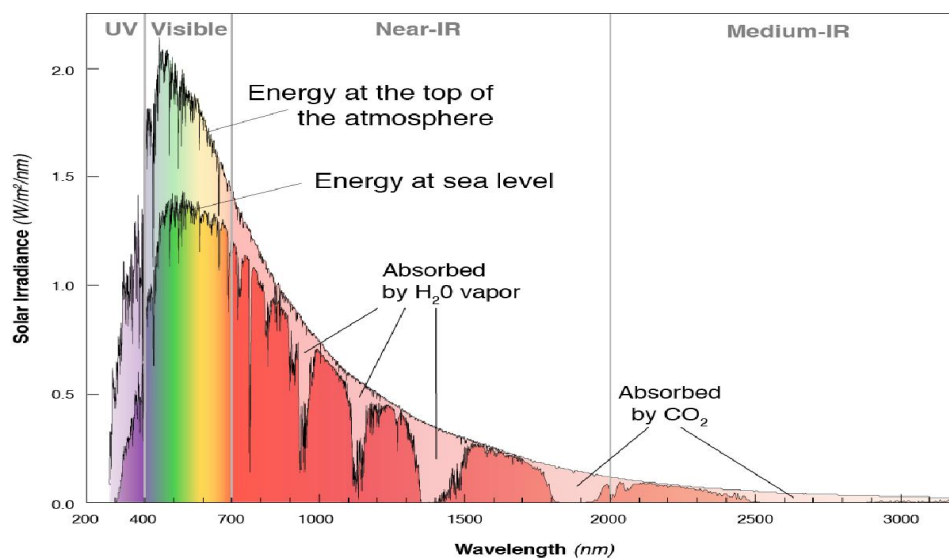


Figure I.2: Solar spectrum[9]

I.4.1. Photovoltaic solar energy

Photovoltaic solar energy harnesses the sun as a source of light. This energy is captured and converted into electricity using solar panels installed on the façades or roofs of buildings. This conversion process is known as the photovoltaic effect [12] [13].

I.4.1.1. The photovoltaic effect

The photovoltaic effect is a process that converts solar energy, emitted in the form of photons, into electrical energy using a semiconductor device called a solar cell [14]

However, this effect can only occur if a potential barrier exists within the semiconductor prior to illumination. Such a barrier appears, for example, at the interface between two differently doped regions, where two types of impurities are introduced at different concentrations, thereby forming a P–N junction. When this material is exposed to light, the incident photons transfer their energy to the electrons in the semiconductor, making them mobile. Under the influence of the potential barrier, the generated electric charges are separated: positive charges

move to one side while negative charges move to the other side, which results in the generation of an electric current [14]

Among the materials used in the fabrication of photovoltaic cells, crystalline silicon is the most widely used and currently accounts for approximately 90% of the photovoltaic panels produce worldwide. Nevertheless, other technologies also exist, such as thin-film solar cells, which are already industrialized, as well as other technologies that are still under research and development [15].

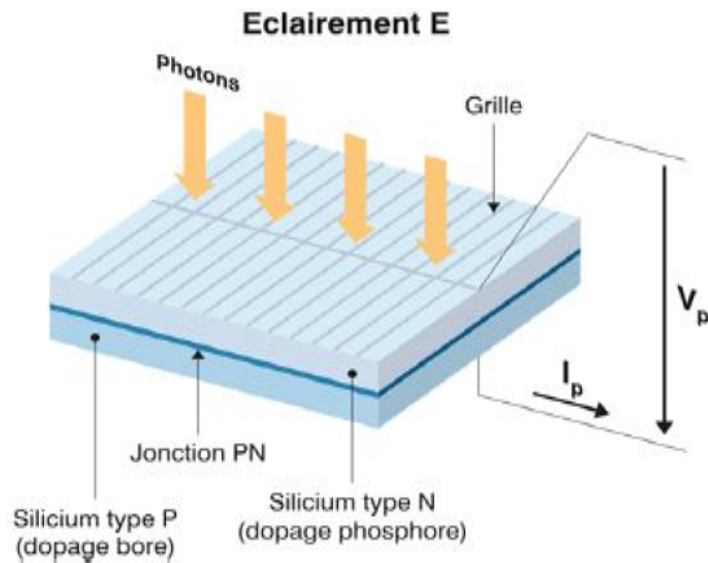


Figure I.3: Working Principle of the Photovoltaic Effect[40]

I.5. Photovoltaic cells

The PV cell, also called a photocell, is the smallest element of a photovoltaic installation. It is composed of semiconductor materials and directly converts light energy into electrical energy [16].

The operation of the photovoltaic cell is based on the photovoltaic effect, generating a voltage that can vary between 0.3 V and 0.7 V depending on the material used, its structure, as well as the temperature and aging of the cell [17].

The energy efficiency performances achieved industrially are 13–14% for mono crystalline silicon cells, 11–12% for polycrystalline silicon, and 7–8% for amorphous silicon thin films. The photocell or solar cell is the basic element of a photovoltaic generator [18].

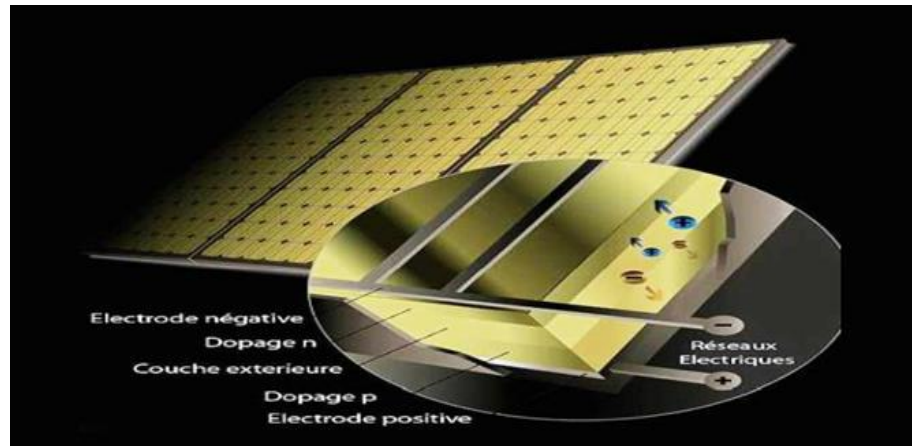


Figure I.4: A photovoltaic cell[29]

I.5.1. Operating Principle of Photovoltaic Cells

A photovoltaic cell can be considered as a photosensitive diode, and its operation is based on the properties of semiconductor materials.

The photovoltaic cell allows the direct conversion of light energy into electrical energy. Its operating principle is based on the photovoltaic effect. A cell is composed of two layers of a semiconductor. These two layers are doped differently. The (N) layer has an excess of valence electrons, while the (P) layer has a deficit of electrons. Thus, the two layers create a potential difference. The energy of the incoming light photons captured by the valence electrons (in the N layer) enables them to cross the potential barrier and generate a direct electric current. To collect this current, electrodes are deposited by screen printing on the two layers of the semiconductor (Figure I.5). The upper electrode is a grid that allows light rays to pass through. An anti-reflection layer is then deposited on this electrode in order to increase the amount of absorbed light [19].

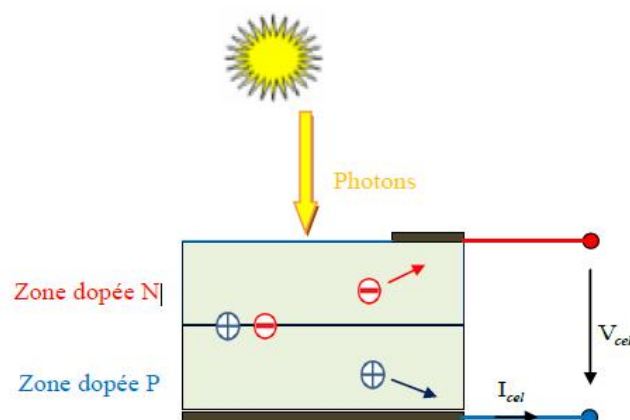


Figure I.5: Principle of Photovoltaic Cells

I.6. Different types of photovoltaic cells

Nowadays, there are several types of cells with diverse and varied characteristics, each suited to a specific function. We will therefore mention the different technologies used in the manufacturing of these cells [14].

I.6.1. Mono crystalline cells

Mono crystalline cells are first-generation photovoltaic cells. They are made from a single block of silicon crystallized into one piece. These cells are generally a uniform blue color. They have good efficiency, typically between 12% and 20% for industrial cells, but the production method is labor-intensive and costly [17].



Figure I.6: Mono crystalline cells[29]

I.6.2. Polycrystalline cells

Polycrystalline cells are made from a block of silicon crystallized into multiple crystals. When viewed closely, the different orientations of the crystals can be seen (different shades). They have an efficiency of about 11% to 13%, but their production cost is lower than that of mono crystalline cells. During the cooling of silicon, several crystals are formed. This type of cell is blue, but not uniform; patterns created by the different crystals can be distinguished [20].



Figure I.7: Polycrystalline cells

I.6.3. Amorphous silicon cells

These cells are composed of a glass or synthetic material substrate on which a thin layer of silicon is deposited (the arrangement of atoms is no longer regular as in a crystal). Their efficiency is around 5–10%, which is lower than that of crystalline cells. They are used in small consumer products (watches, calculators) but are rarely used in solar installations [18].

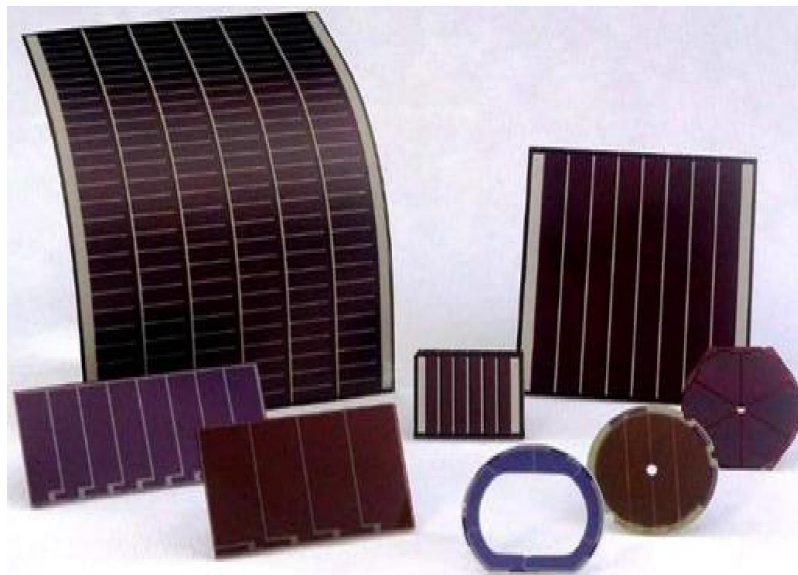


Figure I.8: Amorphous silicon cells[41]

I.6.4. Comparison of different technologies

Table I.1: Comparison of different cell technologies[2]

Technologies	Mono crystalline cells	Polycrystalline cells	Amorphous silicon cells
Efficiency	%17-14	%15-12	%10-6
Advantages	• High efficiency for a cell	• High efficiency for a module	Easy to produce •
Disadvantages	• High costs and loss of raw materials during the manufacturing process.	• High costs and loss of raw materials during the manufacturing process	• Low yield, high costs, and loss of raw materials during the manufacturing process
Life span	Years 35 •	Years 35 •	Years 10> •
Power	to 150 Wp/m ² 100 • 7M ² /kWp	100Wp/m ² • 8M ² /kWp	• Wp/m ² 50 16M ² /kWp
Market share	%43 •	%47 •	%10 •

I.7. Photovoltaic modules

To increase the operating voltage, several photovoltaic cells are connected in series to form a photovoltaic module. The nominal voltage of the module is usually adapted to a 12-volt load, and the module will therefore generally have 36 cells. Moreover, the fragility of the cells to breakage and corrosion requires protection from the environment, and they are generally encapsulated under glass or plastic compound. The whole assembly is called a “photovoltaic module.”

Modules can also be connected in series and in parallel to increase the operating voltage and current [20].

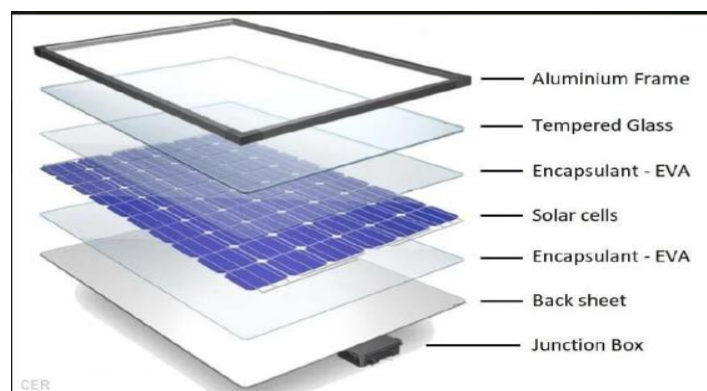


Figure I.9: Composition of a photovoltaic (PV) solar module

I.7.1. Role of the PV solar module

The photovoltaic (PV) solar module is the component of a PV solar system that produces electricity (direct current) when it is exposed to sunlight. The amount of electricity the module can generate depends on the following factors [22] :

- The availability of sunlight (direct, diffuse, reflected, night, etc.)
- The orientation of the module (whether it faces North-South or not)
- The tilt of the module (angle relative to the horizontal)
- The location where the PV solar module is installed.

I.8. Connection of photovoltaic modules

The association of modules with each other forms photovoltaic panels. The three types of association of photovoltaic modules are [23] :

I.8.1. Series connection

The individual cell, an essential component of a photovoltaic system, produces only a very small amount of electrical power, generally around 0.5 W with a voltage of less than one volt. To increase power output, cells are combined to form a module (or panel) [55]. The series connection of photovoltaic modules delivers a voltage equal to the sum of the individual voltages and a current equal to that of a single module [23].

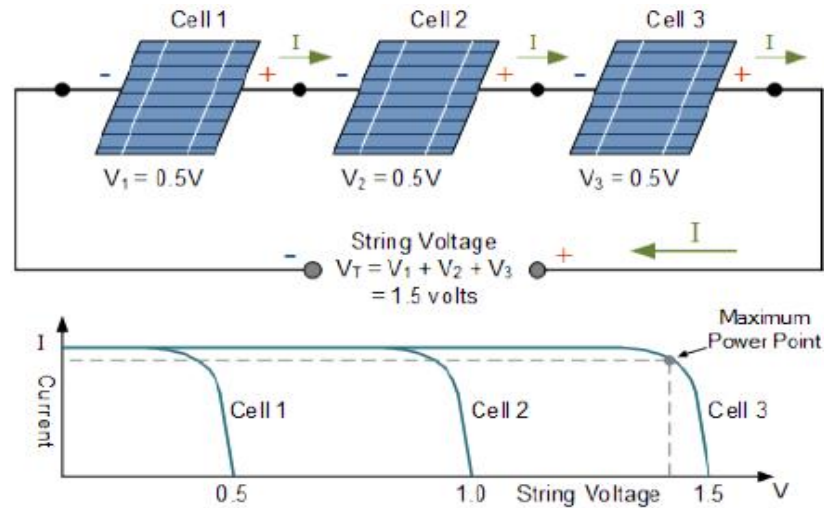


Figure I.10: Series connection of solar cells[38]

I.8.2. Parallel Connection

The parallel connection of photovoltaic modules delivers a current equal to the sum of the individual currents and a voltage equal to that of a single module [23] .

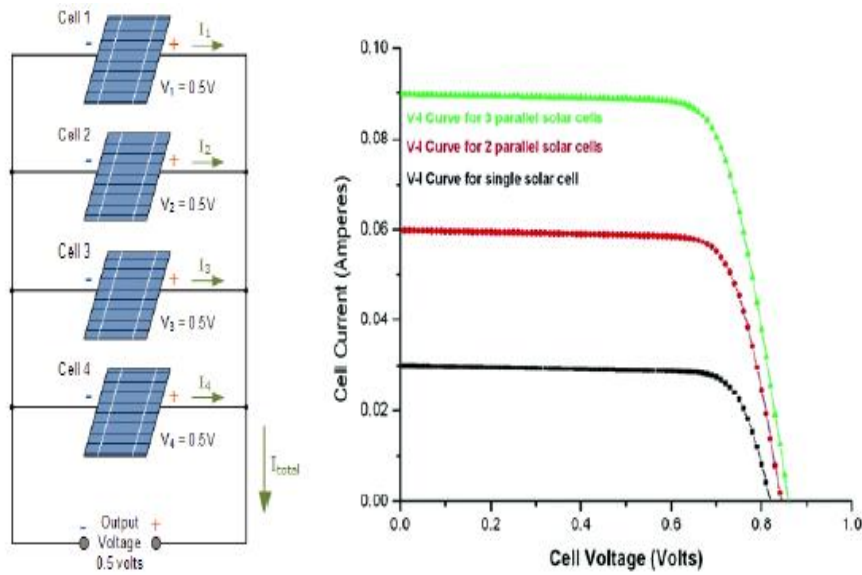


Figure I.11: Parallel connection of photovoltaic cells[38]

I.8.3. Mixed connection (Series – Parallel)

To achieve satisfactory current and voltage, it is necessary to use a mixed arrangement, that is, series-parallel [24].

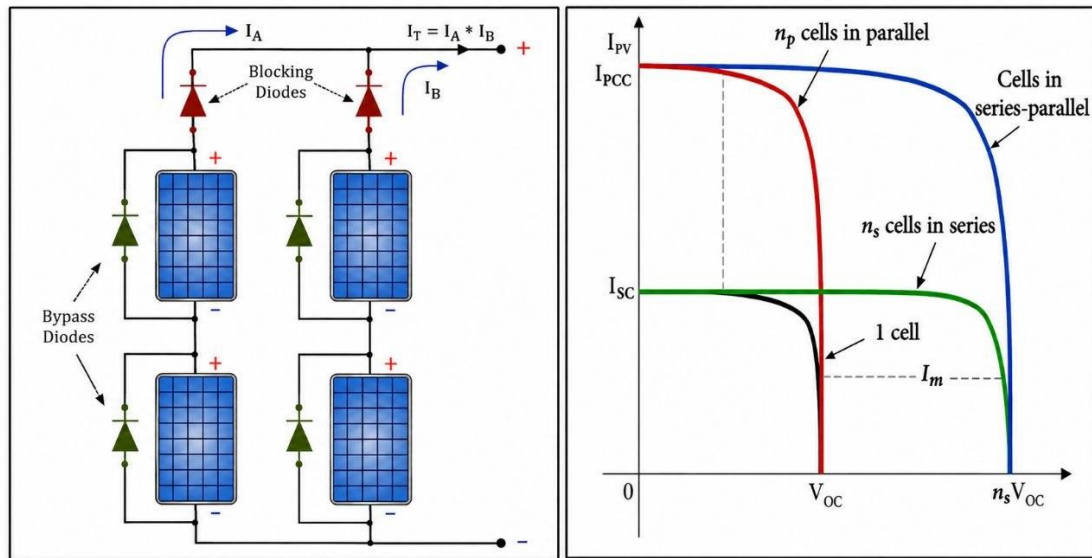


Figure I.12: Parallel and series connection of photovoltaic cells[39]

I.9. photovoltaic system

In addition to the main component, the photovoltaic generator—which represents more than 50% of the total cost of the system—the PV system also includes secondary components such as the storage system and the power conditioning stage.

The storage device often consists of one or more rechargeable batteries. Batteries are very expensive components and must be selected carefully. The power conditioning stage involves a static converter, either DC/DC or DC/AC.

Batteries typically have a lifespan of 8 to 10 years, while PV modules last between 20 and 30 years [25].

I.9.1. Autonomous systems

Autonomous systems play the role of supplying power to one or more consumers in areas far from the electrical grid. A standalone solar panel system consists of a storage system associated with solar generators to ensure continuous power supply at all times and for several days, even in case of production interruption, as well as static converters for the adaptation stage between the solar generator and the loads [26]. Two types can be distinguished:

- Sun-tracking (direct-use) systems.
- Systems with storage.

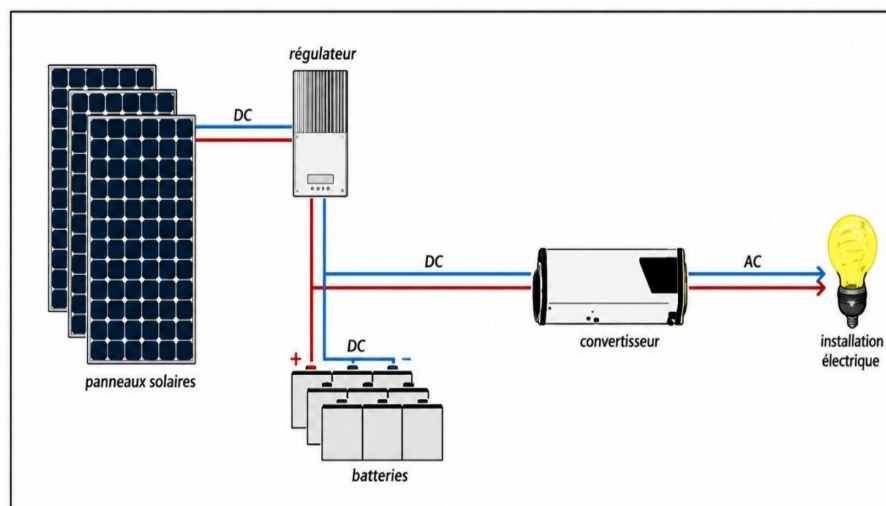


Figure I.13: Autonomous photovoltaic installation[27]

I.9.2. Grid-connected systems

Grid-connected photovoltaic systems are connected to the public grid through an appropriate inverter, because a photovoltaic module only produces direct current (DC).

Grid-connected photovoltaic systems can be divided into two types:

- Decentralized grid-connected photovoltaic systems.
- Centralized grid-connected photovoltaic systems [28].

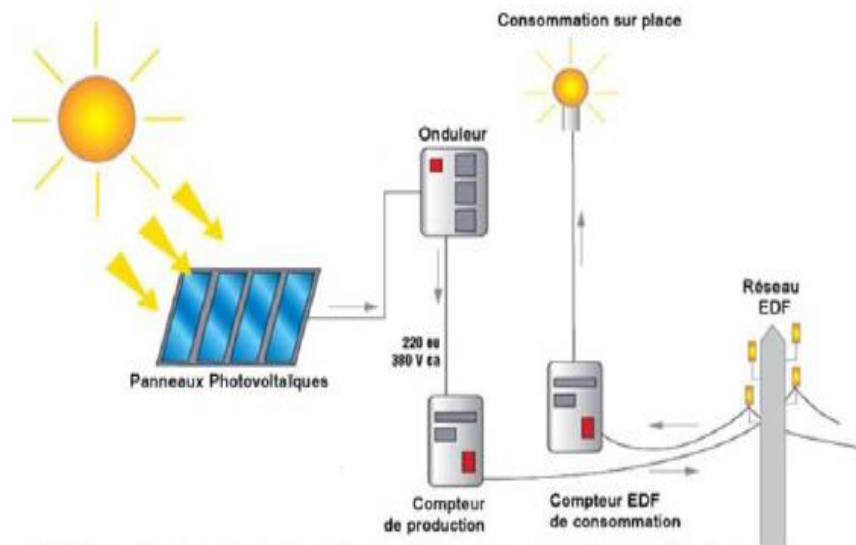


Figure I.14: Diagram of a grid-connected photovoltaic installation[29]

I.9.3. Hybrid systems

Hybrid systems consist of a photovoltaic generator combined with one or more renewable energy sources, a generator, or both simultaneously. In the event of a discharge, these systems may also include batteries that can be recharged by the other source [30].

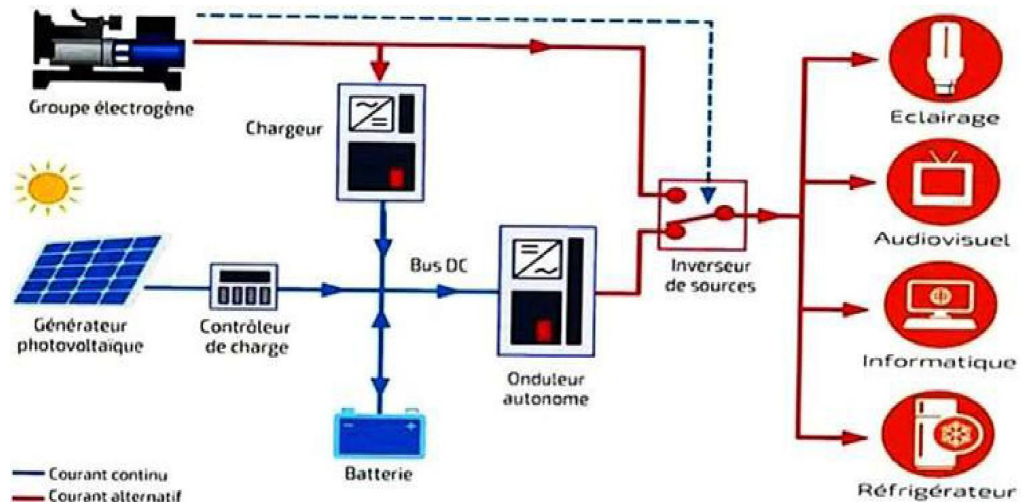


Figure I.15: Autonomous hybrid photovoltaic installation[27]

I.10. Power electronic converters

Power electronic devices play a major role in the functioning of photovoltaic system either in stepping up or stepping down DC the voltage generated by the solar panels and these are known as DC-DC converters or during the conversion of direct current to alternating current and these referred to as (DC-AC converters). The choice of these power electronic devices rests entirely on the types of load used, either AC or DC loads [31].

I.10.1. DC-DC converters

These devices are considered solid-state power electronics, as they are used to step up or step down direct current (DC) voltage. DC-DC converters operate based on pulse width modulation (PWM) technology, where a high-frequency pulse signal is generated to control the switching on and off of electronic switches, allowing precise control of the output voltage level [31].

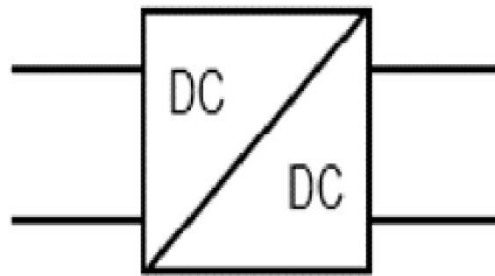


Figure I.16:Symbol of a DC-DC converter[32]

I.10.2. DC-DC Converters for Solar Energy Systems

A chopper can be implemented using a controlled electronic switch (a power transistor operating in 0–1 switching mode), which opens and closes, such as GTO thyristors, bipolar transistors, or insulated-gate field-effect transistors operating in switching (on/off) mode.

The principle of the chopper consists of periodically establishing and interrupting the connection between the source and the load using this electronic switch. This switch must be able to be opened or closed at will in order to obtain an adjustable continuous output voltage. For this purpose, DC-DC converters (or choppers) are used in solar energy systems to adapt the variable DC source (PV panel) to the load, which generally requires a constant DC voltage [33].

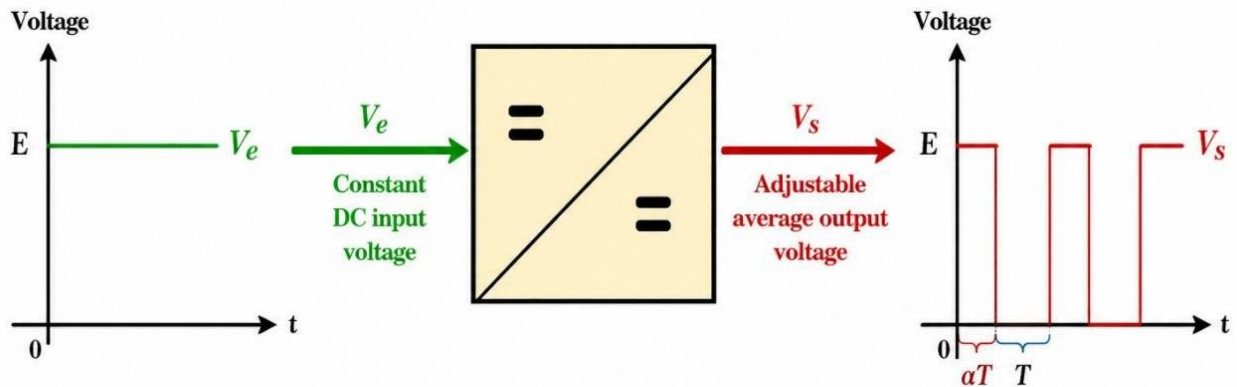


Figure I.17: Principle of DC–DC Converter Voltage Regulation[34]

I.10.3. types of DC-DC converters

DC-DC converters (or choppers) are used in solar energy systems to adapt a variable-amplitude DC source (PV panel) to a load that generally requires a constant DC voltage. The three basic configurations are [35] :

- Buck converters,
- Boost converters.
- Buck – Boost converters.

I.11. Advantages and disadvantages of a photovoltaic system

I.11.1. Advantages

- Solar photovoltaic energy generates neither noise, nor harmful emissions, nor polluting gases.
- Reliable and stable systems.
- Its output varies with the days and seasons, but it is relatively predictable.
- Safe and risk-free technology.

I.11.2. disadvantages

- The investment cost is relatively high.
- The efficiency of PV cells remains quite low.
- There is no electricity production in the evening and at night.

I.12.What constitutes a photovoltaic pumping system

- A photovoltaic water pumping system consists of the following components:
- A generator, composed of photovoltaic modules electrically interconnected to form a direct current (DC) power production unit. It also includes a metallic structure that supports the entire assembly.

- A power conditioning unit, consisting of a converter (inverter) capable of adjusting the output voltage and frequency according to the power available from the solar generator, which itself depends on the level of solar irradiance received.
- A submerged electropump unit, composed of an induction motor coupled with either a centrifugal or a positive displacement pump.
- Electrical wiring, through which electrical energy is transmitted from the generator to the motor, along with signals related to safety control systems.
- A hydraulic infrastructure, responsible for conveying water from its source (typically a well or borehole) to a storage reservoir.
- A water treatment (potabilization) system, designed to meet applicable standards and ensure the sanitary quality of the water.
- A distribution network, which delivers the treated water to end users [42].

I.13. Photovoltaic Pumping Systems

Among the various coupling configurations, two main categories of photovoltaic pumping systems can be distinguished based on their connection mode: standalone systems and grid-connected systems [43].

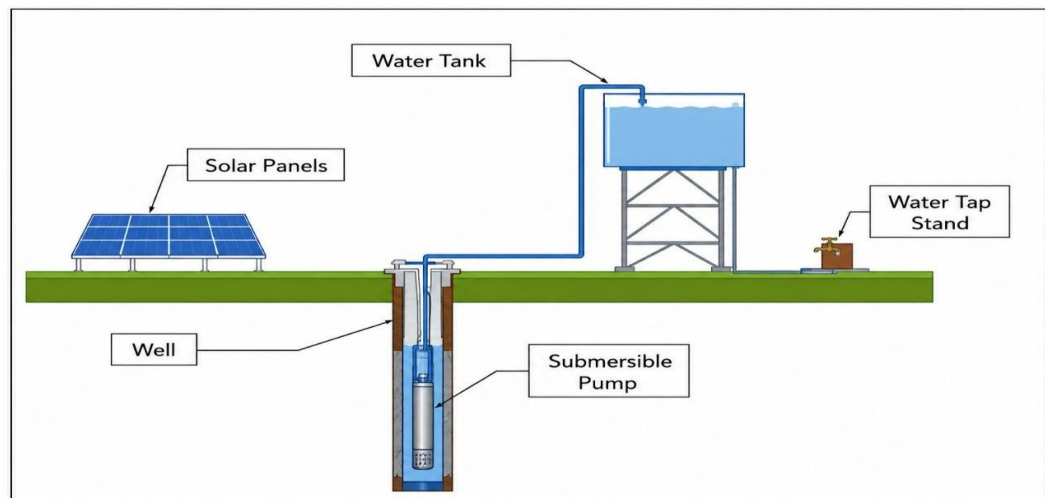


Figure I.18: General configuration of a photovoltaic pumping system

I.13.1. Autonomous Photovoltaic Systems

These photovoltaic systems are installed to ensure autonomous operation without reliance on other energy sources. They are generally used in isolated and remote regions far from the electrical grid. Depending on whether electrochemical storage is employed or not, standalone photovoltaic systems are classified as follows [18] :

a. Standalone photovoltaic systems without electrochemical storage

Irradiance is available to initiate its operation. This is particularly suitable for applications that do not require operation in the absence of light, and for which energy demand coincides with the availability of solar irradiance. However, the photovoltaic generator must be properly sized to ensure it can provide sufficient power even under the lowest irradiance conditions. Photovoltaic water pumping is a typical example of this category of standalone systems, where water storage in a reservoir is generally preferred over electrochemical energy storage.

The solar pump is directly connected to the photovoltaic generator through a DC/DC or DC/AC converter, depending on whether a direct current motor or an alternating current motor is used, respectively. Consequently, the water flow rate into the reservoir is variable and depends on the level of solar irradiance.

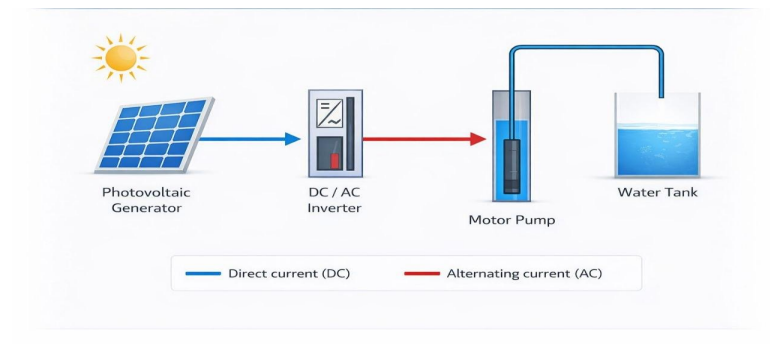


Figure I.19 : Schematic diagram of a standalone system without electrochemical storage

b. Standalone photovoltaic systems with electrochemical storage

This is the most common configuration of standalone photovoltaic systems. It incorporates batteries that store the electrical energy generated by the photovoltaic array during the daytime. Consequently, electrochemical energy storage in batteries is essential to ensure system operation at night or over a predefined number of days, as specified during the photovoltaic system sizing process [43].

I.13.2. Grid-connected photovoltaic systems

Grid-connected photovoltaic generators represent the most widely adopted application in urban areas, particularly through installations on rooftops and building façades. The integration of photovoltaic elements into building structures offers numerous advantages. When connected to the grid, these systems eliminate issues related to energy storage and electricity transmission. Any surplus energy produced, after being converted into alternating current by an inverter, is fed into the grid. During periods of no production, such as at night,

electricity is drawn from the grid. The meter therefore operates in both directions. Consequently, elements such as sunshades, canopies, skylights, and façades contribute to electricity generation, often in forms that are more aesthetically pleasing than conventional components [18].

I.14. Electrochemical energy storage system

Among the available solutions, electrochemical storage using rechargeable batteries provides good reversibility between discharge and recharge processes. The advantage of electrochemical accumulators lies in the availability of a quasi-constant voltage, which establishes the operating point along a vertical line that can be made as close as possible to the line defining the optimal load of a photovoltaic generator [18].

I.14.1. Operating Principle of a Battery

Electrolyte. Chemical reactions take place at both electrode–electrolyte interfaces. At the anode (the negative electrode during discharge), an oxidation reaction occurs.

The electrons released flow through the external circuit toward the cathode (the positive electrode during discharge), where a reduction reaction takes place [18].

I.14.2. Battery Characteristics

The main characteristics of storage batteries for photovoltaic solar systems are as follows:

- **Nominal voltage:** It is the electromotive force of the battery, determined by the electrochemical couple used.
- **Charging voltage:** It is the minimum voltage that must be applied to effectively charge the battery.
- **Nominal capacity:** It is the amount of energy that can be stored in the battery, expressed in ampere-hours (Ah). It is specified under reference conditions (a 20-hour discharge period and a temperature of 25°C).
- **Depth of discharge (DoD):** It is the percentage of the total battery capacity that is utilized during a charge/discharge cycle [44].
- **Lifetime:** Numerous factors influence this parameter, to the extent that manufacturers must specify the operating conditions in order to provide approximate values. Lifetimes expressed in years are generally given for operation in float mode at 25°C.
- **Autonomy:** In the case of lead-acid (Pb) batteries, the electrolyte undergoes degradation, which becomes more pronounced with overcharging. Even at rest, water evaporation is unavoidable.

However, manufacturers have developed methods to limit this effect by using a gelled electrolyte and caps that catalyze the gas recombination reaction in sealed, so-called maintenance-free batteries [43].

I.14.3. The different types of batteries

I.14.3.1. Lead or lead-acid batteries

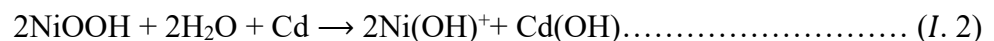
Lead-acid batteries are the most common form of electrical energy storage due to their relatively low cost and wide availability. During its reduction to Pb^{2+} (Equation I.5), the protons produced at the anode and the hydroxide ions at the cathode recombine to form H_2O (Equation I.6).

Excessively deep discharges can lead to an irreversible loss of capacity. Three possible causes are responsible for this phenomenon:

- ✓ . Irreversible transformation of part of the active material of the positive electrode into lead sulfate crystals.
- ✓ . Progressive swelling and loss of cohesion of the active material of the positive electrode. To obtain the desired voltage at the terminals of a battery, several cells are connected in series within the module; however, to increase capacity and current, these cells must be connected in parallel [18].

I.14.3.2. Nickel-cadmium batteries

Nickel–cadmium batteries have a physical structure similar to that of lead–acid batteries. Instead of lead, they use nickel hydroxide for the positive plates and cadmium oxide for the negative plates. The electrolyte is potassium hydroxide, hence the name alkaline accumulator. Their voltage ranges from 1.15 to 1.45 V per cell, with a nominal value of 1.2 V [45]. The following redox reaction describes the operation of nickel–cadmium batteries:



The use of cadmium, which belongs to the family of heavy metals, poses a significant environmental concern due to the risks associated with its recycling. However, nickel–cadmium batteries offer superior performance compared to lead-acid batteries in terms of capacity and lifespan (ranging from 15 to 20 years). Nevertheless, they require a highly stable and clean charging supply, and their cost is considerably higher than that of lead-acid batteries (approximately 1.5 times higher).

I.14.3.3. Les batteries au nickel-zinc

The positive electrode is still made of nickel oxide, while the negative electrode is composed of metallic zinc. In addition to better environmental compatibility (no heavy metals), this type

of battery exhibits a high energy density (approximately 25% higher than that of nickel–cadmium batteries).

However, at present, their lifespan remains limited due to the formation of zinc dendrites on the negative electrode during charging [18].

I.14.3.4. Sodium–nickel chloride batteries

They are also known as ZEBRA batteries, named after a specific brand. The separator between the electrodes is a ceramic material that acts as an ionic conductor. These batteries operate at temperatures around 300°C. They offer relatively high energy density and reliable performance; however, the high temperature is required to ensure the conductivity of the solid electrolyte. Their lifespan is still under evaluation, but it is estimated to exceed 700 cycles. Moreover, their operation does not require maintenance. On the other hand, the solid electrolyte is fragile and difficult to manufacture [18].

I.14.3.5. Lithium-ion batteries

They operate based on a reversible intercalation reaction: lithium atoms are inserted between the layers of the anode's lamellar structure during charging and are deintercalated during discharging.

These accumulators are among the newer types that have been widely deployed over the past decade and are highly promising. Their specific energy and specific power are significantly higher compared to lead–acid batteries.

Typical values are as follows: . For lead–acid batteries: energy density ≈ 60 Wh/kg and power density ≈ 0.5 to 1 W/kg. . For nickel–cadmium batteries: energy density ≈ 120 Wh/kg and power density ≈ 200 W/kg. . For lithium-ion batteries: energy density ≈ 150 Wh/kg and power density ≈ 300 W/kg.

Lithium is indeed the lightest metal and possesses a high electrochemical potential, which makes it the most attractive material for use as the negative electrode in a battery [18].

I.14.3.6. Lithium-ion polymer batteries

The major difference lies in the electrolyte, which in this case is solid and composed of polymers that enable the transport of lithium ions between the two electrodes. The advantage of this architecture is related to the absence of liquid within the battery, which enhances energy density, safety, and lifespan [18].

I.14.3.7. Metal hydride batteries

Nickel oxide is still used as the material for the positive electrode. However, at the other electrode, hydrogen stored in metal hydrides acts as the active species. The electrolyte is potassium hydroxide, which serves to absorb and transport ions.

They can withstand high charging currents (fast charging), provided that adequate cooling is ensured. Their energy density is approximately 170 Wh/kg, and their power density is about 600 W/kg.

In general, they exhibit a relatively high energy density (around 100 Wh/kg) and a power density of approximately 1 W/kg.

One of the main drawbacks is their tendency toward self-discharge due to the diffusion of hydrogen through the electrolyte [18].

I.15. Pumping subsystem

The pumping subsystem consists of a motor–pump unit and a power conditioning unit [46].

I.15.1. Pumps

A pump is a machine that converts mechanical input power into hydraulic power with a certain efficiency. It is directly coupled to the motor and is characterized by parameters such as torque, speed, and flow rate. Proper matching between the pump and the motor leads to optimal performance.

A pump is defined as any device that draws a fluid from a region of low pressure and delivers it to a region of higher pressure. According to this definition, the role of a pump is to increase the pressure of the fluid. This increase in pressure results from the conversion of mechanical energy supplied by a driving motor into hydraulic energy gained by the fluid between the inlet and outlet of the pump.

The volume of pumped water depends on the electrical energy absorbed by the pump, which in turn depends on five essential factors:

- ✓ The level of solar irradiance, which represents the available energy from the sun.
- ✓ The photovoltaic generator.
- ✓ The conversion efficiency of the photovoltaic array
- ✓ The ambient temperature [18].

I.15.1.1. The different types of pumps

Water pumps are generally classified according to their operating principle, either as positive displacement or centrifugal types. In addition to these two classifications, two other types of pumps can be distinguished based on the physical position of the pump relative to the pumped water: suction pumps and discharge pumps.

The suction head of any pump is theoretically limited to 9.8 meters (atmospheric pressure expressed in meters of water), and in practice to about 6 to 7 meters. [47], [48].

I.15.1.2. Positive displacement pump

A positive displacement pump converts the mechanical energy of the motor into a reciprocating motion, allowing the fluid to overcome gravity through successive variations of a volume alternately connected to the suction and discharge ports.

The water flow rate of a positive displacement pump is proportional to the motor speed. However, its torque mainly depends on the total dynamic head (TDH) and is practically independent of the motor's rotational speed. Therefore, the starting torque is essentially independent of the flow rate and is proportional to the TDH. The power consumed is proportional to the speed

For this reason, these pumps are typically used for wells and boreholes with great depths and low flow rates. They are sometimes also used as surface pumps when the torque is slow and irregular [18].

I.15.1.3. Centrifugal pump

A centrifugal pump is designed to operate at a relatively fixed total dynamic head (TDH). The flow rate of this pump varies proportionally with the rotational speed of the motor. Its torque increases rapidly with speed, and the discharge head is proportional to the square of the motor speed. Therefore, the motor must rotate at a high speed to ensure an adequate flow rate.

The power consumption, proportional to $Q \times \text{TDH}$, varies with the cube of the rotational speed. Centrifugal pumps are typically used for high flow rates and for medium or low depths (10 to 100 meters). [47] , [49].

I.15.1.4. Structure of a centrifugal pump

Pumps consist of two essential components:

- . An impeller that imparts rotational motion to the fluid. It is mounted on a shaft supported by bearings and driven by a motor.
- . A pump casing that guides the fluid toward the impeller and then away from it at a higher pressure. The pump casing includes a suction pipe and a discharge pipe, and it supports the bearings as well as the entire rotor assembly. [50], [51].

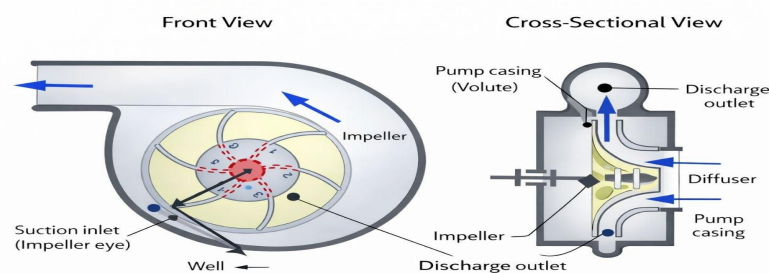


Figure I.20: Components of a Centrifugal Pump

I.15.1.5. Operation of a centrifugal pump

The operating theory of centrifugal pumps shows that between the inlet and the outlet of the impeller, the total mechanical energy of the fluid stream increases. This increase results partly from a rise in pressure energy and also from an increase in kinetic energy, the latter being subsequently converted into pressure energy by a gradual deceleration achieved in a component located around the impeller, called the volute, which ends in a divergent cone [52].

I.16. Motors

The motor in a motor–pump unit converts electrical energy into mechanical energy. It can operate on either direct current (DC) or alternating current (AC). In the latter case, an electronic converter or inverter is required to convert the direct current supplied by a photovoltaic generator into alternating current.

For this reason, the choice of a DC motor may initially seem more advantageous; however, the development of efficient electronic converters now allows the use of AC motors that are both efficient and, above all, less expensive [53].

I.16.1. Direct Current Motor

These motors are supplied with direct current voltages. They offer the advantage of being easily controlled under variable speed operation and are commonly found in servomotors used for low-power applications (below 5 kW).

Direct current motors consist of an armature and a field system. While the armature is generally made of copper windings, the field system can be implemented either with copper windings or with permanent magnets [54].

I.16.2. Synchronous motors

Electricity production, power plants use alternators whose output can reach up to 1500 MW

As the name suggests, the rotational speed of these machines is always proportional to the frequency of the currents flowing through them. This type of machine can also be used to improve the power factor of an electrical installation [18].

I.16.3. Asynchronous motors

An asynchronous machine is an alternating current machine with no electrical connection between the stator and the rotor. The term 'asynchronous' originates from the fact that the rotational speed of these machines is not necessarily proportional to the frequency of the currents flowing through them

For a long time, the asynchronous machine was strongly challenged by the synchronous machine in high-power applications, until the advent of power electronics. Today, it is widely

used in many fields, particularly in transportation (metros, trains, ship propulsion), industry (machine tools), and household appliances. Initially, these machines were used only as motors, but thanks to power electronics, they are increasingly being used as generators. This is, for example, the case in wind turbines [55].

I.17. Conclusion

Solar photovoltaic energy is one of the most important global fields in sustainable development. Despite the mastery of solar cell manufacturing technology and their encapsulation, photovoltaic systems remain relatively expensive. Therefore, mastering the technology alone is no longer sufficient to reduce the cost of PV systems; proper design and sizing techniques also play a crucial role in minimizing the cost per watt-peak produced.

In this chapter, the main focus was on the fundamental components of a photovoltaic system (solar cells and PV modules), as well as the current–voltage (I–V) characteristics of a PV module. Furthermore, the different configurations of photovoltaic systems and the importance of electrochemical energy storage were discussed.

In addition, particular attention was given to photovoltaic water pumping systems, including their operating principles, system configurations, and the role of key components such as pumps, motors, and power conditioning units.

Thus, designing a photovoltaic system requires a thorough understanding of the performance of photovoltaic generators and their behavior under varying environmental conditions, as well as the specific requirements of applications such as photovoltaic pumping systems.

CHAPTER II : Modeling of Photovoltaic Pumping System

II.1.Introduction

The modeling of a photovoltaic water pumping system is an essential step for analyzing its behavior and evaluating its performance under different operating conditions. Such a system is composed of several interconnected subsystems, including the photovoltaic generator, the DC–DC boost converter with an MPPT controller, the voltage source inverter, the three-phase induction motor, and the centrifugal pump. Mathematical modeling of each component makes it possible to accurately describe the energy conversion process from solar radiation to hydraulic energy and to predict the dynamic response of the overall system. This approach provides an effective basis for the design, simulation, and optimization of high-performance photovoltaic pumping systems under varying solar irradiance and temperature conditions[56].

II.2. Photovoltaic generator modeling

II.2.1. Parameters of a photovoltaic cell

II.2.1.1. Short-circuit current I_{sc}

It is the current obtained when the terminals of the cell are short-circuited (by taking ($V = 0$) in the equivalent circuit). It increases linearly with the cell's irradiance and depends on the illuminated surface area, the wavelength of the radiation, the carrier mobility, and the temperature.

In the case of an ideal cell ($R_s \rightarrow 0$ et $R_p \rightarrow \infty$)

$$I_{sc} = I_{ph} = q \cdot g (Ln + Lp) \dots\dots\dots(II. 1)$$

Taking into account the effect of the resistances R_s and R_p , the short-circuit current varies as a function of these two resistances and is directly proportional to the incident flux [56].

II.2.1.2.Open-circuit voltage

The open-circuit voltage is obtained when the current flowing through the cell is zero. It depends on the energy barrier and the shunt resistance. It decreases with temperature and varies only slightly with light intensity.

In the ideal case [57] :

$$V_{oc} = V_{th} \ln \cdot \left(\frac{I_{sc}}{I_s} + 1 \right) \dots\dots\dots(II. 2)$$

V_{oc} is the open-circuit voltage

V_{th} is the thermal voltage,

I is the short-circuit current,

I_s is the saturation current.

II.2.1.3. Maximum power

For an ideal cell, the maximum power $P_{m,ideal}$ at the terminals of the photovoltaic cell corresponds to the open-circuit voltage multiplied by the short-circuit current [57].

$$P_{m,ideal} = Voc * Isc \dots\dots\dots (II.3)$$

In practice, the characteristic curve of a photovoltaic cell is more rounded, and the voltage at the maximum power point V_m is lower than the open-circuit voltage Voc . Similarly, the current at this point I_m is lower than the short-circuit current Isc . The expression of the power at this point is given by:

$$P_m = V_m * I_m \dots\dots\dots (II. 4)$$

II.2.1.4. Efficiency

The efficiency of a photovoltaic (PV) generator is defined as the ratio between the electrical power delivered (the power that can be extracted at the optimal operating point) and the incident radiation power [58].

$$\eta_{pv} = \frac{P_m}{E * A} \dots\dots\dots (II. 5)$$

where:

A: effective surface area of the generator (in m²).

II.2.1.5. Fill Factor

It is the ratio of the area of the rectangle corresponding to the maximum power (P_{max}) to the product of the open-circuit voltage and the short-circuit current [59].

$$ff = \frac{V_m * I_m}{V_{oc} * I_{sc}} \dots\dots\dots (II. 6)$$

II.2.2. Electrical Model of a Photovoltaic Generator

II.2.2.1. Single-Diode Model

The schematic of the equivalent circuit of a photovoltaic cell, which is widely used in the literature, is shown in Figure (II.2).

This model is used to study the current–voltage (I–V) and power–voltage (P–V) characteristics of the photovoltaic generator, as well as its behavior as a function of solar parameters, namely the irradiance on the plane of the panels (E_s) and the junction temperature (T_j).

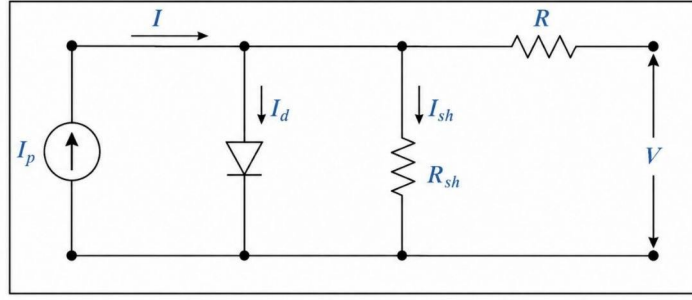


Figure II.1: Equivalent circuit of the single-diode model.

In Figure (II.2), the shunt resistance R_{sh} characterizes the leakage current at the junction, while the series resistance R represents the various contact and connection resistances. The current generated by the module is given by Kirchhoff's law as follows:

$$I = I_p - I_d - I_{sh} \dots\dots\dots(II. 7)$$

Where

- I : the current delivered by the module.
- I_d : the diode current
- I_{sh} : the shunt current

The photocurrent I_p depends directly on the solar irradiance E_s and the cell temperature T_j , and it is given by the following relation [60] :

$$I_p = P_1 \cdot E_s \cdot [1 + P_2 \cdot (E_s - E_{ref}) + P_3 \cdot (T_j - T_{jref})] \dots\dots\dots(II. 8)$$

The cell temperature can be calculated from the ambient temperature and the irradiance as follows:

$$T_j = T_a + E_s \left(\frac{N-20}{800} \right) \dots\dots\dots(II. 9)$$

Where:

- T_a : ambient temperature
- N_{oct} : nominal operating cell temperature provided by the manufacturer (45°C).

The diode current is given by:

$$I_d = I_{sat} \left[\exp\left(\frac{q(V+R_{sl})}{A \cdot n_s \cdot k \cdot T_j}\right) - 1 \right] \dots\dots\dots(II. 10)$$

I_{sat} : saturation current, which strongly depends on temperature; it is given by the following expression:

$$I_{sat} = P_4 T_j^3 \cdot \exp\left(\frac{-E_g}{k \cdot T_j}\right) \dots\dots\dots(II. 11)$$

The current through the shunt resistance is calculated as follows:

$$I_{sh} = \frac{(V+R_s \cdot I)}{R_{sh}} \dots\dots\dots(II. 12)$$

The module current I is given by:

$$I = I_p(E_s, T_j) - I_d(V, I, T_j) - I_{sh}(V) \dots\dots\dots (II. 13)$$

$$I = P_1 E_s \cdot [1 + P_2(E_s - E_{ref}) + P_3(T_j - T_{ref})] - P_4 T_j^3 \cdot \exp\left(\frac{-E_g}{k \cdot T_j}\right) \cdot \left[\exp\left(\frac{q(V + R_s I)}{n_s A k T_j}\right) - 1 \right] - \left(\frac{V_{pv} + R_s I}{R_{sh}} \right) \dots\dots\dots (II. 14)$$

- It should be noted that there are also other models used for analysis

The single-diode model is the most commonly used model for representing the electrical behavior of photovoltaic modules due to its simplicity and satisfactory accuracy. Therefore, it has been adopted in this study. This model requires only a limited number of parameters, namely the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), the current and voltage at the maximum power point (I_{mpp} and V_{mpp}), and the series resistance (R_s). These parameters are sufficient to describe the variations in the current and voltage of the photovoltaic panel under different climatic conditions, particularly changes in solar irradiance and temperature. The current produced by the photovoltaic module can be expressed as follows:

$$I_p = I_{sc} \cdot [1 - K_1(\exp(K_2 \cdot V_{pv}^m) - 1)] \dots\dots\dots (II. 15)$$

Where the coefficients (K_1), (K_2), and (m) are given by the following expressions:

$$K_1 = 0.01175 =$$

$$K_2 = \frac{K_4}{V_{oc}^m} \dots\dots\dots (II.16)$$

$$= m \frac{(\ln \frac{K_3}{K_4})}{(\ln \frac{V_{mpp}}{V_{oc}})} \dots\dots\dots (II. 17)$$

And also (K_3) and (K_4):

$$K_3 = \ln\left(\frac{I_{sc}(1+K_1)-I_{mpp}}{K_1 \cdot I_{sc}}\right) \dots\dots\dots (II. 18)$$

$$K_4 = \left(\ln \frac{1+K_1}{K_1}\right) \dots\dots\dots (II. 19)$$

Such that

- I_{mpp} : current at the maximum power point, also called the optimal current,
- V_{mpp} : voltage at the maximum power point, also called the optimal voltage,
- I_{sc} : short-circuit current
- V_{oc} : open-circuit voltage

(K_1), (K_2), (K_3), (K_4), and (m) are diode parameters that are calculated independently based on standard test conditions (STC) [61].

It should be noted that the equation ($I = I_p - I_d - I_{sh}$) is not only valid under

standard test conditions (STC) $G_{stc} = 1000 \frac{W}{m^2}$, $T_{stc} = 25^\circ C$

When the irradiance and temperature vary, the parameters of the photovoltaic module listed in the appendix table change according to the following equations [62] :

$$\Delta T_c = T_c - T_{stc} \dots\dots\dots (II. 20)$$

$$\Delta I_p = \alpha_{cc} \left(\frac{G}{G_{stc}} \right) \cdot \Delta T_c + \left(\frac{G}{G_{stc}} \right) \cdot I_{sc,stc} \dots\dots\dots (II. 21)$$

$$\Delta V_p = -\beta_{co} \cdot \Delta T_c - R_s \cdot \Delta I_{pv} \dots\dots\dots (II. 22)$$

G_{stc} : reference irradiance (1000 W/m²)

G : irradiance under arbitrary conditions,

T_{stc} : Reference temperature (25 °C)

T_c : temperature under arbitrary conditions,

ΔT_c : Temperature variation (°C)

ΔI_p : variation of current with respect to changes in irradiance and temperature,

ΔV_p : variation of voltage with respect to changes in irradiance and temperature.

α_{cc} : Temperature coefficient of the short-circuit current (I_{cc})

β_{co} : Temperature coefficient of the open-circuit voltage (V_{co})

The new values of the photovoltaic voltage and current are given by:

$$V_{p_{nouv}} = V_{p,stc} + \Delta V_p \dots\dots\dots (II. 23)$$

$$I_{p_{nouv}} = I_{p,stc} + \Delta I_p \dots\dots\dots (II. 24)$$

II.2.3.Effect of Irradiance

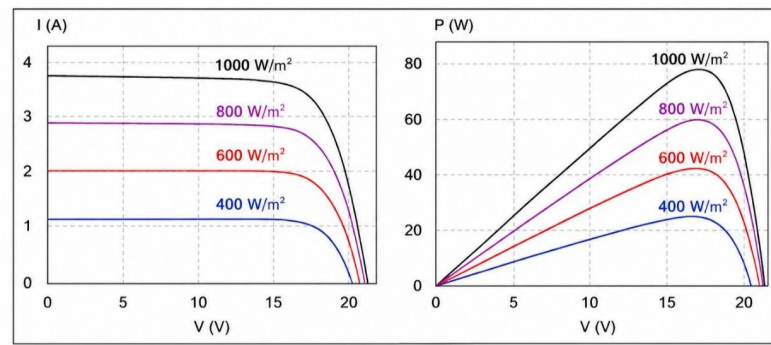


Figure II.2: I–V and P–V curves for different irradiance levels. [63]

At a constant ambient temperature ($T_c = 25^\circ C$), the irradiance was varied ($E = 400, 600, 800$ and 1000 W/m^2) and the following observations were obtained:

- The photovoltaic current strongly depends on solar irradiance; as the irradiance increases, the current also increases, and vice versa.
- The characteristic increases with the increase in irradiance.

II.2.4. Effect of Temperature

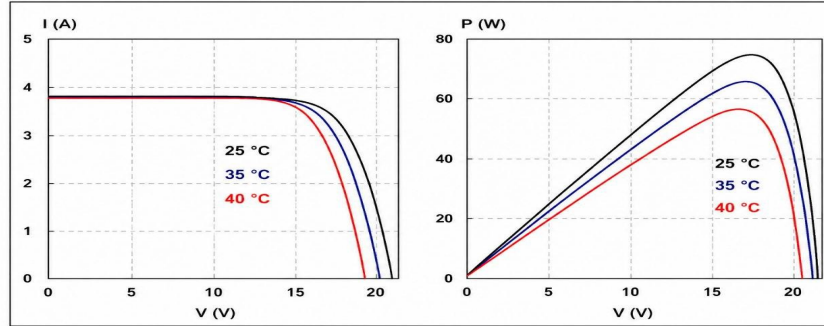


Figure II.3: I–V and P–V curves for different irradiance levels. [63]

For a fixed irradiance ($E=1000 \text{ W/m}^2$), the open-circuit voltage V_{oc} increases as the temperature decreases, while a slight decrease is observed in the short-circuit current I_{sc} the reduction in saturation current is the main cause of the current drop at low temperatures.

For a photovoltaic (PV) generator to operate optimally, the temperature should be low while the irradiance should be high. This is the case, for example, in aeronautical applications [64].

II.3. Step-up converter (Boost converter)

This is a step-up converter, also known as a boost converter or a parallel chopper; it transforms any input voltage into a higher output voltage. Its basic circuit is shown in (Figure II.4) [65].

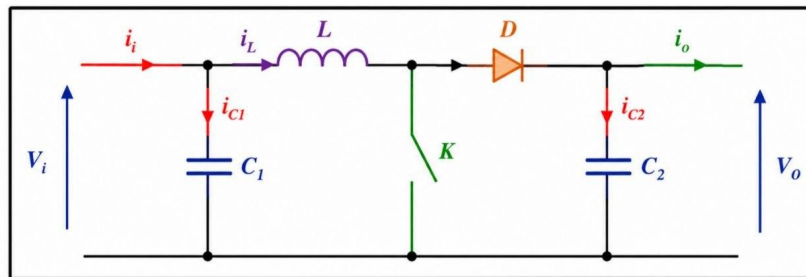


Figure II.4: Basic diagram of a Boost converter

II.3.1. Principle of operation

When switch K is closed, during the period t_{ON} , i.e., $t \in [0, \alpha T_s]$, the current gradually increases, allowing the inductor to store more energy throughout the entire closing time of K. Then the switch turns off, i.e., during the period t_{OFF} , $t \in [\alpha T_s, T_s]$ During this transition from the closed state to the open state, the inductor L opposes the change in the current I_L in its

circuit. This variation also causes a change in the magnetic flux in its core, and thus it generates a voltage across its terminals that adds to the source voltage, the whole appearing across the capacitor C_2 [66].

II.3.2. Equivalent mathematical model

To be able to synthesize the functions of the boost chopper in steady state, it is necessary to present the equivalent circuit diagrams for each position of switch K. The one in (Figure II.5) presents the equivalent circuit of the boost converter when K is closed, i.e., between $[0; \alpha \cdot T_s]$ [65].

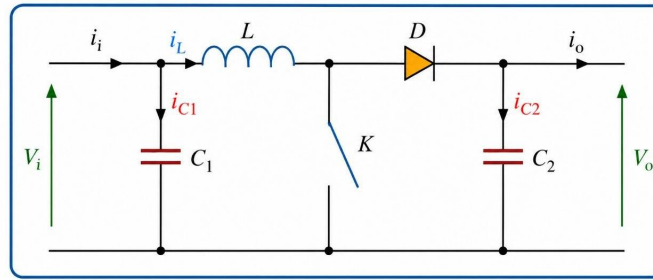


Figure II.5: Equivalent circuit diagram of the boost chopper when $t \in [0; \alpha, T_s]$

Similarly to the buck circuit, applying Kirchhoff's laws to the equivalent circuits of the two operating phases gives:

$$\begin{cases} i_{c1}(t) = C_1 \frac{dv_i(t)}{dt} = i_i(t) - i_L(t) \\ i_{c2}(t) = C_2 \frac{dv_o(t)}{dt} = -i_o(t) \\ V_L(t) = L \frac{di_L(t)}{dt} = V_i(t) \end{cases} \dots\dots\dots (II. 25)$$

At the open state of switch K, the equivalent circuit for the operation of the boost converter is as follows:

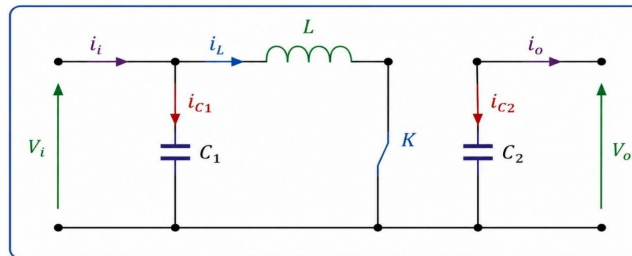


Figure II.6: Equivalent circuit of a boost chopper when $t \in [\alpha, T_s; T_s]$

$$\begin{cases} i_{c1}(t) = C_1 \frac{dv_i(t)}{dt} = i_i(t) - i_L(t) \\ i_{c2}(t) = C_2 \frac{dv_o(t)}{dt} = i_L(t) - i_o(t) \\ V_L(t) = \frac{di_L(t)}{dt} = V_i(t) - V_o(t) \end{cases} \dots\dots\dots (II. 26)$$

II.3.3. Conversion and yield report

We can calculate the conversion ratio $\frac{V_0}{V_i}$ as follows: [65]

$$M(\alpha) = \frac{V_0}{V_i} = \frac{1}{1-\alpha} \quad \dots\dots\dots (II. 27)$$

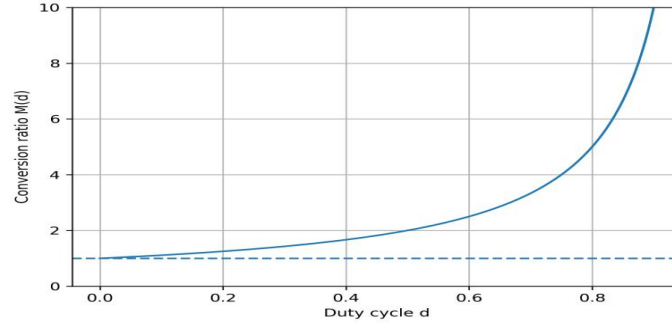


Figure II.7: Shape of the conversion ratio as a function of the duty cycle

II.4. Step-down converter (Buck converter)

The step-down converter (Figure II.9) is often found in the literature under the name Buck converter or series chopper. The latter, which is a switch, can only connect two sources of different types (current/voltage or vice versa).

The use of the Buck converter in photovoltaic conversion systems is quite appropriate, since the photovoltaic generator is a direct current source, while the load—generally a battery—behaves like a voltage source.

Its typical application is to convert the input voltage into a lower output voltage, where the conversion ratio $\alpha = V_0/V_i$ varies with the duty cycle of the switch [68].

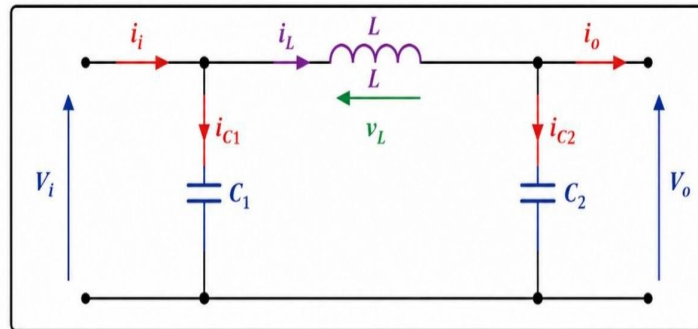


Figure II.9 : Principle diagram of a Buck converter

II.4.1. Principle of operation

A buck converter is an electronic circuit used to step down a higher DC voltage to a lower DC voltage with high efficiency. Its operation is based on the rapid switching of an electronic switch (usually a transistor) along with energy storage elements such as an inductor and a

capacitor. When the switch is closed (ON state), energy is transferred from the source to the load, and the inductor stores part of this energy in the form of a magnetic field, while the diode is reverse-biased. When the switch is opened (OFF state), the inductor maintains the current flow by releasing its stored energy and supplying it to the load through the diode. This switching process repeats at a high frequency, resulting in a stable output voltage that is lower than the input voltage. The output voltage is controlled by the duty cycle, following the approximate relation $V_{out} = D \times V_{in}$. The inductor and capacitor help smooth the signal and reduce ripple, making the buck converter highly efficient and widely used in modern electronic applications.

II.4.2. Equivalent Mathematical model

To determine the actual behavior of this converter, it is necessary to know its mathematical model in detail. For this purpose, we must represent the equivalent circuit in both states of the switch and then derive the mathematical model that relates the input and output variables.

(Figure II.10) shows the equivalent circuit diagram of a step-down (buck) converter with the switch closed during αT_s , while (Figure II.9) represents the step-down converter with the switch open during $(1 - \alpha)T_s$ [69].

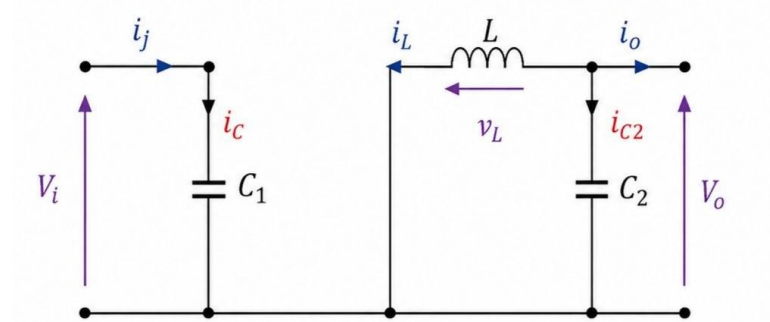


Figure II.10: Equivalent circuit diagram of the series chopper when $t \in [0, \alpha T_s]$.

When Kirchhoffs law is applied to the circuit above, the following equations are obtained:

$$\begin{cases} i_{C1}(t) = C_1 \frac{dv_i(t)}{dt} = i_i(t) - i_L(t) \\ i_{C2} = C_2 \frac{dv_0(t)}{dt} = i_L(t) - i_0(t) \\ V_L = L \frac{di_L(t)}{dt} = V_i(t) - V_0(t) \end{cases} \dots\dots\dots (II. 28)$$

II.4.3. Conversion and yield report

The conversion ratio M is defined as the ratio between the output voltage and the input voltage as follows [67]:

$$M(\alpha) = \frac{V_o}{V_i} = \eta \alpha \dots\dots\dots(II. 29)$$

Where η is the efficiency of the converter, defined as the ratio of the output power to the input power:

$$\eta = \frac{P_o}{P_i} = \frac{V_o I_o}{V_i I_i} \dots\dots\dots(II. 30)$$

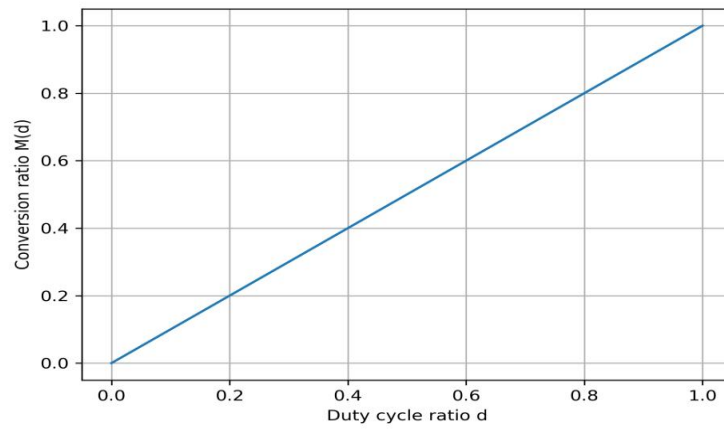


Figure II.11: the conversion ratio $M(d)$ of a series chopper (DC-DC converter)

II.5. Buck-Boost Converter

This converter combines the two previous functionalities, namely step-up and step-down. It transforms any input voltage into either a lower or higher output voltage depending on the requirements. Its basic schematic is illustrated in (Figure II.12) [65].

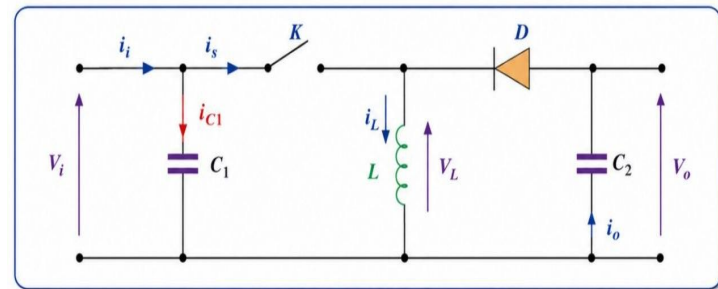


Figure II.12: Buck-Boost Converter

II.5.1. Principle of operation

When the switch K is closed, during the time interval $t_{ON, i.e.}, t \in [0, \alpha T_s]$ the diode is blocked, while the current increases linearly inside the inductor with a slope equal to $\alpha = \frac{V_i}{L}$. This allows the inductor to store more energy throughout the entire time K remains closed.

When the switch opens, i.e., during t_{OFF} with $t \in [\alpha T_s, T_s]$ the diode conducts through the inductor, in which the current also decreases linearly with a slope equal to $\beta = -\frac{V_o}{L}$ [67].

When the switch K is closed, the equivalent circuit is shown in (Figure II.13).

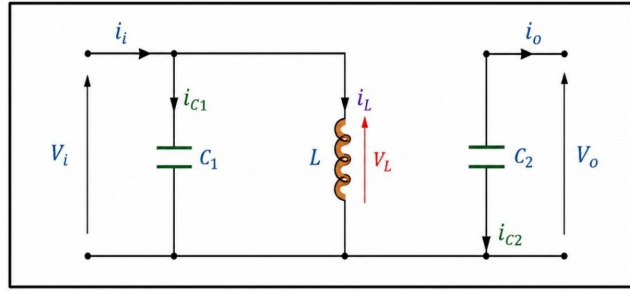


Figure II.13: Equivalent circuit of a Buck-Boost converter when $t \in [0, \alpha T_s]$

By applying Kirchhoff's law to this circuit, we obtain the following equations [67] [68]:

$$\begin{cases} i_{C1}(t) = C_1 \frac{dv_i(t)}{dt} = i_i(t) - i_L(t) \\ i_{C2}(t) = C_2 \frac{dv_o(t)}{dt} = -i_o(t) \\ V_L(t) = L \frac{di_L(t)}{dt} = V_i(t) \end{cases} \dots\dots\dots (II. 31)$$

When switch K is open, the equivalent circuit is shown in (Figure II 14).

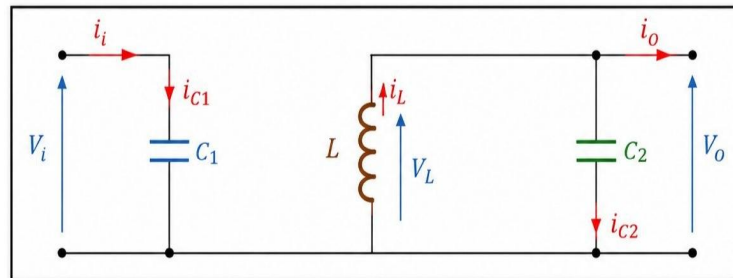


Figure II.14: Equivalent circuit of a Buck-Boost converter when $t \in [\alpha T_s, T_s]$

The equation model in this configuration is as follows:

$$\begin{cases} i_{C1}(t) = C_1 \frac{dv_L(t)}{dt} = i_i(t) \\ i_{C2}(t) = C_2 \frac{dv_0(t)}{dt} = i_L(t) - i_0(t) \dots\dots\dots(II. 32) \\ V_L(t) = \frac{di_L(t)}{dt} = V_0(t) \end{cases}$$

II.5.2. Conversion and yield report

The conversion ratio is calculated as follows [65] :

$$M(\alpha) = \frac{V_0}{V_I} = \frac{1}{1-\alpha} \dots\dots\dots(II. 33)$$

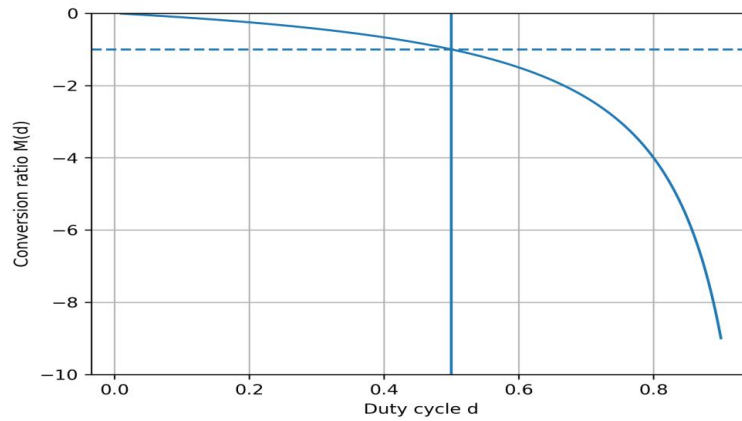


Figure II.15: Conversion ratio as a function of the duty cycle

II.5. Modeling of the PWM Voltage Inverter

Figure (II.16) shows the basic schematic of the three-phase voltage inverter. It is placed between a DC voltage source assumed to be ideal, thus with a constant voltage E , and a three-phase AC current source also assumed to be ideal, with currents i_a , i_b , and i_c forming a balanced sinusoidal three-phase system [72].

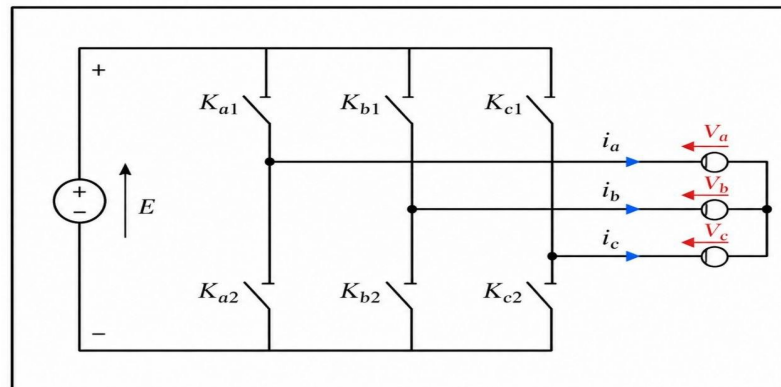


Figure II.16: Representative diagram of a three-phase inverter

It should be noted that the switching states of the switches in the same leg are complementary.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S1 \\ S2 \\ S3 \end{bmatrix} \dots\dots\dots (II. 34)$$

Where:

. V_{an} , V_{bn} , and V_{cn} are the phase voltages

. V_{DC} : DC voltage

$S1, S2, S3$ logical (PWM) signals representing the switching states of the switches K_i

Knowing that the switching states can be defined by three Boolean control variables $S_i (i=1, 2, 3)$:

$S_i = 1$: the case where the upper switch is ON (closed) and the lower switch is OFF (open).

$S_i = 0$: the case where the upper switch is OFF (open) and the lower switch is ON (closed).

II.6. Modeling of the Asynchronous Machine (Induction Machine)

Electrical machines are highly complex systems, as their modeling must account for all the physical phenomena they involve. It is therefore essential to adopt certain conventional simplifying assumptions, which nevertheless do not affect the validity of the machine model within the scope of this work. [72]

II.6.1.Simplifying Assumptions

The simplifying assumptions adopted in this work are presented as follows:

- Sinusoidal spatial distribution of the air-gap magnetomotive forces. This implies considering a sinusoidal variation of the mutual inductances between the stator and rotor windings as a function of the angle between their magnetic axes.
- Linear magnetic characteristic of the machine (unsaturated magnetic circuit). The values of the self and mutual inductances are independent of the current magnitudes.
- Iron losses (hysteresis losses and eddy current losses) are neglected.
- The variation of the winding resistances with temperature is considered negligible. The values corresponding to operation under nominal load, after thermal stabilization of the windings, are used.
- The symmetry of the machine.

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

Flux additivity, Constancy of self-inductances, Constancy of stator and rotor resistances.

II.6.2.Equivalent Mathematical model of IM

Faraday's law allows us to write:

$$V = Ri + \frac{d\phi}{dt} \dots\dots\dots (II. 35)$$

By applying this formula to the three phases of the asynchronous machine, the following equations are obtained:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = [R_s] \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{as} \\ \varphi_{bs} \\ \varphi_{cs} \end{bmatrix} \dots\dots\dots (II. 36)$$

$$\begin{bmatrix} V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} = [R_r] \begin{bmatrix} I_{ar} \\ I_{br} \\ I_{cr} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{ar} \\ \varphi_{br} \\ \varphi_{cr} \end{bmatrix} \dots\dots\dots (II. 37)$$

Where:

$$[R_r] = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} [R_r] = R_r \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \dots\dots\dots (II. 38)$$

Les équations du flux statorique et rotorique (équations magnétiques) peut être exprimé sous forme matricielle comme suit :

$$[\varphi_s] = [L_s][I_s] + [M_{sr}][I_r] \dots\dots\dots (II. 39)$$

$$[\varphi_r] = [L_r][I_r] + [M_{rs}][I_s] \dots\dots\dots (II. 40)$$

Where:

$$[L_s] = \begin{bmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{bmatrix} \dots\dots\dots (II. 41)$$

$$[L_r] = \begin{bmatrix} L_r & M_r & M_r \\ M_r & L_r & M_r \\ M_r & M_r & L_r \end{bmatrix} \dots\dots\dots (II. 42)$$

$$[M_{sr}] = \overline{M_{sr}} \begin{bmatrix} \cos(\theta) & \cos(\theta + \frac{2}{3}\pi) & \cos(\theta - \frac{2}{3}\pi) \\ \cos(\theta - \frac{2}{3}\pi) & \cos(\theta) & \cos(\theta + \frac{2}{3}\pi) \\ \cos(\theta + \frac{2}{3}\pi) & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta) \end{bmatrix} \dots\dots\dots (II. 43)$$

Where:

$L_{i,i}$ and $L_{i,j}$ represent the self-inductance of the i^{th} phase and the mutual inductance between the i^{th} and j^{th} phases ($i + j$).

M_{sr} : mutual inductances between the stator phases.

$$P^{-1}(\theta) = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \cos(\theta) & -\sin(\theta) \\ \frac{1}{\sqrt{2}} & \cos(\theta - \frac{2}{3}\pi) & -\sin(\theta - \frac{2}{3}\pi) \\ \frac{1}{\sqrt{2}} & \cos(\theta - \frac{4}{3}\pi) & -\sin(\theta - \frac{4}{3}\pi) \end{bmatrix} \dots\dots\dots (II. 44)$$

The general equations describing the operation of AC machines in the d-q reference frame are widely available in the technical literature devoted to electrical machines and are given as follows:

$$\begin{aligned}
V_{ds} &= R_s I_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_a \varphi_{qs} \\
V_{qs} &= R_s I_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_a \varphi_{ds} \\
V_{dr} &= R_r I_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_a - \omega_r) \varphi_{qr} \\
V_{qr} &= R_r I_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_a - \omega_r) \varphi_{dr}
\end{aligned} \dots\dots\dots (II. 45)$$

By rewriting the previous equations in a stationary d-q reference frame ($\omega_a=0$) the model of the electrical part of the asynchronous motor is obtained:

$$\begin{aligned}
V_{ds} &= R_s I_{ds} + \frac{d\varphi_{ds}}{dt} \\
V_{qs} &= R_s I_{qs} + \frac{d\varphi_{qs}}{dt} \\
0 &= R_r I_{dr} + \frac{d\varphi_{dr}}{dt} + (\omega_r) \varphi_{qr} \\
0 &= R_r I_{qr} + \frac{d\varphi_{qr}}{dt} - (\omega_r) \varphi_{dr}
\end{aligned} \dots\dots\dots (II. 46)$$

Since the rotor of the squirrel-cage asynchronous motor is short-circuited, (V_{dr}) and (V_{qr}) are taken equal to zero.

By substituting the fluxes in the previous equations with these expressions:

$$\begin{aligned}
\varphi_{ds} &= L_s I_{ds} + M I_{dr} \\
\varphi_{qs} &= L_s I_{qs} + M I_{qr} \\
\varphi_{dr} &= L_r I_{dr} + M I_{ds} \\
\varphi_{qr} &= L_r I_{qr} + M I_{qs}
\end{aligned} \dots\dots\dots (II. 47)$$

The following system is obtained:

$$\begin{aligned}
V_{ds} &= R_s I_{ds} + L_s \frac{dI_{ds}}{dt} + M \frac{dI_{dr}}{dt} \\
V_{qs} &= R_s I_{qs} + L_s \frac{dI_{qs}}{dt} + M \frac{dI_{qr}}{dt} \\
0 &= R_r I_{dr} + L_r \frac{dI_{dr}}{dt} + M \frac{dI_{ds}}{dt} - \omega_r (L_r I_{qr} + M I_{qs}) \\
0 &= R_r I_{qr} + L_r \frac{dI_{qr}}{dt} + M \frac{dI_{qs}}{dt} + \omega_r (L_s I_{dr} + M I_{ds})
\end{aligned} \dots\dots\dots (II. 48)$$

The electromagnetic torque equation of the motor is given by:

$$T_{em} = \frac{3}{2} PM (I_{qs} I_{dr} - I_{ds} I_{qr}) \dots\dots\dots (II. 49)$$

The equation of motion, linking the electrical and mechanical parts, is written as follows:

$$T_{em} - T_r = J \frac{d\omega_r}{dt} \dots\dots\dots (II. 50)$$

The inverse transformation equations of the stator currents are given by:

$$I_{as} = \sqrt{\frac{2}{3}} I_{ds} \quad I_{bs} = \sqrt{\frac{2}{3}} \left(-\frac{1}{2} I_{ds} + \sqrt{\frac{3}{2}} I_{qs} \right) \quad I_{cs} = \sqrt{\frac{2}{3}} \left(-\frac{1}{2} I_{ds} - \sqrt{\frac{3}{2}} I_{qs} \right) \dots\dots\dots (II.51)$$

II.7. Modeling of the Centrifugal Pump

Thanks to advances in the use of electromotive force, the development of centrifugal pumps has been very rapid. Coupled with electric motors, they form lightweight, compact, low-cost

units with high efficiency. However, these systems these pumps must be used rationally to ensure optimal operation of the overall system

The hydraulic power is given by the following relation [70] :

$$P_{hyd} = \frac{\rho \cdot g \cdot HMT \cdot Q}{3600} \dots\dots\dots (II. 52)$$

Where:

P_{hyd} : hydraulic power of the pump, expressed in W.

ρ : water density (equal to 1000 kg / m^3).

g : gravitational acceleration (equal to 9,81 m/ s^2).

Q : flow rate (m^3 / h).

The resisting torque T_r imposed by the centrifugal pump applies a load torque proportional to the square of the motor rotational speed [71].

$$T_r = K_p \cdot \omega_r^2 + T_s \dots\dots\dots (II.53)$$

Where:

K_p : proportionality constant [(Nm/ rad.s⁻¹)²].

T_s : static torque, which is very small.

The mechanical power equation of the pump is also determined as a function of the speed and is given by the following relation:

$$P_{mec} = K_p \cdot \omega^3 \dots\dots\dots (II. 54)$$

II.8. Conclusion

The modeling of the photovoltaic pumping chain represents a crucial step toward understanding system behavior and enhancing overall performance, as it offers a structured framework for analyzing the interactions among its different components.

Accordingly, this chapter establishes a solid groundwork for further stages, including simulation, optimization, and practical implementation, while paving the way for a detailed investigation of control strategies to be addressed in the following chapter

CHAPTER III : Control of Photovoltaic Pumping System

III.1.Introduction

The control of a photovoltaic pumping system plays a crucial role in ensuring efficient and reliable operation under continuously changing environmental conditions. Since the power generated by the photovoltaic array depends mainly on solar irradiance and cell temperature, an appropriate control strategy is required to maximize the extracted energy while maintaining stable system performance. In photovoltaic pumping applications, the control system generally combines a Maximum Power Point Tracking (MPPT) algorithm with power electronic converters to regulate the energy flow from the PV generator to the motor–pump set. This approach improves the overall efficiency, enhances the dynamic response, and guarantees optimal water pumping performance over a wide range of operating conditions[74].

III.2. Control of the Photovoltaic Pumping System

III.2.1.MPPT Control (Maximum Power Point Tracking)

Photovoltaic energy production is nonlinear and varies with solar irradiance and temperature. The operating point of the photovoltaic (PV) panel does not always coincide with the maximum power point. Therefore, a mechanism known as Maximum Power Point Tracking (MPPT) is used to search for and track the maximum power point so that maximum power is continuously generated.

The principle of this control is based on the automatic adjustment of the duty cycle α , bringing it to its optimal value in order to maximize the power delivered by the PV panel. A large number of MPPT control techniques have been developed since the 1970s, starting with simple methods based on voltage and current feedback and progressing to more advanced controllers that use algorithms to determine the maximum power point (MPP) of the PV generator. Among the most widely used techniques is the Perturb and Observe (P&O) algorithm, which is appreciated for its simplicity, ease of implementation, and satisfactory performance in photovoltaic energy conversion systems.

III.2.1.1. Perturb and Observe (P&O) Method

The P&O method is generally the most widely used due to its simplicity and ease of implementation. As its name suggests, this method is based on perturbing (either increasing decreasing) the reference voltage V_{ref} or the reference current I_{ref} and observing the effect of this perturbation on the measured power ($P = V \cdot I$) [74].

However, the ideal variable for characterizing the PV generator is the one that varies little under changing climatic conditions. Variations in irradiance affect the current more than the photovoltaic voltage, whereas temperature variations have a greater impact on the PV voltage.

Nevertheless, temperature dynamics are slow and vary within a limited range. Therefore, it is preferable to control the PV generator voltage.

This algorithm aims to operate the system at its maximum power by incrementing or decrementing the operating voltage and observing the effect of this perturbation on the power delivered by the PV generator. Based on this observation, the algorithm decides the action to be taken during the next iteration.

Four possible cases for the P&O method are illustrated in Figure (II.6) and summarized in Table (II.6):

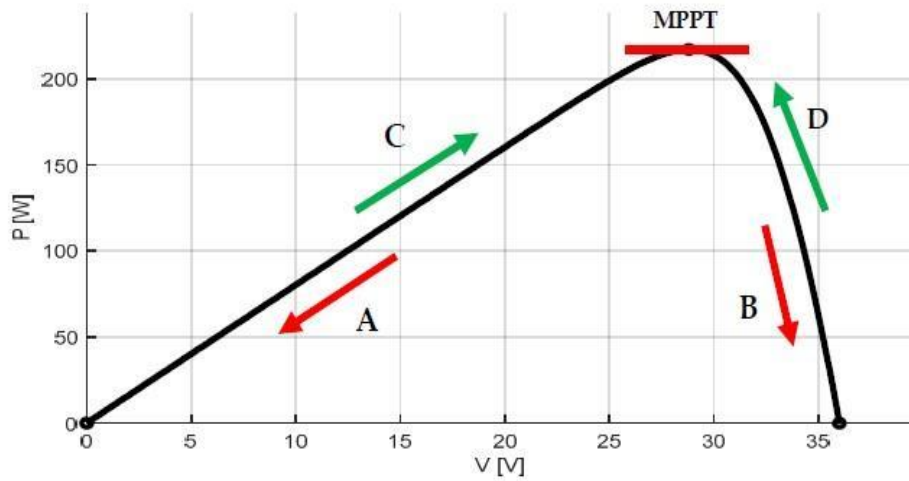


Figure III.1: Operating characteristic of the P&O method

Figure (II.6) shows the four possible cases encountered during MPP tracking, where point 1 represents the previous position and point 2 represents the current position for each case (A, B, C, and D).

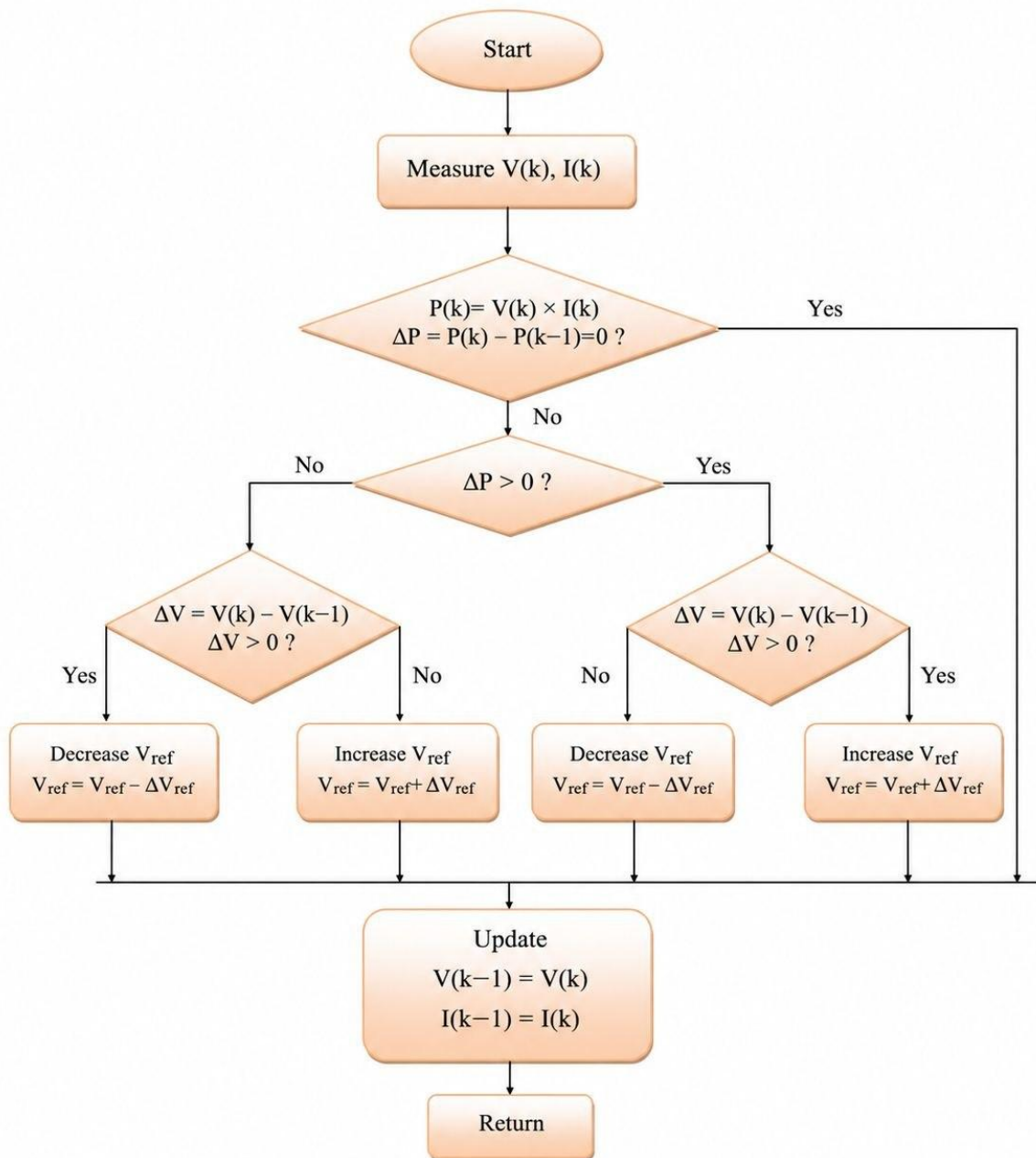
- Cas A : $\Delta P < 0$ and $\Delta V < 0$
- Cas B : $\Delta P < 0$ and $\Delta V > 0$
- Cas C : $\Delta P > 0$ and $\Delta V > 0$
- Cas D : $\Delta P > 0$ and $\Delta V < 0$

In cases A and C, the duty cycle must be decreased, resulting in an increase in the PV module voltage.

Whereas in cases B and D, the duty cycle must be increased so that the PV module voltage decreases.

Table III.1: Principle of the P&O Algorithm.

ΔV	ΔP	$\Delta P/\Delta V$
Positive	Positive	Positive
Négative	Négative	Positive
Positive	Négative	Négative
Négative	Positive	Négative

**Figure III.2: Flowchart of the P&O Method**

It should be noted that although the P&O method is widely used due to its ease of implementation, it presents some drawbacks related to oscillations around the maximum power point (MPP) in steady state. This is because the MPP tracking procedure must be repeated periodically, forcing the system to continuously oscillate around the MPP once it is reached [75]. These oscillations depend on the perturbation step size [76]:

- If the perturbation step size is large, the MPPT algorithm will respond rapidly to sudden changes in operating conditions; however, losses will increase under steady or slowly varying conditions.
- If the perturbation step size is very small, losses under steady or slowly varying conditions will be reduced; however, the system will no longer be able to track rapid changes in temperature or irradiance.

A compromise must therefore be found between accuracy and speed, which makes this control method difficult to optimize. Another drawback of the P&O method appears during rapid changes in atmospheric conditions.

As illustrated in Figure (II.3) Starting from an operating point A, if the climatic conditions remain constant, a perturbation ΔV in the voltage V will move the operating point to point B, and the direction of the perturbation will be reversed due to the decrease in power. However, if, for example, the irradiance increases and shifts the power curve from P_1 to P_2 during one MPPT cycle, the operating point will move from A to C. This represents an increase in power, and the algorithm interprets this increase as being caused by the previous perturbation; therefore, it continues in the same direction, which is actually incorrect, moving the system away from the true maximum power point.

This process continues until the irradiance stabilizes, at which point the system returns to the actual maximum power point. This behavior causes a delay in response during sudden changes in operating conditions and leads to power losses [77].

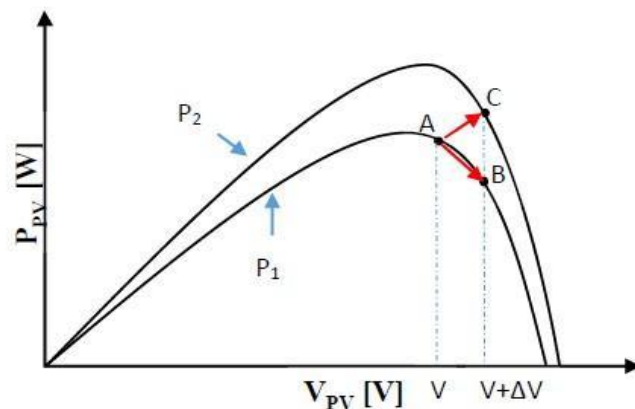


Figure III.3: Divergence of the P&O Method

III.2.2. Inverter Control

The objective of inverter control is to ensure the best possible tracking of the reference currents or voltages by means of the switching commands applied to the power switches.

In fact, the three most commonly used current control strategies to achieve this objective are [78]:

- ✓ Predictive control
- ✓ Ramp comparison control
- ✓ Hysteresis control

For this study, hysteresis current control has been selected, as it is the simplest technique to implement for current control in high-speed drive systems. This is due to:

- ✓ Its ease of implementation
- ✓ Its robustness
- ✓ Its accuracy in tracking the reference current,
- ✓ Its very high dynamic performance.

III.2.2.1. Current Control Using Hysteresis Regulators

The principle of this control consists first in generating the error signal, defined as the difference between the reference current I_{ref} and the currents produced by the inverter I_a , I_b and I_c . This error is then compared with a template called the hysteresis band in order to determine the switching commands of the power switches.

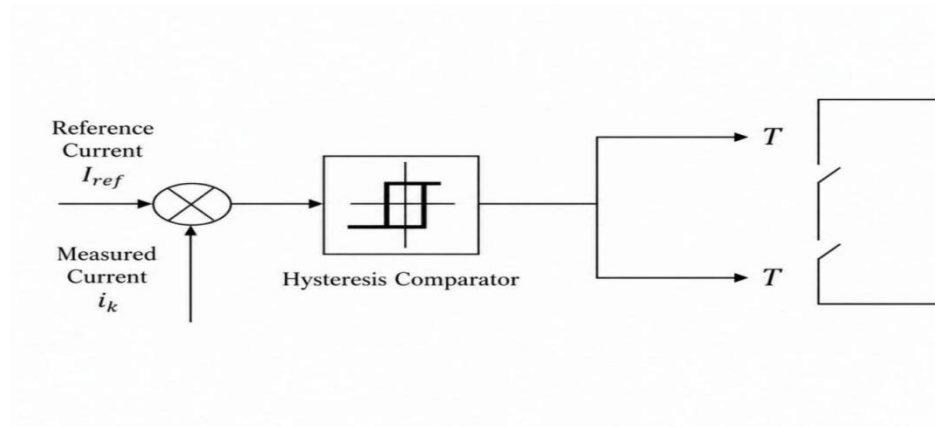


Figure III.4: Principle of Hysteresis Current Control.

Despite all the advantages of this control method mentioned previously, it also presents some drawbacks, namely:

The switching frequency largely depends on the machine parameters and the DC bus voltage [78].

The sum of the three currents is not necessarily zero, which leads to current imbalance depending on the hysteresis band [77].

III.3. Field-Oriented Control

Field-Oriented Control (FOC) is one of the most widely used control techniques for induction motors due to its ability to provide high dynamic performance and precise, independent control of both flux and torque.

Field-Oriented Control (FOC) separates flux control from torque control by aligning the flux vector with the direct (d) axis, enabling independent control of flux and torque. It is one of the most widely used control methods for electrical machines, providing high dynamic performance and precise operation through the optimal orientation of current and flux vectors.

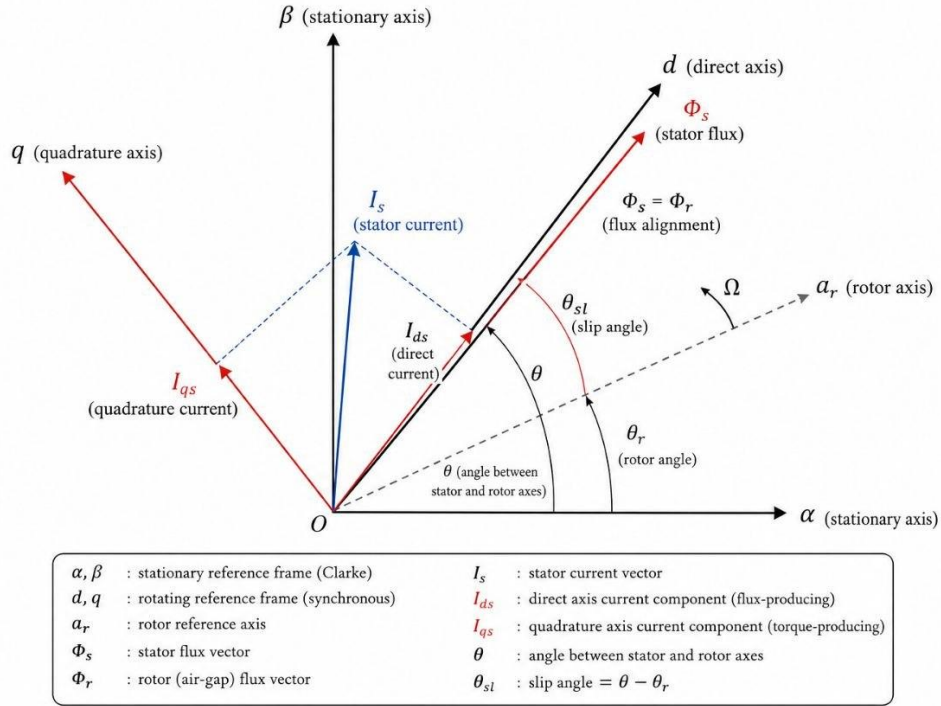


Figure III.5: Flux Orientation (Rotor, Stator, and Air-Gap Flux)

III.3.1 Flux Orientation Selection

The orientation of the reference axes can be chosen according to one of the machine flux vectors, namely the rotor flux, stator flux, or air-gap flux.

$$\phi_{sd} = 0, \quad \phi_s = \phi_{sd} \text{ Stator flux orientation.}$$

$$\phi_{rq} = 0, \quad \phi_r = \phi_{rd} \text{ Rotor flux orientation.}$$

$$\phi_{mq} = 0, \quad \phi_m = \phi_{md} \text{ Air-gap flux orientation.}$$

In all three cases, the electromagnetic torque is proportional to the product of the flux and the quadrature-axis component of the stator current.

III.3.2. Types of Vector Control

There are two main vector control methods commonly used in research. The first is the Direct

Field-Oriented Control (DFOC) method, developed by F. Blaschke, while the second is the Indirect Field-Oriented Control (IFOC) method, developed by K. Hasse.

III.3.2.1 Direct Vector Control

Direct Vector Control (DFOC) requires accurate knowledge of the flux vector, including its magnitude and position. It is based on the estimation or measurement of the electromagnetic torque and flux variables. The flux position is determined using Hall-effect sensors mounted on the stator teeth.

However, this method has several disadvantages:

- Limited reliability of flux measurement.
- Difficulties in filtering the measured signal.
- Reduced measurement accuracy due to temperature variations (machine heating) and magnetic saturation.
- High implementation cost because of the required sensors and filtering circuits.

III.3.2.2 Indirect Vector Control

The indirect vector control method consists of using the reference value of the rotor flux magnitude (ϕ_{dr}) instead of estimating the actual rotor flux magnitude. The main advantage of this method is that it relies only on reference quantities, which are inherently free from measurement noise.

Unlike the direct vector control method, indirect vector control does not require a rotor flux sensor. However, it requires either a rotor position/speed sensor or an estimator to determine the rotor position or speed. This method can be classified into two main approaches:

- The first approach obtains the rotor flux vector indirectly from the measured stator voltages and currents.
- The second approach estimates the rotor flux vector using the measured stator currents and the rotor speed, based on the rotor circuit equations of the induction motor expressed in a synchronous reference frame aligned with the rotor flux vector.

Despite its advantages, this method has some drawbacks. It requires a relatively complex control structure and its performance is highly sensitive to variations in machine parameters, particularly those caused by temperature changes, which may affect the accuracy of the flux estimation.

III.4. Principle of Vector Control

The principle of vector control is to simplify the electromagnetic torque equation of the induction motor so that its behavior becomes comparable to that of a separately excited DC motor.

The rotating reference frame (d,q) is selected such that the d-axis is aligned with the rotor flux vector, while the q-axis is perpendicular to it and corresponds to the torque-producing current component. Accordingly, the d-axis current i_{sd} controls the rotor flux, whereas the q-axis current i_{sq} controls the electromagnetic torque independently.

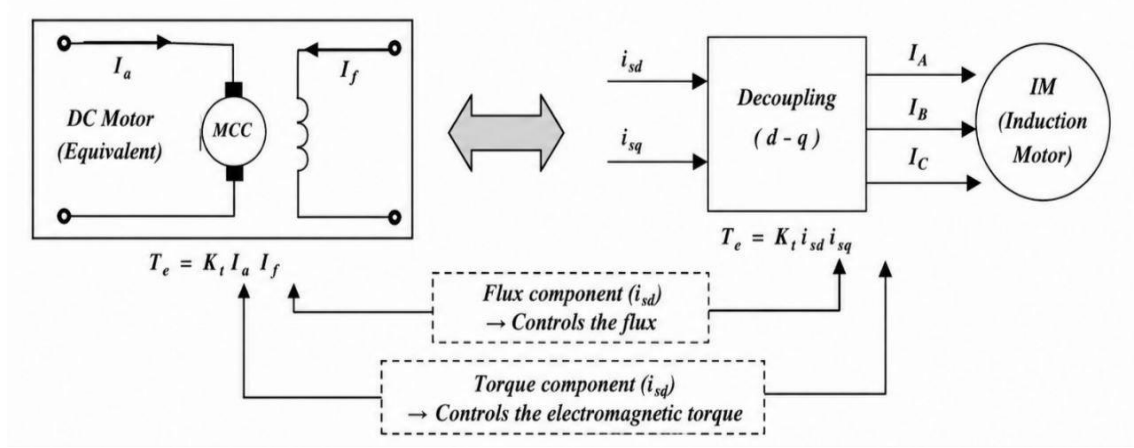


Figure III.6: Principle of decoupling control of the Induction Motor (IM)

There are three methods of flux-oriented vector control according to the selected flux orientation:

- Rotor Flux-Oriented Vector Control (RFOC).
- Stator Flux-Oriented Vector Control (SFOC).
- Magnetizing Flux-Oriented Vector Control (MFOC).

Among these methods, Rotor Flux-Oriented Vector Control (RFOC) is the most widely used because, in a non-saturated induction motor (IM), it provides complete decoupling of the rotor equations, allowing independent control of the flux and electromagnetic torque.

The vector model of the induction motor is described by the state equations expressed in the rotating reference frame aligned with the rotor flux vector, as follows:

$$\begin{aligned}
 V_{ds} &= R_s \cdot I_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \cdot \varphi_{qs} \\
 V_{qs} &= R_s \cdot I_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s \cdot \varphi_{ds} \\
 V_{dr} &= R_r \cdot I_{dr} + \frac{d\varphi_{dr}}{dt} = 0 \\
 V_{qr} &= R_r \cdot I_{qr} + \omega_r \cdot \varphi_{dr} = 0
 \end{aligned} \quad \dots \dots \dots (III. 1)$$

III.4.1. Input–Output Decoupling

The objective of input–output decoupling is to minimize, as much as possible, the effect of each input on a single output. Under this approach, the system can be modeled as a

set of independent single-input single-output (SISO) subsystems operating in parallel. Consequently, the control loops become non-interacting.

Among the various decoupling techniques that employ a controller, compensation-based decoupling is the most widely used.

- Compensation-Based Decoupling

Compensation-based decoupling provides a simple and effective way to formulate the equations of both the induction motor and the control system. It also enables the definition of two new control variables, V_{sd1} and V_{sq1} .

$$\begin{aligned} V_{sd} &= V_{sd1} - e_{sd} \\ V_{sq} &= V_{sq1} - e_{sq} \end{aligned} \quad \dots\dots\dots (III. 2)$$

$$\begin{aligned} e_{sd} &= -W_s \sigma L_s I_{sq} - R_r \frac{M}{L_r^2} \phi_r \\ e_{sq} &= W_s \sigma L_s + R_r \frac{M}{L_r} \phi_r W_r \dots\dots\dots (III. 3) \end{aligned}$$

The voltages V_{sd1} and V_{sq1} reconstruct the stator voltages V_{sd} and V_{sq} .

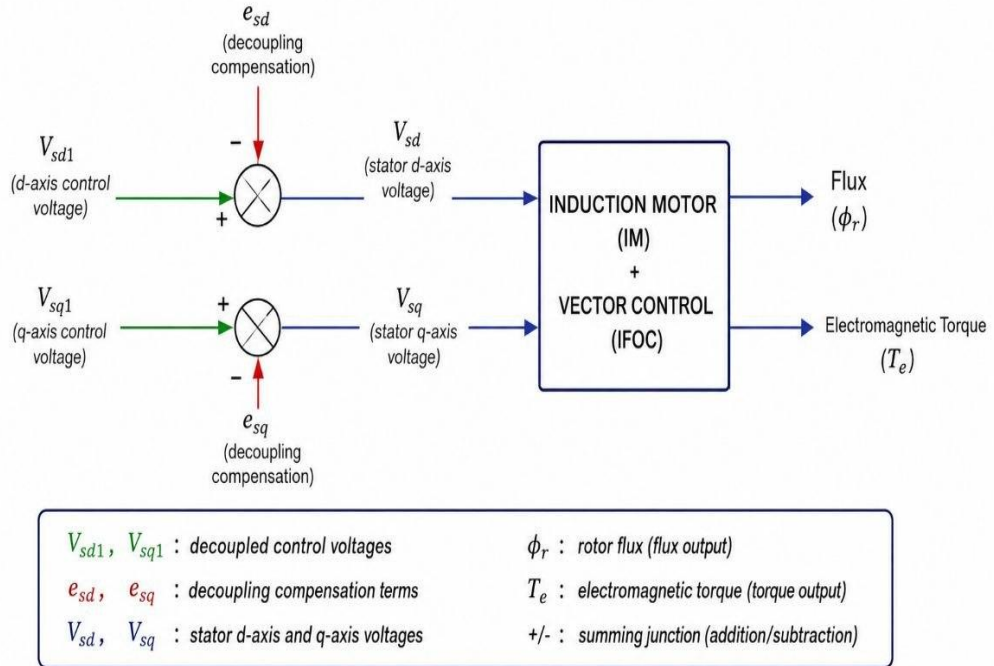


Figure III.7: Reconstruction of the V_{sd} and V_{sq} Voltages

Thus, a new system can be defined as follows:

$$\begin{aligned} V_{sd1} &= \sigma L_s \frac{dI_{sd}}{dt} + \left(R_s + R_r \frac{L_m^2}{L_r^2} \right) I_{sd} \\ V_{sq1} &= \sigma L_s \frac{dI_{sq}}{dt} + \left(R_s + R_r \frac{L_m^2}{L_r^2} \right) I_{sq} \end{aligned} \quad \dots\dots\dots (III. 4)$$

From this point onward, the control actions along the d - and q -axes are completely decoupled. By explicitly expressing the rotor flux and the electromagnetic torque, the following relationships are obtained:

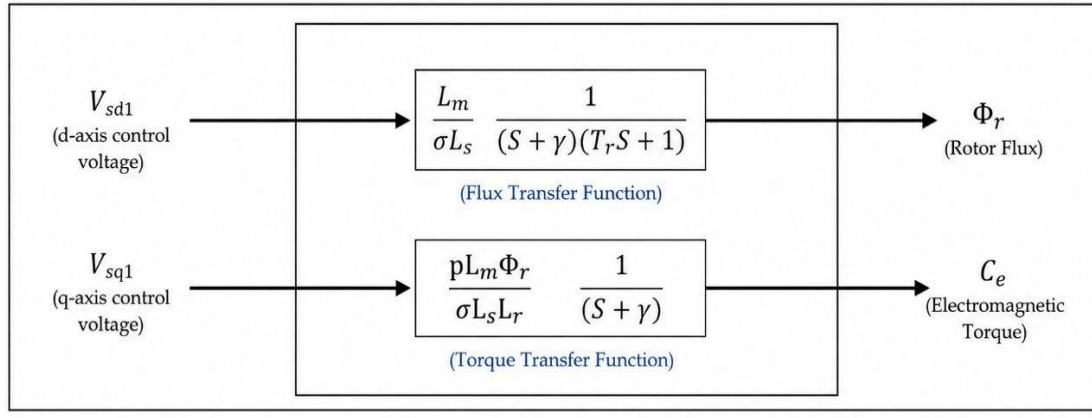


Figure III.8: Decoupled Control – Expressions of the Rotor Flux and the Electromagnetic Torque

$$\gamma = \frac{R_s + R_r \left(\frac{M}{L_r} \right)^2}{\sigma L_s} \dots \dots \dots (III. 5)$$

- Problems Associated with Decoupling

In a decoupled control system, if the compensation is correctly designed, any action applied to one input does not produce any variation in the other output. However, inadequate compensation may cause the other output to vary in a way that reinforces the control action, leading to system divergence. Consequently, this may introduce a risk of instability and reduce the robustness of the control system.

One possible solution is to select a lower gain in the compensating transfer functions during the controller design stage. This approach is particularly useful for the practical implementation of the control system.

III.4.2. Basic Block Diagram of Vector Control

Based on the induction motor model and the decoupling equations, the basic block diagram of the vector control system can be derived.

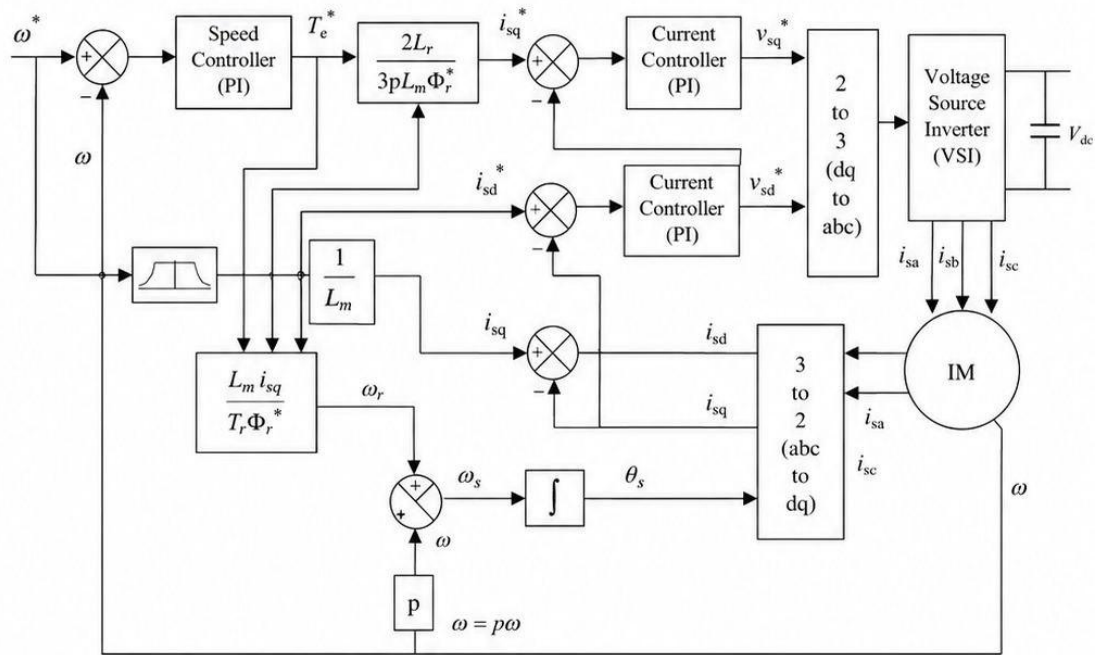


Figure III.9: Basic Block Diagram of Vector Control

III.5. Regulation

In this study, the control strategy is limited to the Proportional–Integral (PI) controller. The PI controller is one of the most widely used controllers in industrial applications due to its effective performance in regulating a wide range of physical variables. The PI controller improves the stability of the system response and eliminates the steady-state error.

In general, the objective of control is to achieve a high-performance system.

III.5.1. Controller Design

Let:

$Y(t)$: Output signal of the controlled system.

Y.(t): Reference signal (desired signal) to be tracked.

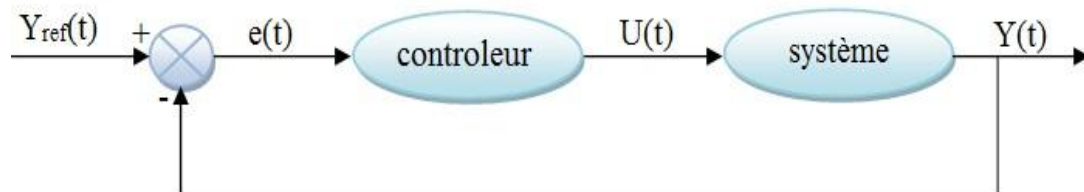


Figure III.10:Block Diagram of the PI Control

The control law is given by:

$$U(t) = K_p e(t) + K_i \int e(t) dt \dots\dots\dots (III. 6)$$

Proportional Action (P)

The proportional action depends on the proportional gain :

A high provides a faster response but increases the risk of overshoot and oscillations.

A low results in a slower response with fewer oscillations.

Integral Action (I)

The integral action gradually eliminates the steady-state error by continuously adjusting the control signal until the error becomes zero.

III.5.2. Characteristics of Controllers**- Stability**

A system is stable if its output remains bounded for any bounded input despite disturbances.

- Response Speed

Response speed describes how quickly the system reacts to changes in the reference signal and is usually evaluated by the 5% settling time.

- Accuracy

Accuracy is determined by the steady-state error, which should be as small as possible.

III.5.3. Calculation of regulators**III.5.3.a. Speed Controller**

The speed control loop can be represented by the following functional block diagram:

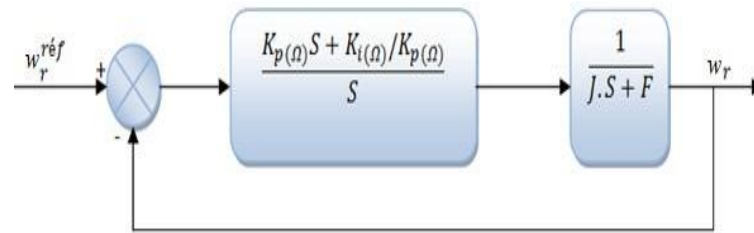


Figure III.11:Block Diagram of Speed Control

From the functional block diagram, we obtain:

$$\Omega = \frac{1}{Js+f} (C_e - C_r) \dots \dots \dots (III.7)$$

With the classical PI controller, the speed is expressed as:

$$\Omega = \frac{1}{Js+f} \left(\frac{K_{p1}s + K_{i1}}{s} \right) (\Omega_{ref} - \Omega) - \frac{1}{Js+f} C_r \dots \dots \dots (III.8)$$

Closed-loop transfer function

$$\frac{\Omega}{\Omega_{ref}} = \frac{\frac{K_{p1}}{K_{i1}}s+1}{\frac{J}{K_{i1}}s^2 + \left(\frac{K_{p1}}{K_{i1}} + \frac{f}{K_{i1}}\right)s+1} \dots\dots\dots(III.9)$$

By identifying the denominator with the canonical second-order form:

$$\frac{J}{K_{i1}} = \frac{1}{\omega_n^2} \dots\dots\dots(III.10)$$

$$\frac{K_{p1}}{K_{i1}} + \frac{f}{K_{i1}} = \tau_1 + \frac{f}{K_{i1}} = \frac{2\xi}{\omega_n} \dots\dots\dots(III.11)$$

III.5.3.b. Flux Controller

From the decoupling defined in Fig. II.6, we obtain:

$$\phi_r = \frac{K_3}{(s+\gamma)\left(s+\frac{1}{T_r}\right)} V_{sd1} \dots\dots\dots(III.12)$$

With

$$K_3 = \frac{L_m}{\sigma L_s T_r} \dots\dots\dots(III.13)$$

The system can be represented by the following functional block diagram.

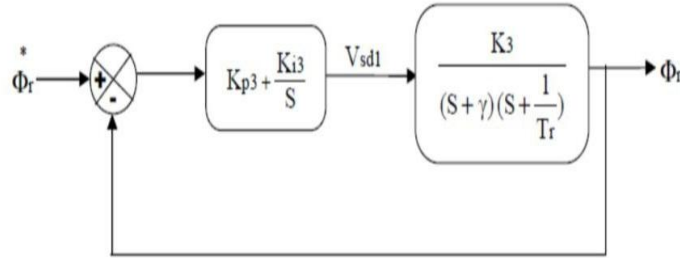


Figure III.12:Functional Block Diagram of the Flux Controller

With

$$K_3 = \frac{L_m}{\sigma L_s T_r} \dots\dots\dots(III.14)$$

The closed-loop transfer function of the system is given by:

$$\frac{1}{K_{p3}K_3} s^2 + \frac{\gamma}{K_{p3}K_3} s + 1 = 0 \dots\dots\dots(III.15)$$

By comparing with the canonical second-order form, we obtain:

$$\begin{cases} \frac{1}{K_{p3}K_3} = \frac{1}{\omega_n^2} \\ \frac{\gamma}{K_{p3}K_3} = \frac{2\xi}{\omega_n} \end{cases} \dots\dots\dots(III.16)$$

The following equations are obtained:

$$\begin{cases} K_{p3} = \frac{\gamma^2}{K_3(2\xi)^2} \\ K_{i3} = \frac{K_{p3}}{T_r} \end{cases} \dots\dots\dots(III.17)$$

III.6. Conclusion

This chapter has demonstrated that the adoption of the Perturb and Observe (P&O) MPPT algorithm, together with Indirect Field-Oriented Control (IFOC), significantly improves the efficiency and stability of photovoltaic pumping systems. Accordingly, these control strategies provide a solid foundation for the development of more efficient, reliable, and high-performance solar water pumping systems in practical applications

CHAPTER IV: Simulation of Photovoltaic Pumping System

IV.1.Introduction

In this chapter, a comprehensive simulation of the photovoltaic pumping system is presented to evaluate the overall performance of the proposed system. The study is based on the integration of a photovoltaic generator supplying a three-phase induction motor through a DC–DC boost converter and a voltage source inverter. The main objective is to ensure efficient utilization of solar energy while maintaining stable and reliable operation of the pumping system. To achieve this objective, the Maximum Power Point Tracking (MPPT) algorithm based on the Perturb and Observe (P&O) method is implemented to continuously extract the maximum available power from the photovoltaic generator under different solar irradiance levels. Furthermore, the Indirect Field Oriented Control (IFOC) strategy is employed to regulate the speed and torque of the induction motor, ensuring accurate control and improved dynamic performance. The simulation results obtained using the MATLAB/Simulink environment are then analyzed to evaluate the effectiveness of the proposed control strategy.

IV.2.System under processing

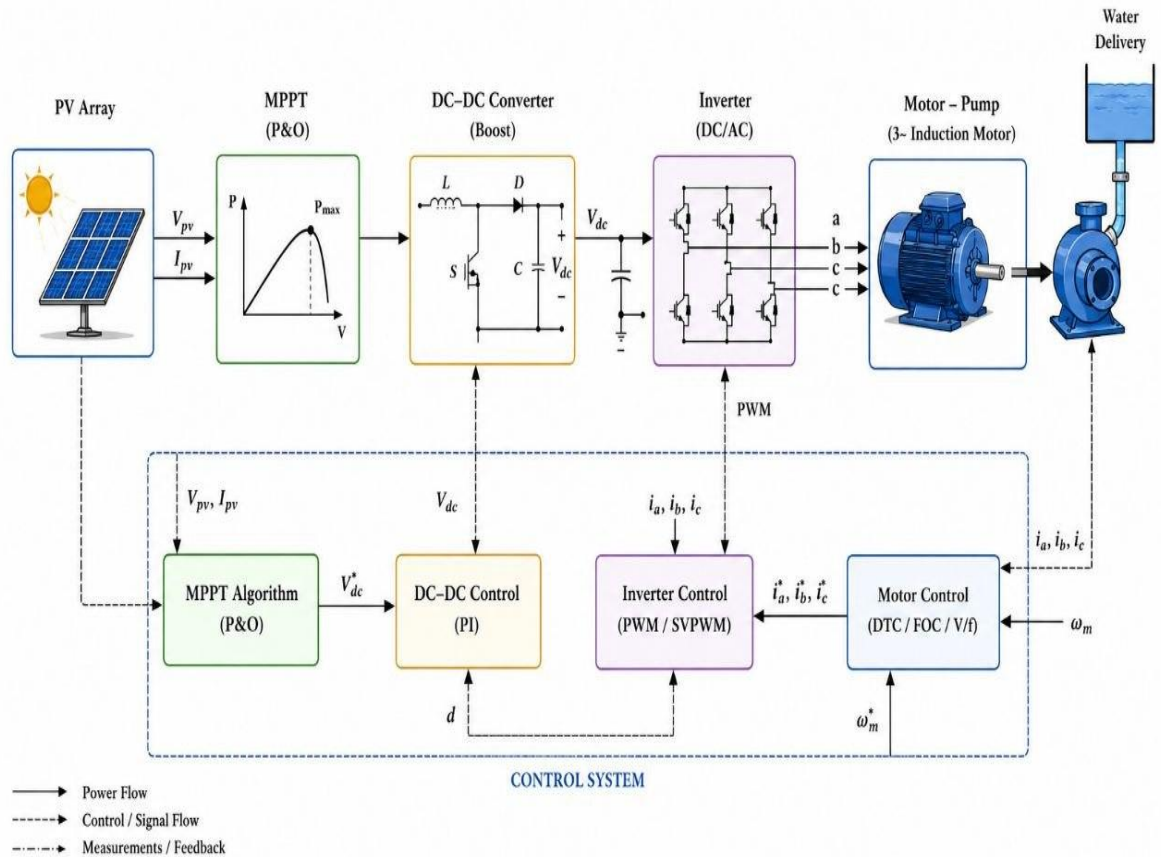


Figure IV.1: Block Diagram of the Photovoltaic Water Pumping System

IV.3. System Description

The proposed photovoltaic water pumping system consists of an energy conversion chain and control strategy designed to efficiently exploit solar energy for water pumping applications.

The system converts the electrical energy generated by the photovoltaic generator into suitable alternating current power to drive a three-phase induction motor coupled to a centrifugal pump, while ensuring maximum power extraction and optimal dynamic performance.

At the first stage, the Photovoltaic (PV) array converts solar irradiance into direct current (DC) electrical energy. The output voltage and current of the PV generator vary according to environmental conditions such as solar irradiance and temperature, resulting in continuous variations in the operating point of the photovoltaic system.

To ensure maximum power extraction from the solar panels, a Maximum Power Point Tracking (MPPT) algorithm is integrated into the system. The MPPT controller continuously measures the PV voltage and current in order to determine the optimal operating point corresponding to the maximum available power.

In this work, the Perturb and Observe (P&O) algorithm is implemented. The P&O algorithm generates the appropriate control signal for the DC-DC converter by adjusting the duty cycle, thereby maintaining operation around the maximum power point under varying atmospheric conditions.

The generated DC power is then processed by a DC-DC Boost Converter, whose main function is to step up and regulate the PV output voltage. In addition, the converter ensures proper adaptation between the photovoltaic source and the inverter stage while stabilizing the power transfer.

The energy is subsequently delivered to the DC Bus, which acts as an intermediate energy storage and filtering stage. The DC-link capacitor reduces voltage ripples and maintains a stable DC voltage required for the inverter operation.

The next stage consists of a Voltage Source Inverter (VSI) responsible for converting the DC voltage into a three-phase AC voltage suitable for supplying the induction motor. The inverter operation is generally based on switching techniques such as Pulse Width Modulation (PWM) and Space Vector Pulse Width Modulation (SVPWM). These modulation techniques improve the quality of the output voltage waveform and reduce harmonic distortion.

The inverter feeds a Three-Phase Induction Motor mechanically coupled to a centrifugal water pump. The induction motor converts electrical energy into mechanical rotational energy, which drives the pump to deliver water to the desired location.

IV.4. Simulation Results

According to the simulation carried out using Simulink, the following results were obtained:

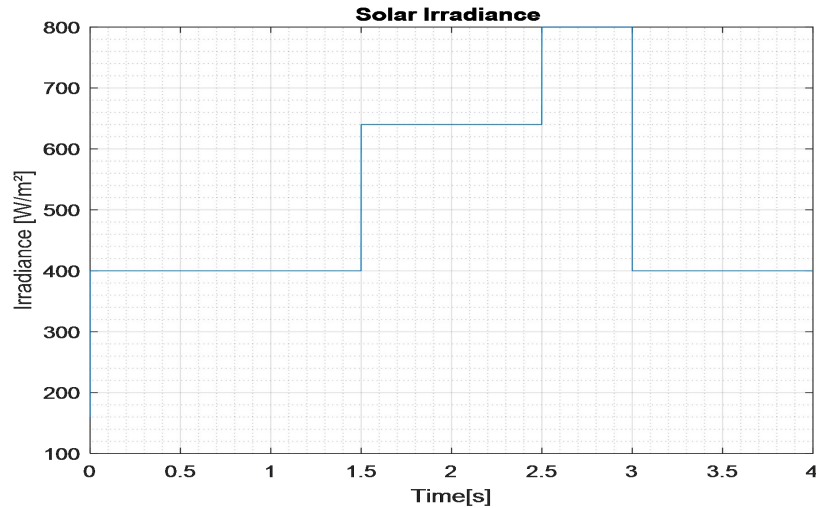


Figure IV.2: Solar Irradiance Variation Profile

This figure IV.2 presents the variation of solar irradiance applied to the photovoltaic system during the simulation period. The irradiance is initially maintained at 400 W/m², then increased to 630 W/m² at $t = 1.5$ s, followed by a second increase to 800 W/m² at $t = 2.5$ s. At $t = 3$ s, the irradiance decreases again to 400 W/m², creating different operating conditions for the photovoltaic system. These irradiance variations are used to evaluate the dynamic performance and robustness of the adopted control strategy under changing environmental conditions.

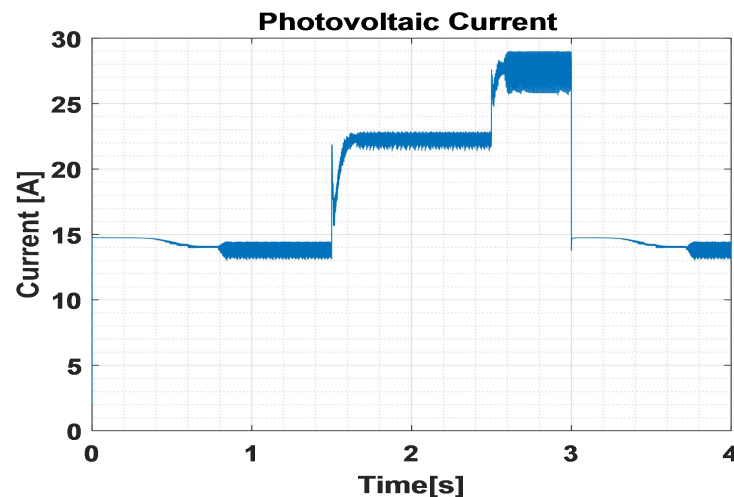


Figure IV.3: Dynamic Response of Photovoltaic Current

This figure IV.3 illustrates the variation of the photovoltaic current during system operation under different irradiance conditions. Initially, the photovoltaic current remains around 14 A under stable operating conditions. At $t = 1.5$ s and $t = 2.5$ s, the current increases significantly due to the rise in solar irradiance, reaching approximately 22 A and 28 A, respectively. Around $t = 3$ s, the current decreases rapidly as a result of the irradiance reduction before stabilizing again near its initial value. These results demonstrate the capability of the photovoltaic system and the MPPT control strategy to efficiently adapt to changing environmental conditions.

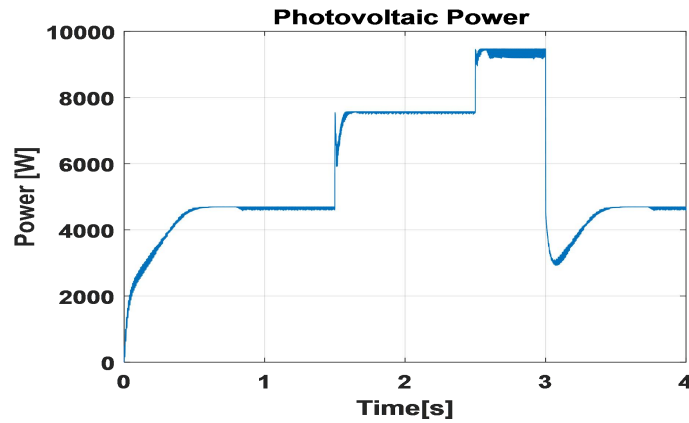


Figure IV.4: Dynamic Response of Photovoltaic Power

This figure IV.4 illustrates the dynamic response of the photovoltaic output power during system operation. At startup, the generated power increases progressively until it reaches a stable operating value of approximately 4.6 kW, indicating effective photovoltaic energy conversion and proper MPPT operation. Power variations can be observed around $t = 1.5$ s and $t = 2.5$ s due to changes in operating conditions or solar irradiance levels. A significant transient drop appears around $t = 3$ s, after which the system rapidly restores stability and reaches a new steady-state value. This behavior demonstrates the effectiveness of the adopted control strategy and the good dynamic performance of the photovoltaic system.

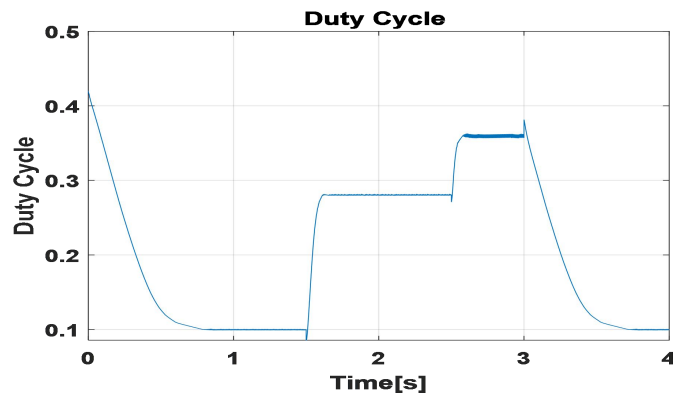


Figure IV.5: Dynamic Response of Duty Cycle

This figure IV.5 illustrates the variation of the duty cycle during system operation. At startup, the duty cycle decreases rapidly from its initial value before stabilizing around 0.1 under steady-state conditions. At $t = 1.5$ s and $t = 2.5$ s, the duty cycle increases to higher operating levels in response to changes in irradiance and load conditions. Around $t = 3$ s, a significant decrease occurs before the signal gradually returns to its steady-state value. This behavior confirms the capability of the control system to continuously adapt the converter switching operation according to the system operating conditions.

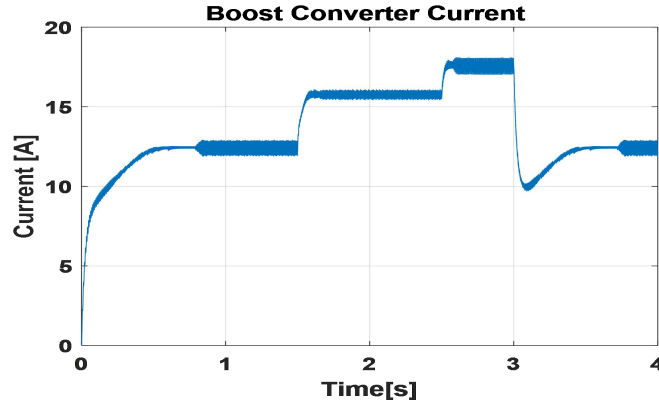


Figure IV.6: Dynamic Response of Boost Converter Current

This figure IV.6 illustrates the evolution of the boost converter current during system operation. At startup, the current increases progressively until it reaches a stable operating value close to 12 A, indicating proper converter operation and effective current regulation. Current variations can be observed around $t = 1.5$ s and $t = 2.5$ s due to changes in irradiance or load conditions, causing the current to rise to higher operating levels. Around $t = 3$ s, a sudden current drop appears following the decrease in operating conditions before the system rapidly stabilizes again near its nominal value. These results demonstrate the fast dynamic response and robustness of the adopted control strategy.

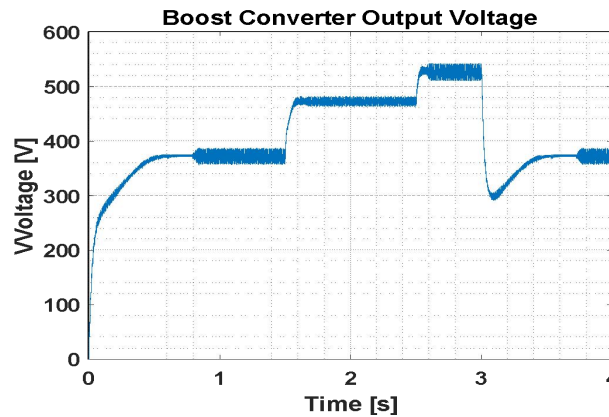


Figure IV.7: Dynamic Response of the Boost Converter Output Voltage

This figure IV.7 illustrates the dynamic response of the boost converter output voltage during system operation. At startup, the output voltage increases progressively until it reaches a stable operating value, indicating proper converter operation and effective voltage regulation. Voltage variations can be observed around $t = 1.5$ s, $t = 2.5$ s, and $t = 3$ s due to changes in operating conditions or load disturbances. Despite these transient disturbances, the output voltage quickly returns to its steady-state value, demonstrating the robustness and fast dynamic response of the adopted control strategy.

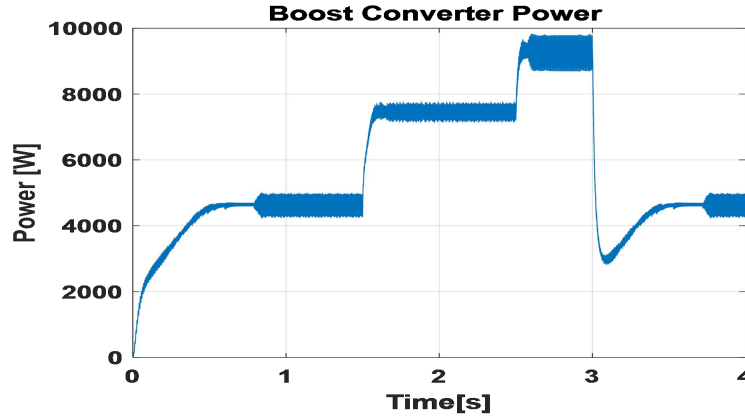


Figure IV.8 Dynamic Response of Boost Converter Power

This figure IV.8 presents the evolution of the boost converter power during system operation. At startup, the converter power increases progressively until it reaches a stable operating level, reflecting the proper energy conversion process and effective power management. Noticeable power variations appear around $t = 1.5$ s and $t = 2.5$ s due to changes in operating conditions or load requirements. A significant power drop can also be observed around $t = 3$ s, followed by a rapid recovery toward a new steady-state value. These results confirm the fast dynamic response and the robustness of the adopted control strategy under varying operating conditions.

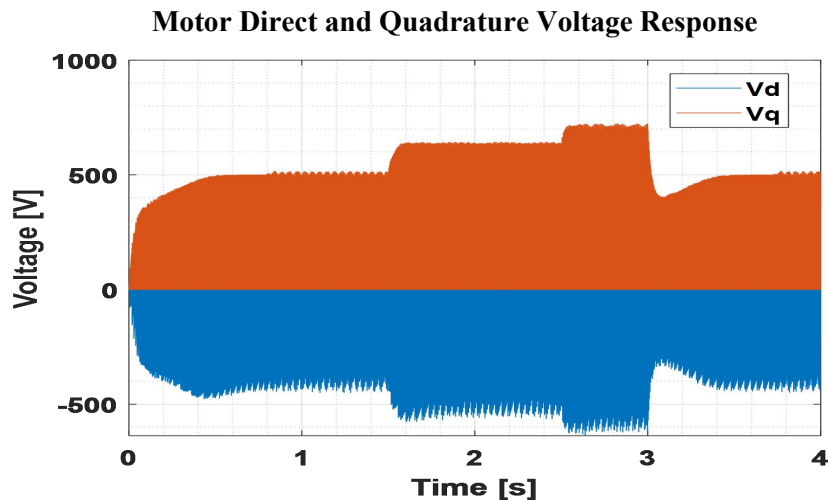


Figure IV.9: Motor Direct and Quadrature Voltage Response

This figure IV.9 illustrates the dynamic response of the direct and quadrature voltages (V_d , V_q) during system operation. At startup, both voltage components increase progressively before reaching stable operating values, indicating a proper establishment of the motor control process. Variations and transient changes can be observed around $t = 1.5$ s and $t = 3$ s due to changes in operating conditions or load disturbances. Despite these disturbances, the voltage components quickly return to stable values, demonstrating the robustness and effectiveness of the adopted control strategy.

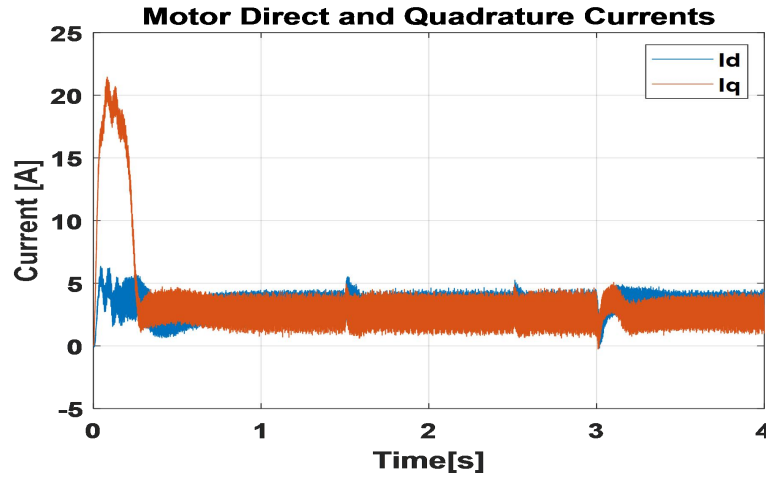


Figure IV.10: Dynamic Response of Direct and Quadrature Currents

This figure IV.10 illustrates the dynamic behavior of the direct and quadrature axis currents during system operation. At startup, the quadrature current I_q reaches a high transient value of approximately 20 A to provide the required electromagnetic torque for motor acceleration, while the direct current I_d remains within a limited range. After the startup phase, both current components gradually stabilize around their steady-state operating values with small oscillations caused by the inverter switching process and control dynamics. Transient disturbances can also be observed around $t = 1.5$ s and $t = 3$ s due to variations in operating conditions. Nevertheless, the system rapidly restores stable operation, demonstrating the effectiveness and robustness of the adopted control strategy.

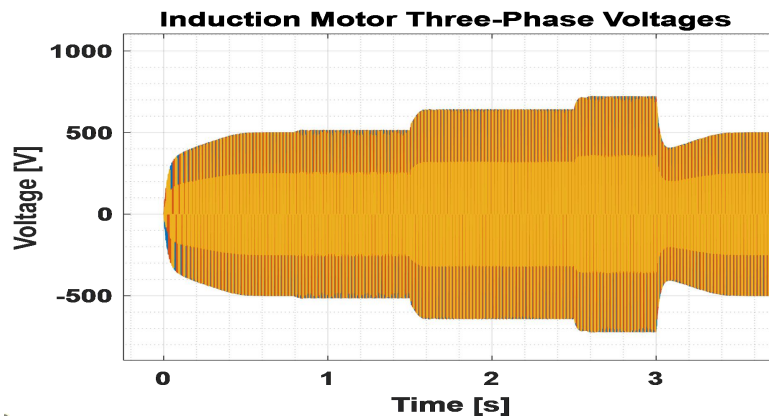


Figure IV.11: Induction Motor Three-Phase Voltages

This figure IV.11 illustrates the dynamic response of the three-phase voltages (V_a , V_b , V_c) during system operation. At startup, the voltage amplitudes increase progressively until stable operating conditions are reached, indicating proper inverter operation and effective control performance. Variations in the voltage amplitudes can be observed around $t = 1.5$ s, $t = 2.5$ s, and $t = 3$ s due to load changes or operating condition disturbances. Nevertheless, the three-phase voltages maintain a balanced sinusoidal behavior, demonstrating the robustness of the adopted control strategy and the stability of the electrical system.

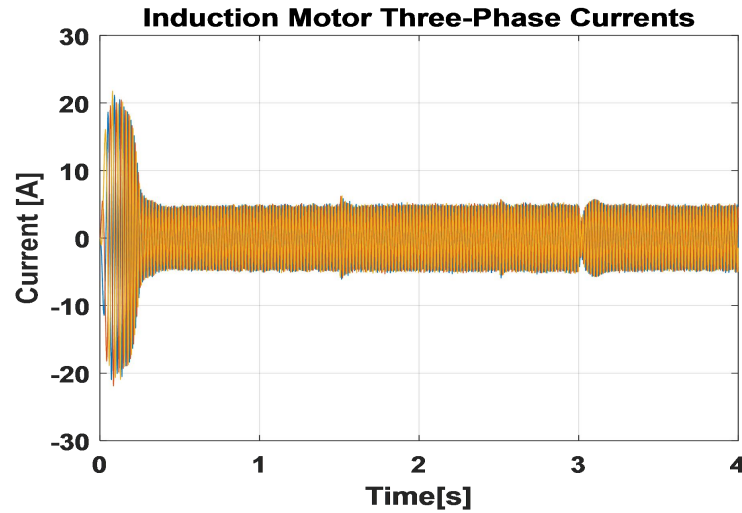


Figure IV.12: Induction Motor Three-Phase Currents

This figure IV.12 illustrates the behavior of the three-phase stator currents during system operation. At startup, the currents exhibit high transient amplitudes reaching approximately ± 20 A due to the motor starting conditions and the required acceleration torque. After the transient period, the three-phase currents become balanced and stabilize around their steady-state operating values with nearly sinusoidal waveforms. Small disturbances can also be observed around $t = 1.5$ s and $t = 3$ s as a result of operating condition variations. However, the system rapidly restores stable operation, confirming the effectiveness of the adopted control strategy and the good dynamic performance of the drive system.

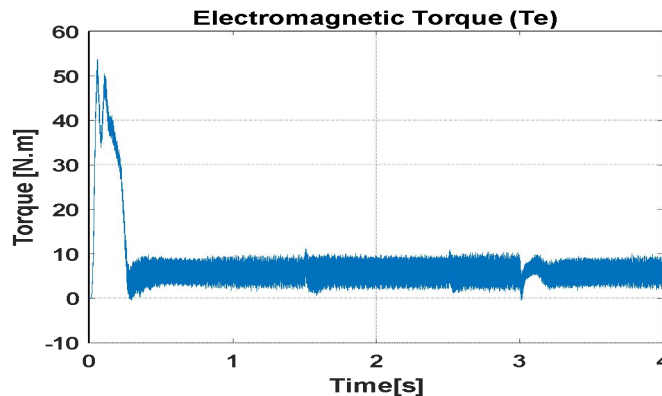


Figure IV.13: Dynamic Response of Electromagnetic Torque

This figure IV.13 illustrates the dynamic response of the electromagnetic torque during system operation. At startup, the torque reaches a high transient peak of approximately 50 N.m in order to provide the required acceleration torque for motor starting. After the transient period, the electromagnetic torque decreases and stabilizes around its steady-state value with small oscillations caused by the switching behavior of the control strategy. Disturbances can also be observed around $t = 1.5$ s and $t = 3$ s due to load or operating condition variations. However, the system rapidly restores stability, demonstrating good dynamic performance and effective torque control.

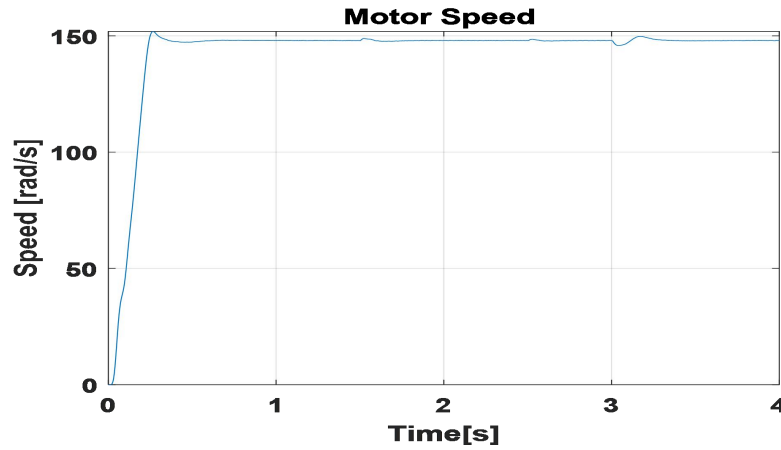


Figure IV.14: Dynamic Response of Motor Speed

This figure IV.14 illustrates the variation of the motor speed during system operation. At startup, the motor speed increases rapidly until it reaches a steady-state value close to 150 rad/s, indicating a fast and smooth acceleration process. Small transient oscillations can be observed during the startup phase and around $t = 3$ s due to operating condition variations. However, the motor speed remains stable with minimal fluctuations, demonstrating the effectiveness of the adopted control strategy and the good stability of the drive system.

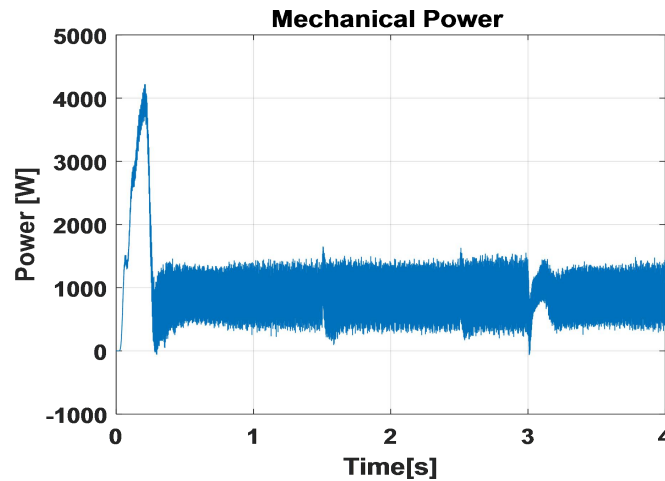


Figure IV.15: Dynamic Response of Mechanical Power

This figure IV.15 illustrates the evolution of the mechanical power during the operation of the pumping system. During the startup phase, the mechanical power reaches a peak value of approximately 4 kW due to the high energy demand required for motor acceleration and pump starting. After the startup transient, the mechanical power gradually decreases and stabilizes around a nearly constant operating value, with small oscillations related to the control system dynamics and the power conversion process. Transient variations can also be observed at certain time instants due to load disturbances or changes in operating conditions. Nevertheless, the system maintains stable operation and rapidly returns to its normal operating state, demonstrating the efficiency and reliability of the adopted control strategy.

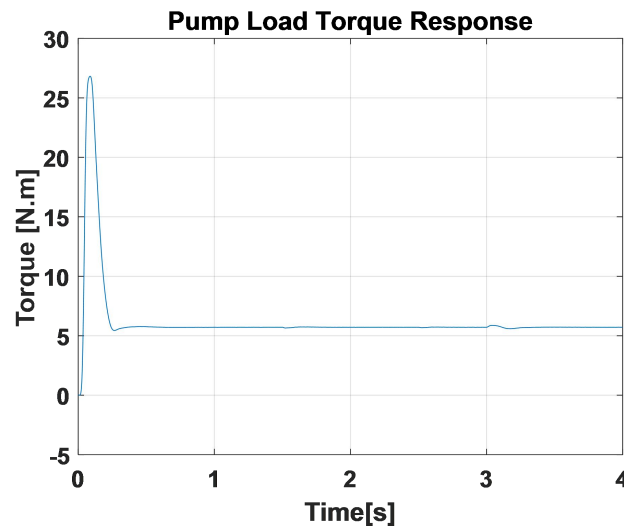


Figure IV.16: Dynamic Response of Pump Load Torque

This figure IV.16 illustrates the dynamic response of the pump load torque during system operation. At startup, the torque exhibits a high transient peak reaching approximately 27 N.m due to the motor acceleration and pump starting conditions. After the transient period, the torque rapidly decreases and stabilizes around 5.5 N.m with very small oscillations, indicating stable pump operation and effective load regulation. The fast stabilization of the torque demonstrates the good dynamic performance and robustness of the adopted control strategy.

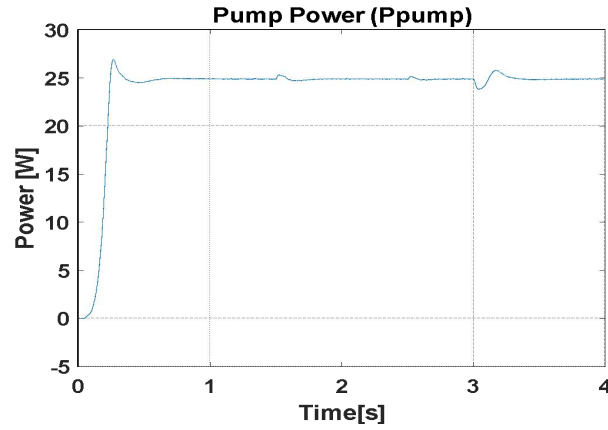


Figure IV. 17: Dynamic Response of Pump Power

This figure IV.17 illustrates the dynamic response of the pump power during system operation. At startup, the pump power increases rapidly and reaches a transient peak of approximately 27 W before settling around its steady-state value of nearly 25 W. Small transient variations can be observed around $t = 1.5$ s and $t = 3$ s due to changes in operating conditions or load disturbances. However, the system quickly restores stability after each disturbance, demonstrating the effectiveness and robustness of the adopted control strategy.

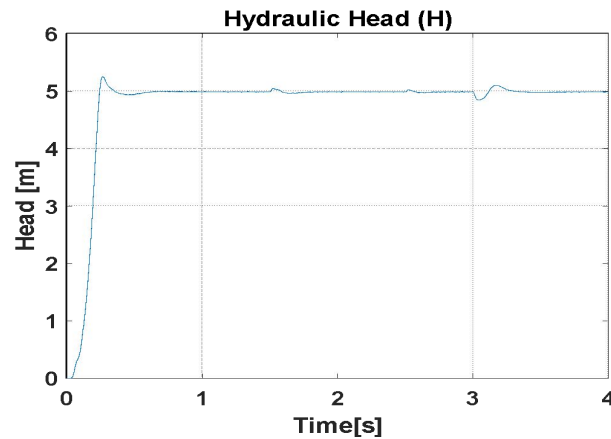


Figure IV.18: Dynamic Response of Hydraulic Head

This figure IV.18 illustrates the variation of the hydraulic head during system operation. At startup, the hydraulic head increases rapidly and reaches a peak value slightly above 5 m before stabilizing around its steady-state operating point. Small transient fluctuations can be observed around $t = 1.5$ s and $t = 3$ s due to variations in operating conditions. However, the hydraulic head quickly returns to stable operation with minimal oscillations, demonstrating the good dynamic behavior and stability of the pumping system under the adopted control strategy.

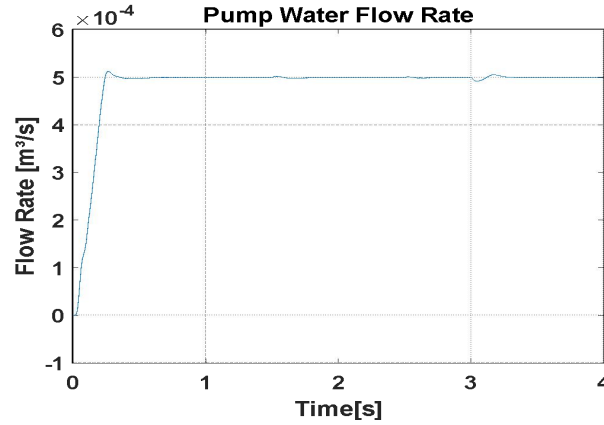


Figure IV.19: Dynamic Response of Pump Water Flow Rate

This figure IV.19 illustrates the dynamic response of the pump water flow rate during system operation. At startup, the flow rate increases rapidly until it reaches a steady-state value of approximately $5 \times 10^{-4} m^3/s$, indicating effective pump operation and fast system response. Small transient variations can be observed around $t = 1.5 s$ and $t = 3 s$ due to operating condition or load changes. However, the flow rate quickly stabilizes after each disturbance, demonstrating the stability and robustness of the adopted control strategy.

IV.5. Conclusion

Based on the simulation results presented in this chapter, it can be concluded that the proposed standalone photovoltaic water pumping system achieves stable and efficient performance under various operating conditions. The Perturb and Observe (P&O) MPPT algorithm effectively maximizes the extracted photovoltaic power, improving the overall energy efficiency of the system. In addition, the Indirect Field Oriented Control (IFOC) strategy ensures accurate speed and torque control of the induction motor, providing stable operation and a satisfactory dynamic response.

The MATLAB/Simulink simulation results validate the effectiveness and robustness of the proposed system under varying environmental conditions and load changes. Therefore, the combination of the P&O MPPT algorithm and the IFOC strategy provides an effective solution for standalone photovoltaic water pumping applications.

General Conclusion

The present study has focused on the analysis, modeling, control, and simulation of a standalone photovoltaic water pumping system designed to provide an efficient, reliable, and sustainable solution for water supply in remote and isolated areas. The integration of photovoltaic energy conversion with advanced control techniques has demonstrated the significant potential of renewable energy systems to enhance energy utilization while reducing dependence on conventional energy sources.

The theoretical analysis presented throughout this work has provided a comprehensive understanding of the operating principles of photovoltaic conversion systems and their associated power electronic interfaces. In addition, the mathematical modeling of the photovoltaic generator, the DC-DC converters, the voltage source inverter, the induction motor, and the centrifugal pump has established a solid foundation for analyzing the dynamic behavior of the overall system and evaluating its performance under different operating conditions.

Particular attention has been devoted to the implementation of the Perturb and Observe (P&O) Maximum Power Point Tracking algorithm to maximize the extraction of photovoltaic power under varying solar irradiance and temperature conditions. The simulation results demonstrate that the adopted MPPT technique effectively tracks the maximum power point, thereby improving the overall energy conversion efficiency and reducing energy losses.

Furthermore, the implementation of Indirect Field Oriented Control (IFOC) has ensured accurate regulation of the induction motor speed and electromagnetic torque. This control strategy provides a fast dynamic response, minimizes transient oscillations, and enhances the stability and reliability of the pumping system during changes in environmental and operating conditions.

The performance of the proposed system has been validated through detailed simulations carried out using MATLAB/Simulink. The obtained results confirm the effectiveness of the developed model and demonstrate its capability to maintain stable operation while ensuring efficient photovoltaic power utilization and reliable water pumping performance under variable climatic conditions.

In conclusion, the proposed photovoltaic water pumping system represents a technically feasible and environmentally friendly solution for sustainable water management, particularly in regions with abundant solar energy resources. Besides reducing dependence on fossil fuels, the system contributes to lower operating costs, improved energy autonomy, and reduced environmental impact.

As future work, further research may focus on the integration of intelligent optimization techniques based on artificial intelligence, fuzzy logic, or adaptive control to

further improve the system performance, efficiency, and robustness. In addition, experimental implementation and real-time validation of the proposed system would provide valuable insights into its practical applicability under real operating conditions.

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Appendices

Appendix A. The Electrical Parameters of the PV Generator

Parameter	Value
Parallel strings	4
Series-connected modules/string	11
Maximum Power (W)	270.116
Cells per module	60
Voc (V)	37.9
Isc (A)	9.07
Vmp (V)	30.8
Imp (A)	8.77
Temp. coeff. Voc (%/°C)	-0.4
Temp. coeff. Isc (%/°C)	0.05

Appendix B – Boost Converter Specifications

Parameter	Value
Converter type	DC-DC Boost Converter
Input voltage range (V)	280 – 416.9
Output voltage (V)	500
Input current (max) (A)	36.28
Switching frequency (kHz)	5
Inductor (L)	6 mH
Capacitor (C)	470 μ F
Duty cycle (D)	0.1 – 0.9
Efficiency (%)	96
MPPT algorithm used	Perturb & Observe
Maximum output power (W)	12,000

Appendix C – Inverter Specifications

Parameter	Value
Inverter type	Three-phase Inverter (VSI)
Input DC voltage (V)	500
Output voltage (V, line-to-line)	380
Output frequency (Hz)	50
Switching frequency (kHz)	5
Modulation technique	Sinusoidal
Rated output power (kW)	11
Efficiency (%)	97

Appendix D – Motor Specifications

Parameter	Value
Motor type	Three-phase Induction Motor
Rated power (kW)	11
Rated voltage (V)	380
Rated current (A)	22.5
Rated speed (RPM)	2900
Number of Pole Pairs	2
Efficiency (%)	92
Power factor	0.85
Starting current (A)	135

Appendix E – Pump Specifications

Parameter	Value
Pump type	Centrifugal Pump
Rated power (kW)	11
Rated flow rate (m ³ /h)	45
Total Dynamic Head – TDH (m)	60
Pump efficiency (%)	75
Number of stages	6